CMOS Image Sensors – From Zero to Billions: A Story of Technology Innovation

Eric R. Fossum

Connecticut Symposium on Microelectronics & Optoelectronics

April 1, 2015

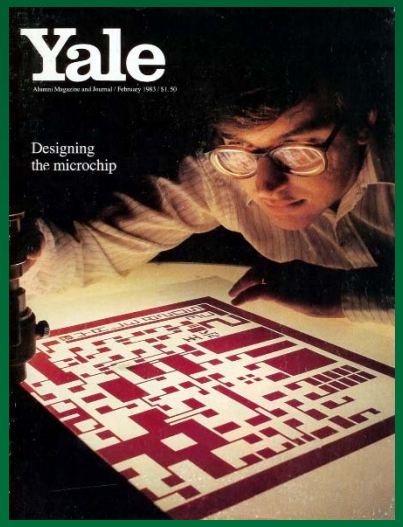
Univ. of Bridgeport, CT

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

Agenda

- Story of the CMOS image sensor invention and commercialization

Trinity College
HARTFORD CONNECTICUT



Feb 1983

COLUMBIA | ENGINEERING
The Fu Foundation School of Engineering and Applied Science

1990

NASA JPL
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

This story starts here

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CMOS Image Sensors Enable Billions of Cameras Each Year

http://img.gawkerassets.com/img/18caaca96tsnsjpg/original.jpg

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Many kinds of digital cameras

Photography
- Camera phone
- Digital single lens reflex (DSLR)
- Mirrorless and Point-and-shoot

Video
- TV (0.3Mpix), HDTV (2Mpix) UDTV (133Mpixel)
- Webcam
- High speed – slow motion
- Motion capture
- Gaming
- Glass

Medical
- Endoscopy
- Pill camera
- X-ray camera

Machine Vision
- Automotive (e.g. “smart beam” headlight dimmer)
- Security
- Inspection

3D ranging
- Gesture control

Etc.

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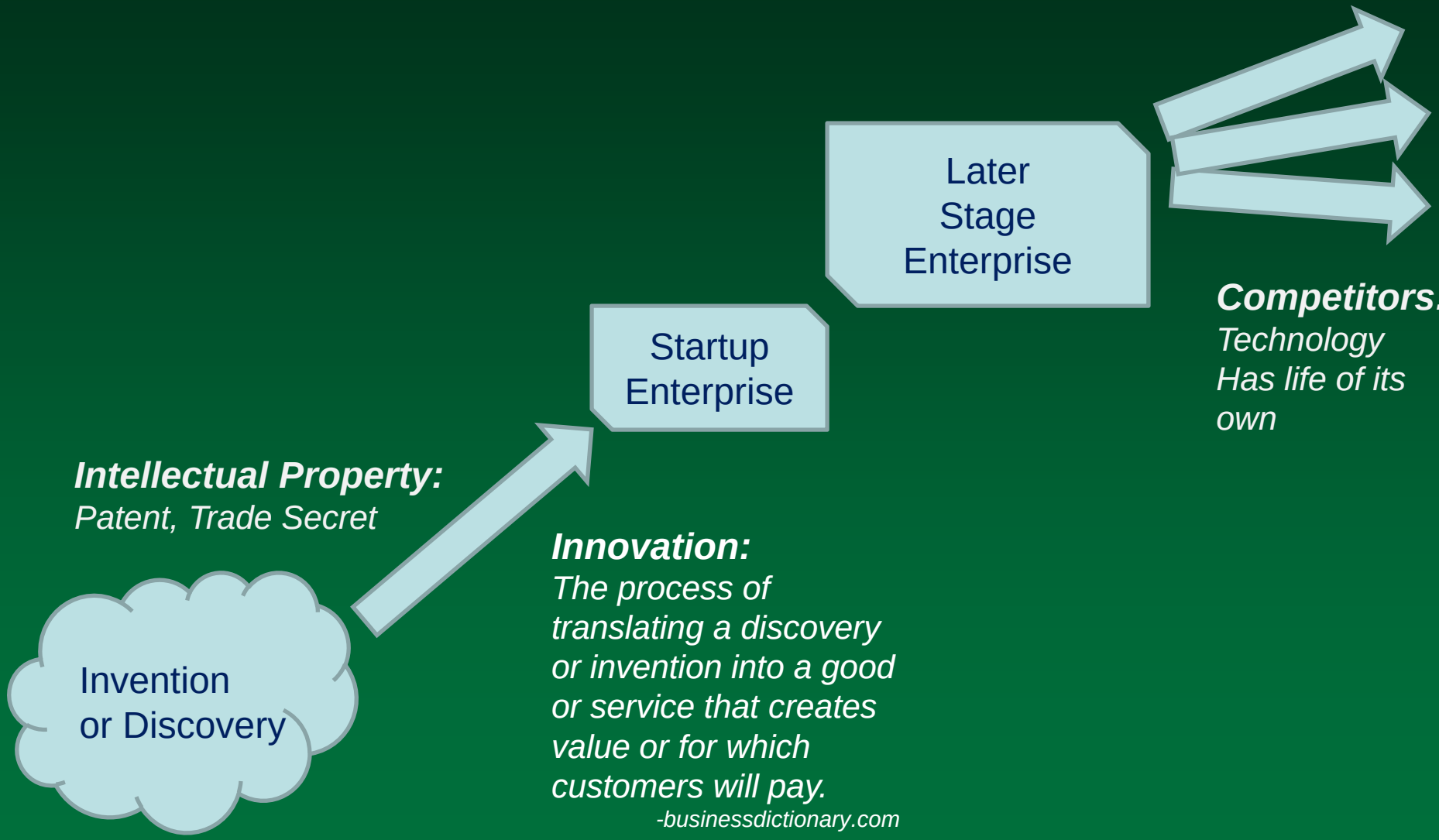
Technology Innovation and Entrepreneurship Arc



