The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2223-15

Winter College on Optics in Imaging Science

31 January - 11 February, 2011

Four Centuries of Optical Imaging Technology

RHODES William T.

Florida Atlantic University
Dept. of Computer and Electrical Engrng & Compuater Science
FL 33431 Boca Raton
U.S.A.

Four Centuries of Optical Imaging Technology

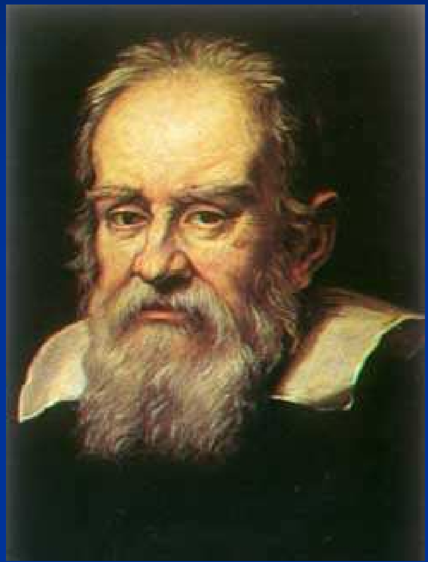
William T Rhodes, Ph.D.

Professor Emeritus, Georgia Institute of Technology
Professor of Electrical Engineering and
Affiliate Professor of Physics
Associate Director, Imaging Technology Center
Florida Atlantic University
wrhodes@fau.edu

Preliminary thoughts

- Technological advances come primarily through technologists, not scientists – but through technologists who *know science*.
- Optics is frequently referred to as an *enabling science.* It continues to foster important technological developments at a high rate.
- *Economics* plays an extremely important motivational role in technology development.

Our starting point



Four centuries ago…

Galileo Galilei, 15 February 1564 – 8 January 1642), scientist-technologist, 200 km from Trieste.

Galileo has been called the "father of modern observational astronomy, the "father of modern physics,“ the "father of science,” and "the father of modern science.” (He also fathered two daughters and a son.) Stephen Hawking says, "Galileo, perhaps more than any other single person, was responsible for the birth of modern science.“ He was also a technologist, who ground lenses, built telescopes, and sold them, thereby starting a new industry.

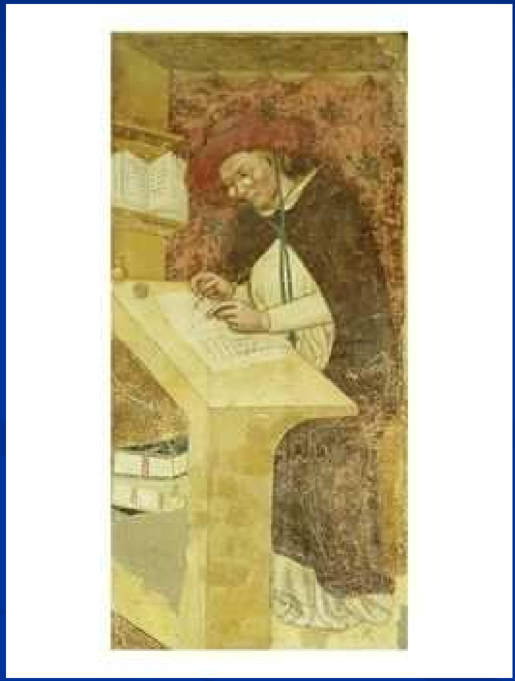
What existed four centuries ago?

- Eyeglasses: crude but quite useful for older people
- Magnifiers: some of remarkably high quality
- Telescopes: seriously limited by imperfections but nevertheless astonishing in what they revealed

1. Eyeglasses

Clerical reader with
eye glasses, ca. 1435

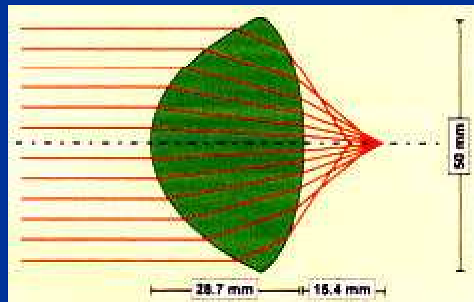
Hugues De Provence at His Desk, by Tommaso Da Modena, ca. 1355



Eye glasses were in use as early as the late 1200s, 300 years before the telescope, probably as an extension of the magnifier.