Competitors:
Technology Has life of its own

Intellectual Property:
Patent, Trade Secret

Innovation:
The process of translating a discovery or invention into a good or service that creates value or for which customers will pay.
-businessdictionary.com

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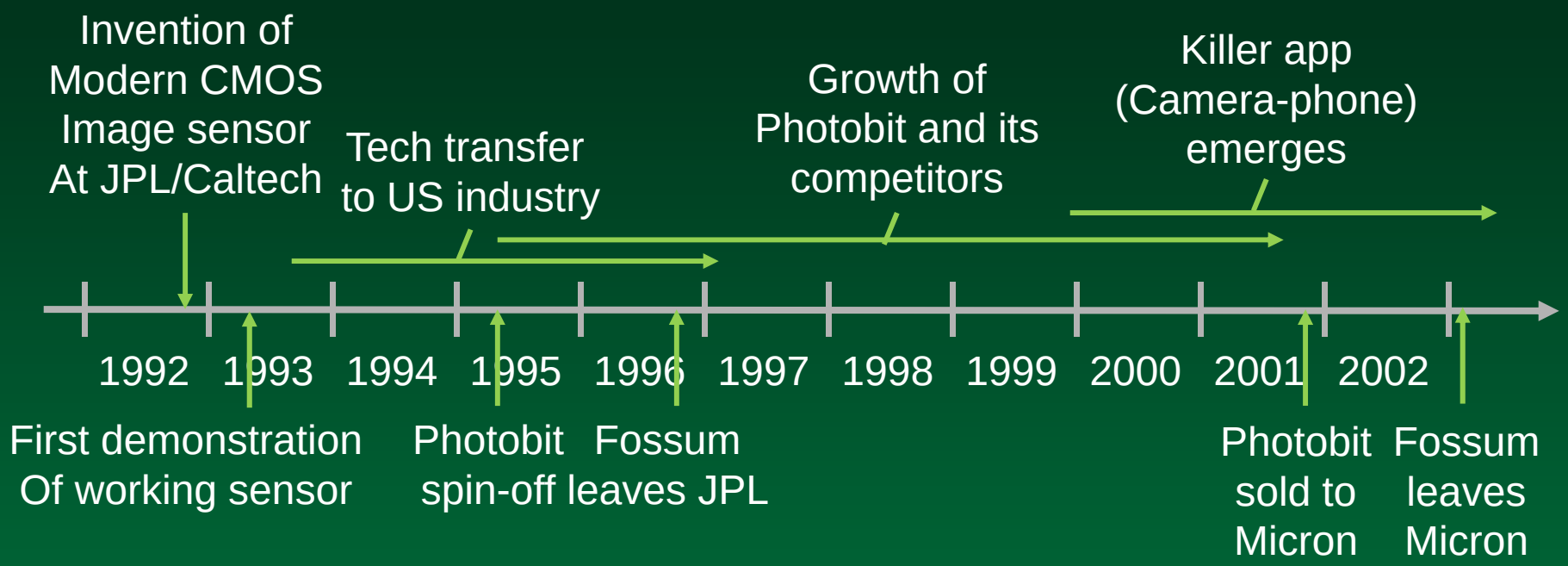
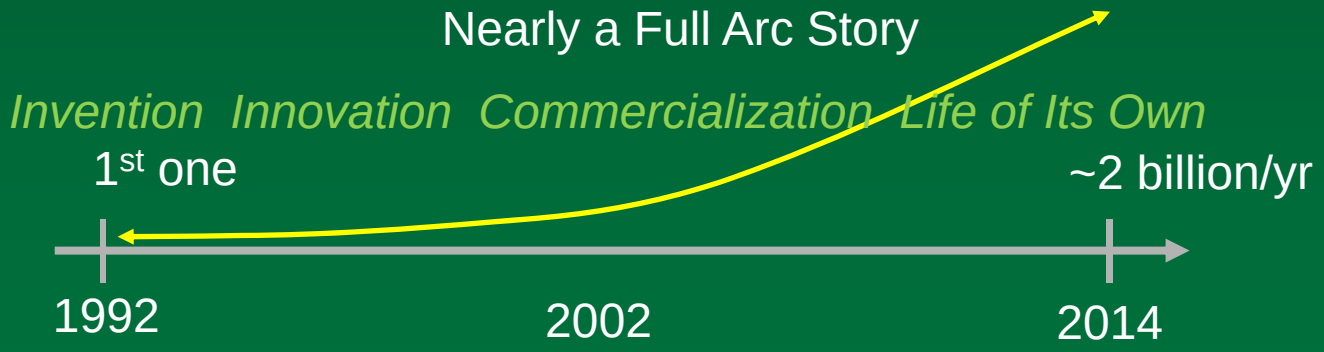
Timeline for the early story





E.R. Fossum, Camera-on-a-Chip: Technology Transfer From Saturn to Your Cell Phone, Technology and Innovation, Vol. 15, pp. 197–209, December 2013.

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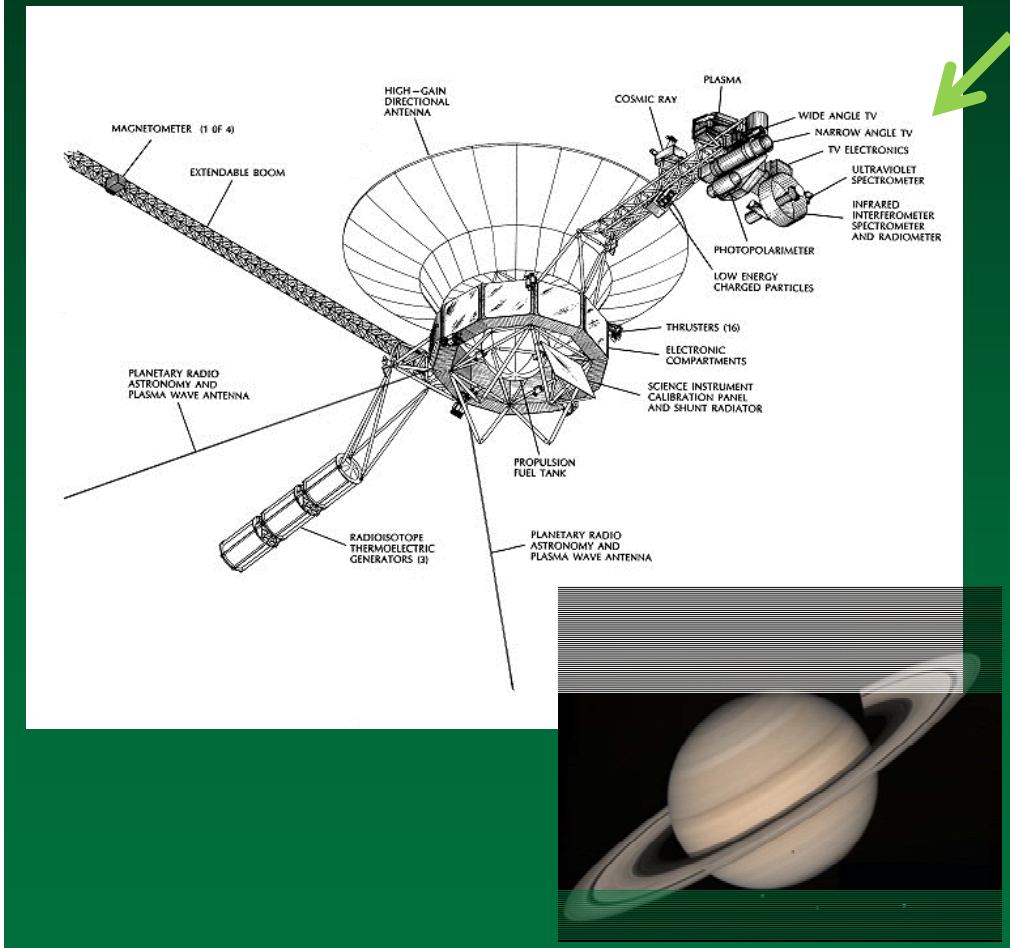
"Necessity is the Mother of Invention"

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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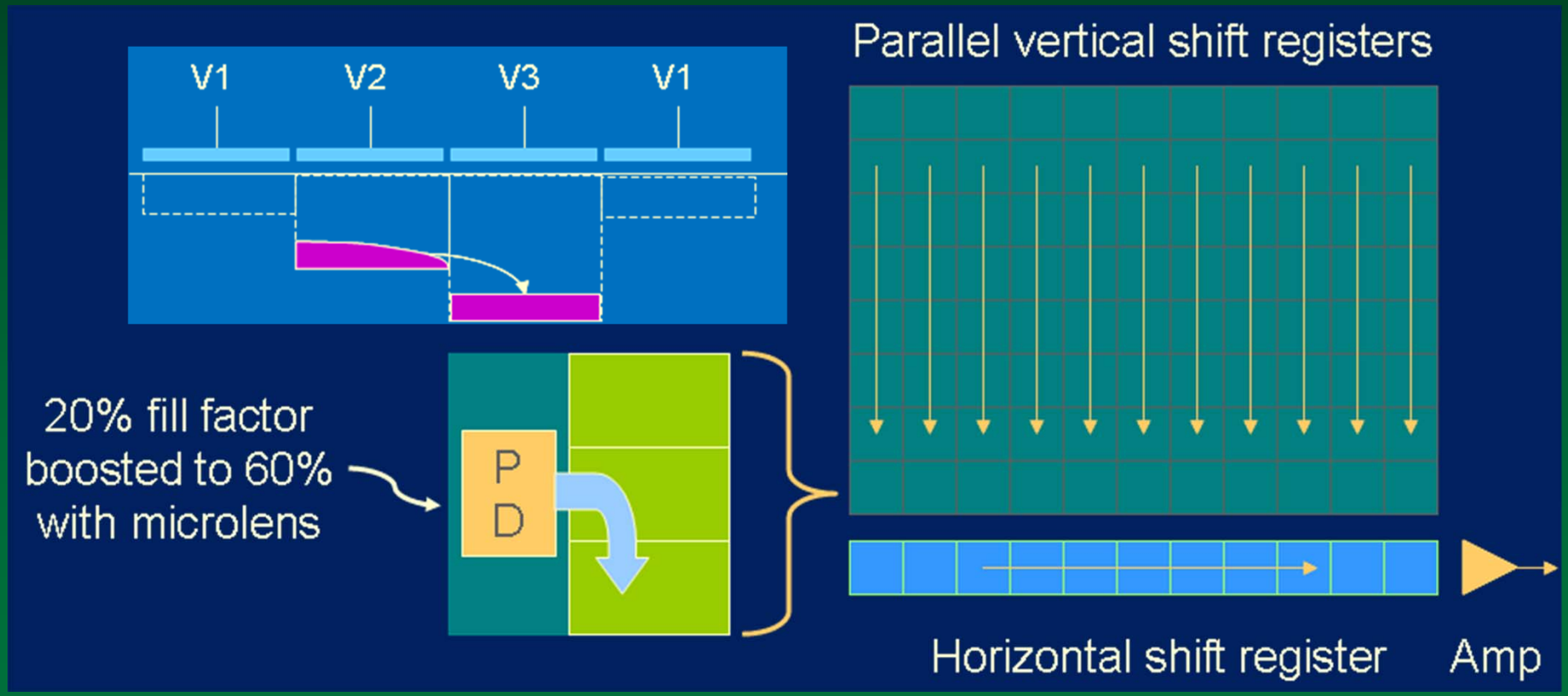
Charge-Coupled Device
1st Generation Image Sensor

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

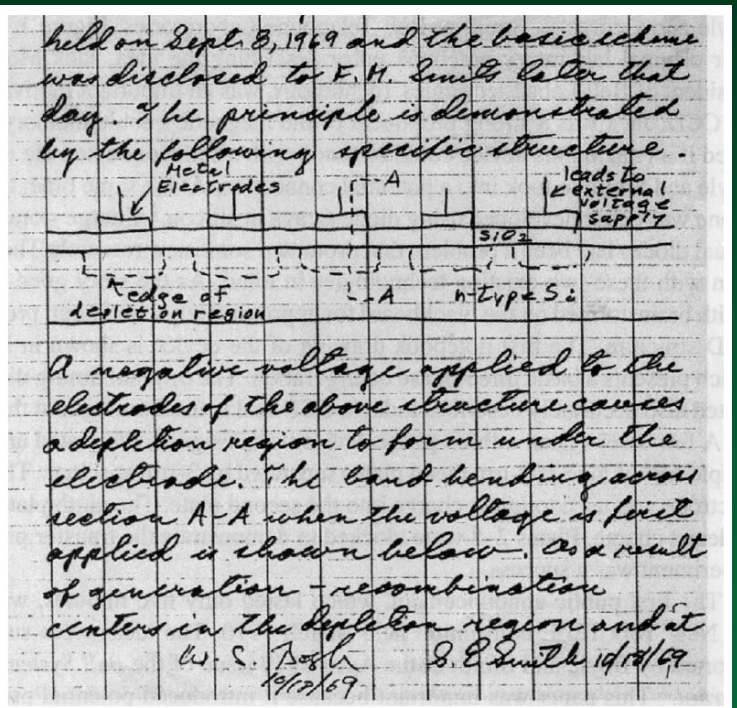
held on Sept. 8, 1969 and the basic scheme was disclosed to F. H. Smith later that day. The principle is demonstrated by the following specific structure.
Metal Electrodes
A
Leads to external voltage supply
SiO_2
Edge of depletion region
A
n-type Si
A negative voltage applied to the electrodes of the 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 9/12/69
G. E. Smith 9/12/69

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

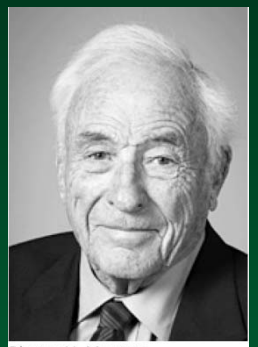
Photo: U. Montan
Willard S. Boyle


Photo: U. Montan
George E. Smith

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

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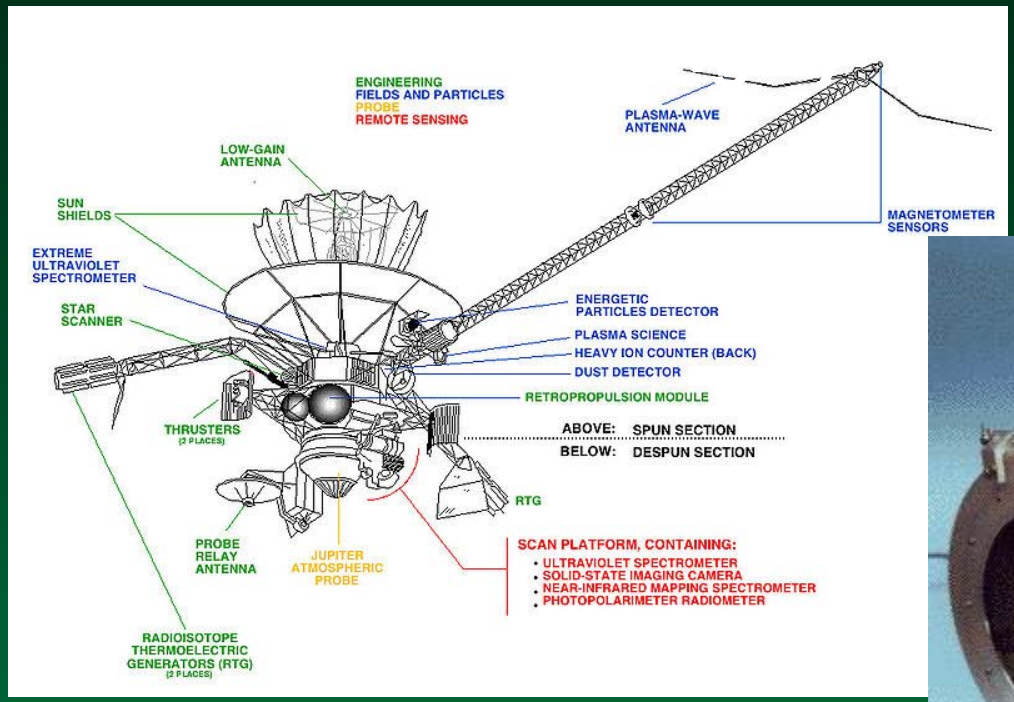
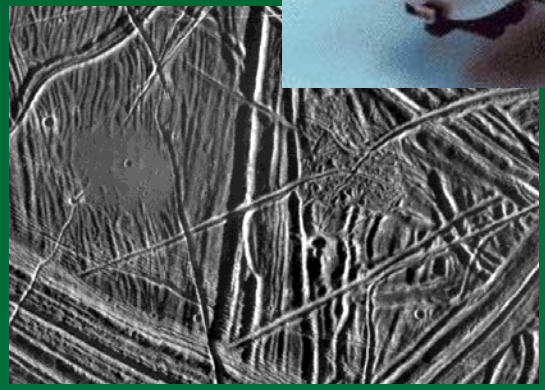
Galileo (1989) SSI had CCD cameras (wide angle and narrow



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

Callisto



Europa

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

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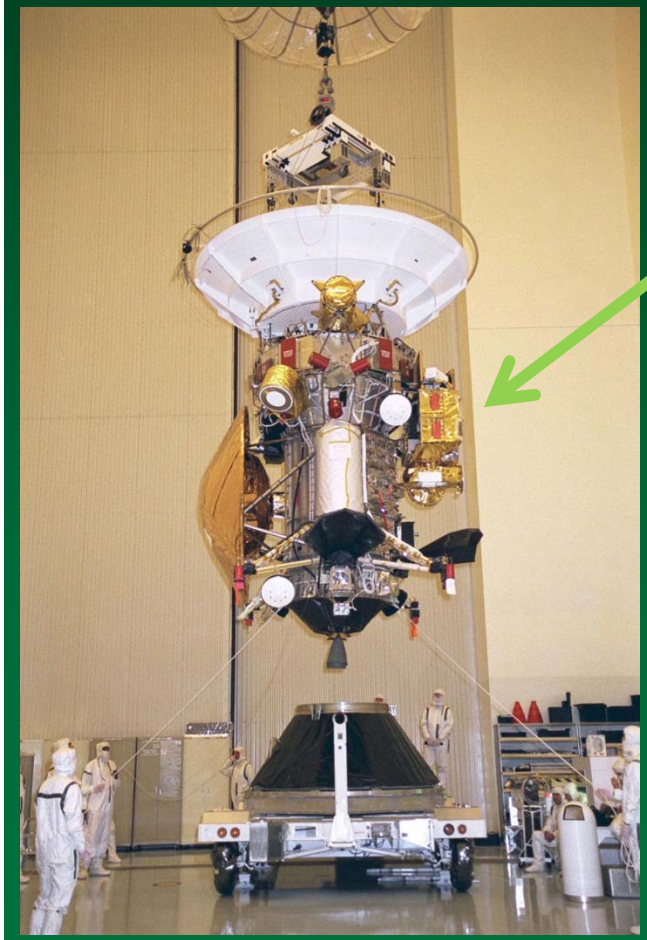
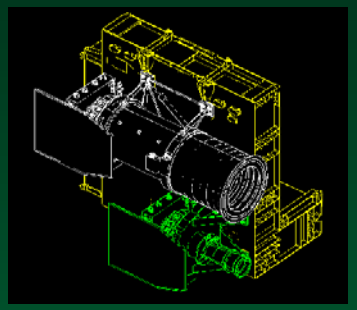
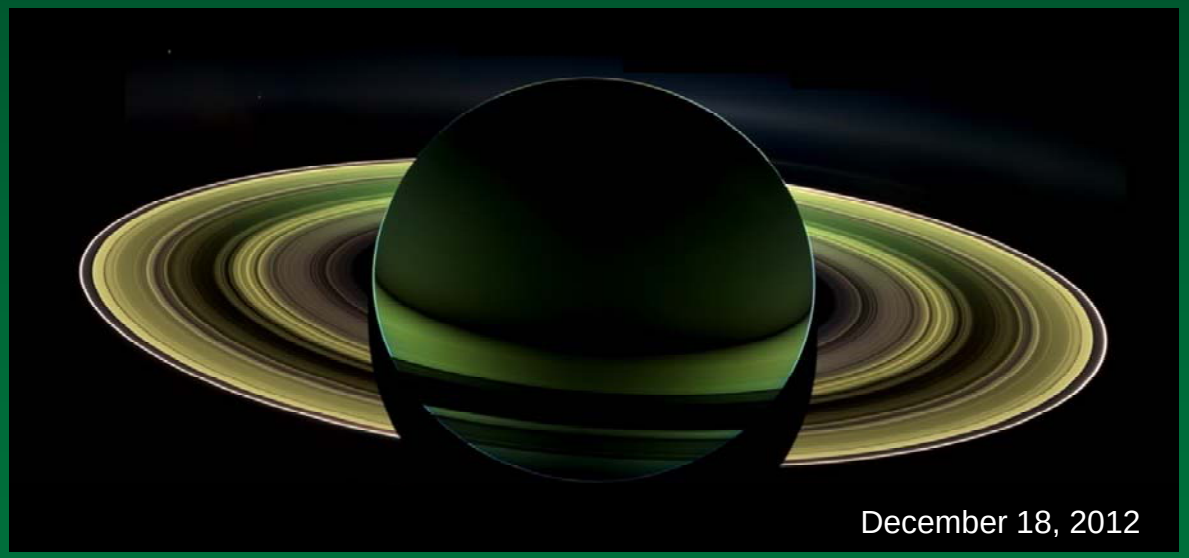
Cassini (1997) ISS has CCD cameras (wide angle and narrow angle)

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







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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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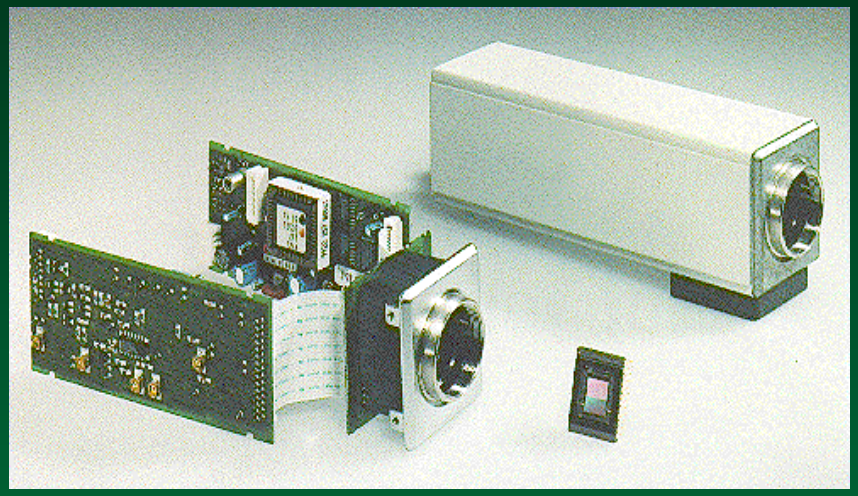
Need for a New Image Sensor Technology



CCD cameras have many components and consume significant power.

BUT, the CCD is not amenable to electronics integration

Already looking at existing active pixel sensors (APS) to address problems with space-based CCD imaging:

- Radiation impact on CCD charge transfer efficiency
- High voltages needed for CCD charge transfer
- Impact of temperature on CCD operation
- Slow readout rate
- Serial access to data

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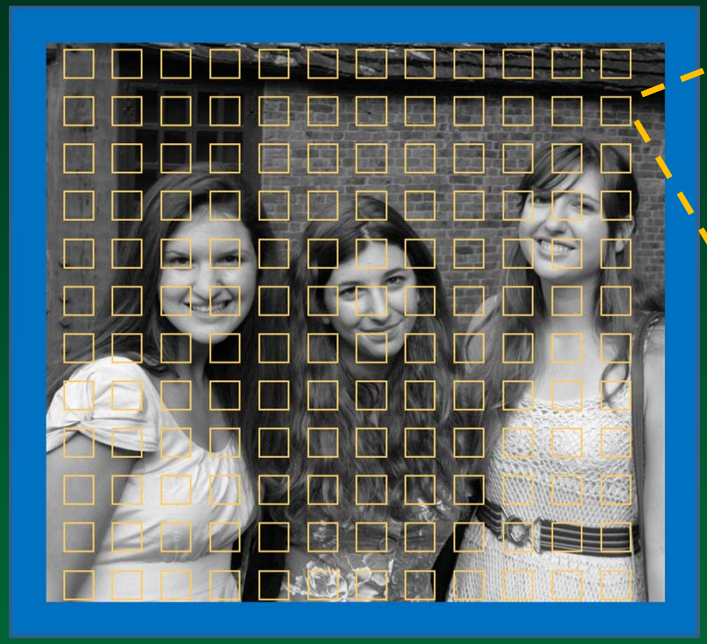
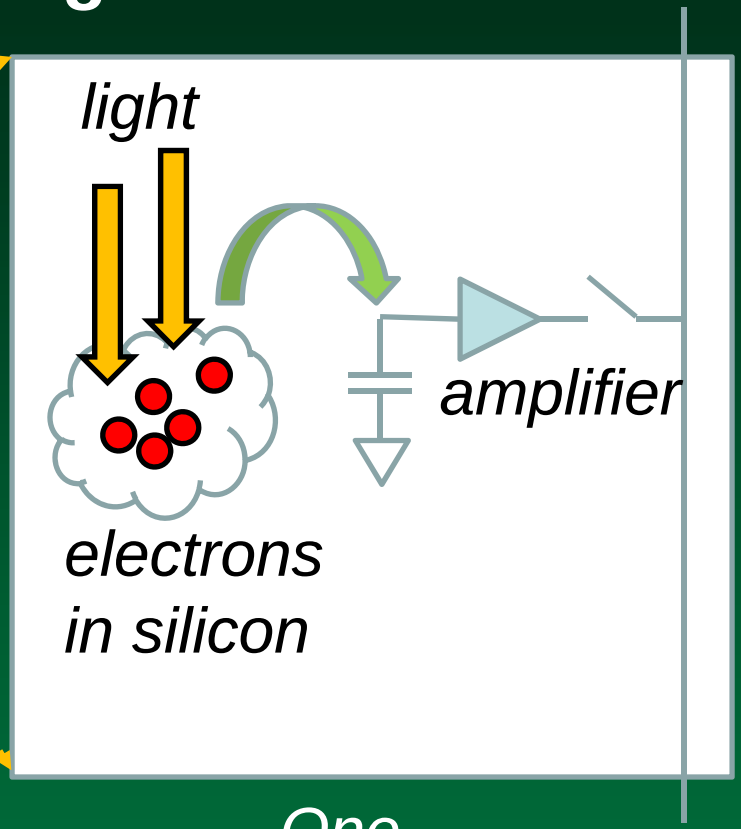
Active Pixels with Intra-Pixel Charge Transfer





One pixel

United States Patent [19]

Fossum et al.

[11] **Patent Number: 5,471,515**

[45] **Date of Patent: Nov. 28, 1995**

[54] **ACTIVE PIXEL SENSOR WITH INTRA-PIXEL CHARGE TRANSFER**

[75] Inventors: **Eric R. Fossum**, LaCrescenta; **Sunetra Mendis**, Pasadena; **Sabrina E. Kemeny**, LaCrescenta, all of Calif.

[73] Assignee: **California Institute of Technology**, Pasadena, Calif.

[21] Appl. No.: **188,032**

[22] Filed: **Jan. 28, 1994**

4,859,624	8/1989	Goto	257/371
5,184,203	2/1993	Taguchi	257/370
5,192,990	3/1993	Stevens	377/60
5,198,880	3/1993	Taguchi et al.	257/370
5,323,052	6/1994	Koyama	257/294

FOREIGN PATENT DOCUMENTS

5235317	9/1993	Japan	257/258

Primary Examiner—Gene M. Munson
Attorney, Agent, or Firm—Michael L. Keller; Robert M. Wallace

[57] **ABSTRACT**

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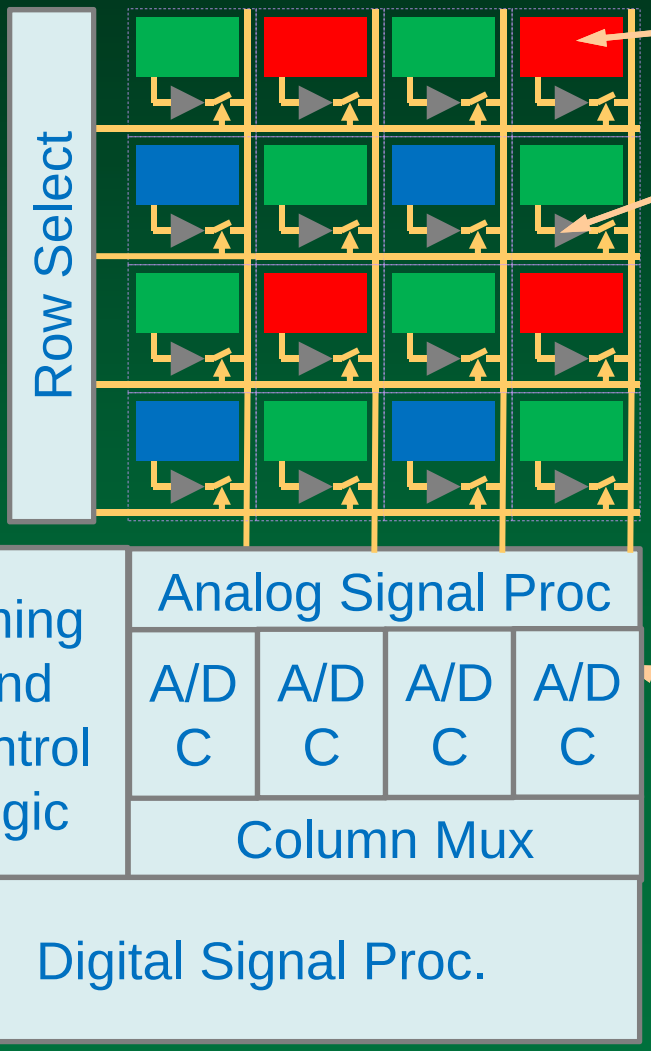
CMOS Active Pixel Sensor
2nd Generation Image Sensor
Read pixel signals out thru switches and wires



Row select logic chooses which row is selected for readout.

Timing and control logic controls the timing of the whole sensor

SoC functionality for color processing, compression, etc.

Photodetector converts photons to electrons

Amplifier converts electrons to voltage after intrapixel complete charge transfer

Analog signal processor suppresses noise and further amplifies signal

Analog-to-digital converters (ADC) convert signals from volts to bits (usually 10-12 bits resolution) in parallel

Column multiplexer used to scan ADC outputs

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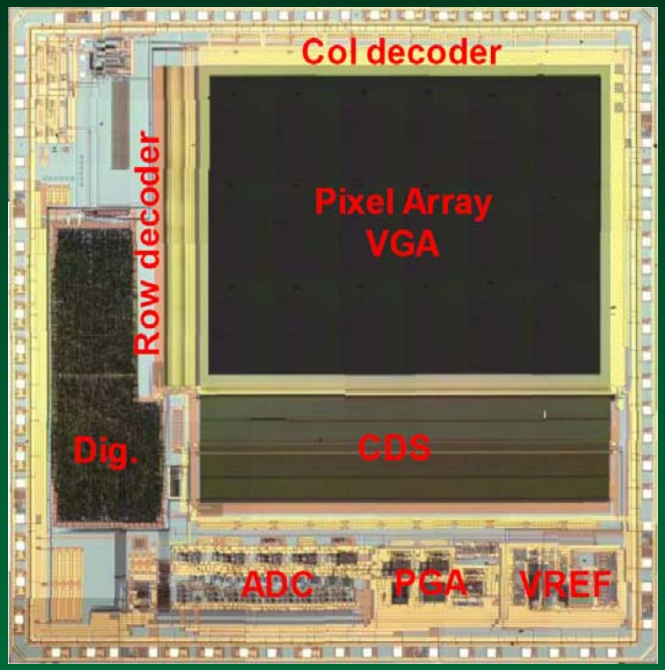
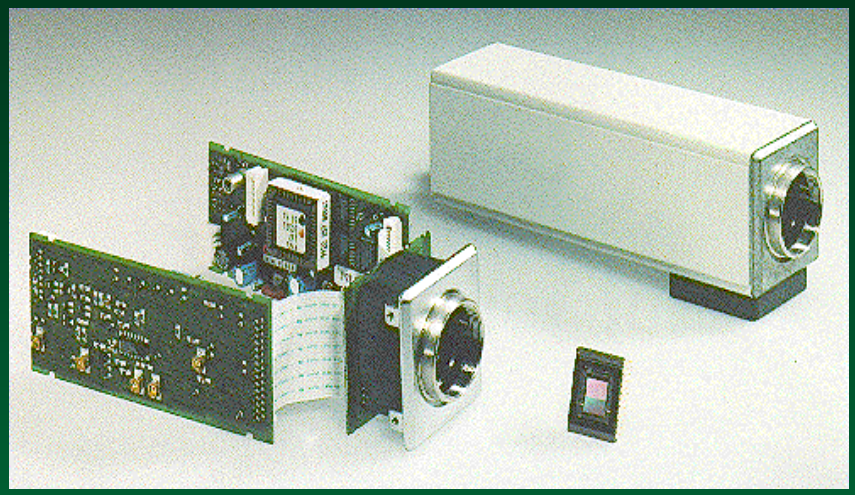
Camera-on-a-Chip Enables Much Smaller Cameras



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



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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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Technology Transfer

It was immediately clear that this technology would be useful for "down-to-earth" applications.

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 in dental radiography)

And other agreements/visits with

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

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Technology Transfer

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

S.Kemeny, N. Doudoumopoulos, E. Fossum, R. Nixon

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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

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

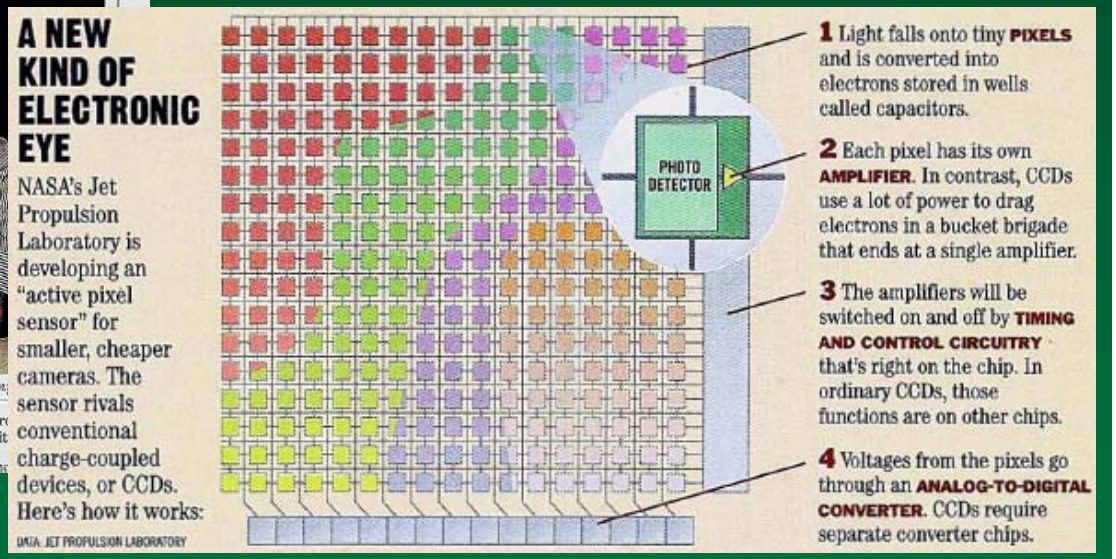
Get ready for the camera-on-a-chip. Since the 1970s, camera makers have dreamed of a one-chip camera containing all the components necessary to take a snapshot or make a movie. With all the smarts on one chip instead of several, designers figure they could make a camera small and cheap enough to open 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

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

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



March 6, 1995 Business Week article

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Spin-off is a loose term

- For Caltech in 1995, licensing the inventors at JPL (an FFRDC) to commercialize their own technology was a new thing never done before. Caltech very worried about possible appearance of a conflict of interest.
- No organized plan to spin-off the company. We just did it. Some people at Caltech and JPL were supportive, some were not.
- Hiring away people from JPL to Photobit caused some concern as well.
- Ultimately, the exclusive license was fair and reasonable to all parties.
- Success has many mothers and fathers.

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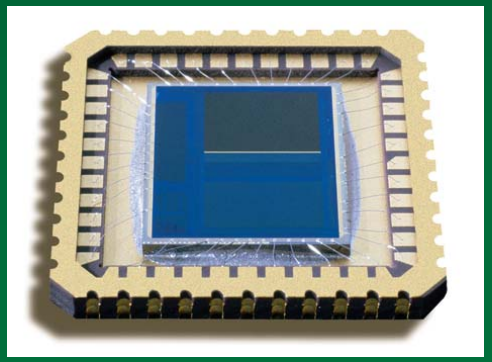
Perspiration Phase

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

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Miller Time

Nov. 2001 – Photobit acquired by Micron Technology and license reverts back to Caltech

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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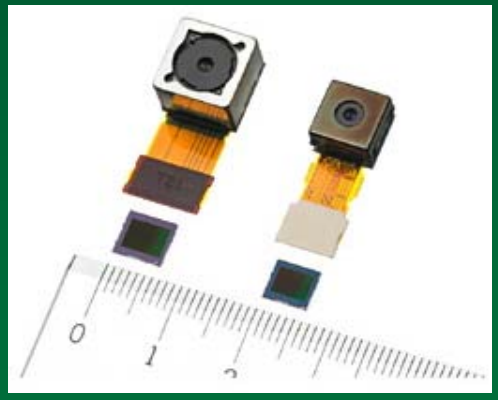
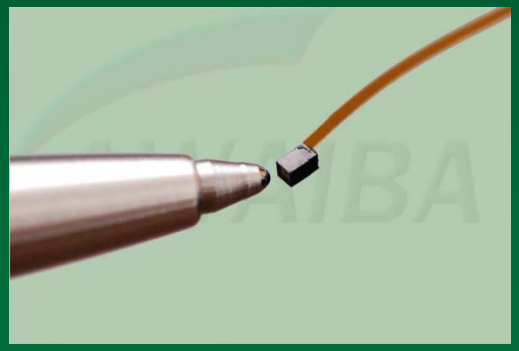
The Technology Develops a Life of its Own

- Today, over 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. Thousands of engineers working on this.
- Caltech has successfully enforced its patents against all the major players.
- NASA is now just adopting the technology for use in space.



16Mpix camera modules
From Sony ~2012



Endoscopy Camera
From Awaiba ~2012

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New Technology Invariably Brings New Social Issues

Body Cameras

Rapid Social Change (Arab Spring)

Inappropriate use

Visual overload (e.g. Japanese Tsunami)

Security v. Privacy

New Weapons

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Ad hoc advice for Faculty Entrepreneurs

- Decide if you are going to be CEO (you can learn the business skills, it is not rocket science). Most faculty skills translate well into the business sector.
- Business is NOT collegial. It is Darwinian in action.
- Being CEO Is a full contact sport, and full time. Might require taking leave from a faculty position.
- If you are CEO, remember: not only do you have a duty to your shareholders, you also have a duty to nurture your growing tribe that is your company.
- Turning over the leadership to someone else is a lot like marrying so that some else will take care of your child. Use extreme care in vetting this person. Divorce will be ugly.
- Avoid giving any appearance of a conflict of interest – students, sponsors, investors, time.

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

-Business Week
1995

- Became true but…..but no one would have licensed this invention if we and Caltech had not tackled each of these daunting tasks:
  - Innovating the invention at JPL
  - Growing a company to commercialize the technology
  - Delivering on the promises of cheaper, lower power, smaller, etc. in a **COMPELLING** way relative to the incumbent CCD technology
  - Selling the company
  - Caltech asserting its patents against the big companies.

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Fast Forward

past 1st "retirement" '03-'04

Siimpel Corporation '05-'07 CEO

2nd brief "retirement"

Samsung Electronics '08-'13 consulting

to

Current Work on Quanta Image Sensor (QIS) at Dartmouth

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Group at Dartmouth

L-R: Song Chen, Saleh Masoodian, Rachel Zizza, Donald Hondongwa, Dakota Starkey, Eric Fossum, Jiaju Ma, Leo Anzagira

-30-