2. Magnifiers

Vikings in Gotland appear to have ground and polished high-quality aspheric magnifiers from quartz around 1000 AD. Resolution: 25-30 µm

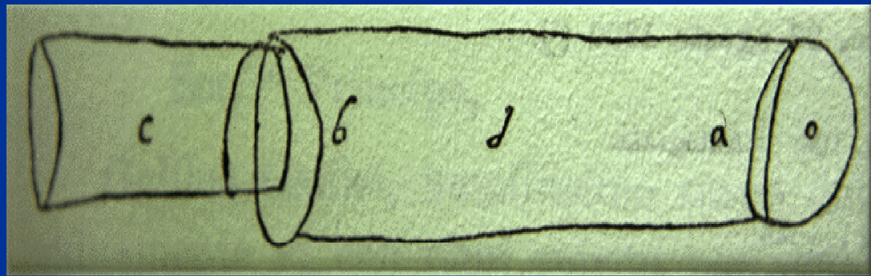


These magnifiers discovered in the 1970s

According to researchers, “It is clear that the craftsmen who figured the lenses knew more about applied optics than did the scientists of the time. They must have worked by trial and error because the mathematics to calculate the best shape for a lens did not become available for several hundred years.”

3. Telescopes

Giambattista della Porta 1589,
Magiae naturalis libri XX



Compound telescope by Sacharias Jansen, ca. 1604

A telescopy by Jansen was probably the first seen by Galileo.

Eye Glasses: The first optics industry

Glasses were sold in the city markets in the 1500's.

The Spectacle Vendor by Johannes Stradanus, engraved by Johannes Collaert, 1582.

Eye Glasses: Technology Advances

- Positive lenses (1300s)
- Negative lenses (1700s)
- Bifocals (1780)
- Astigmatism correction
- Progressive lenses
- New Materials
- Photochromic lenses
- Contact lenses
- Intraocular implant lenses
- Accommodating intraocular lenses

Progress has sometimes been a result of new science, but primarily motivated by commercial opportunities.

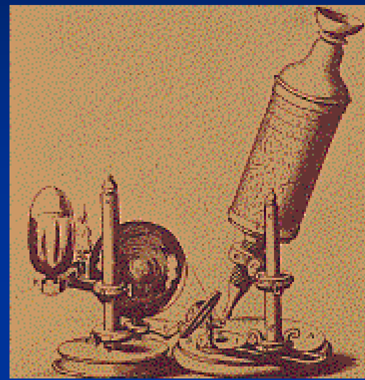
From Magnifiers to Microscopes

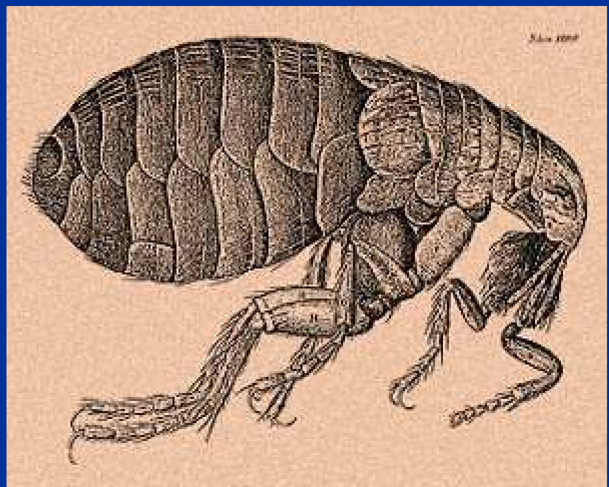
1665: Robert Hooke, compound microscope with doublet eyepiece, 30x magnification. Greatest experimental scientist of 17th century.

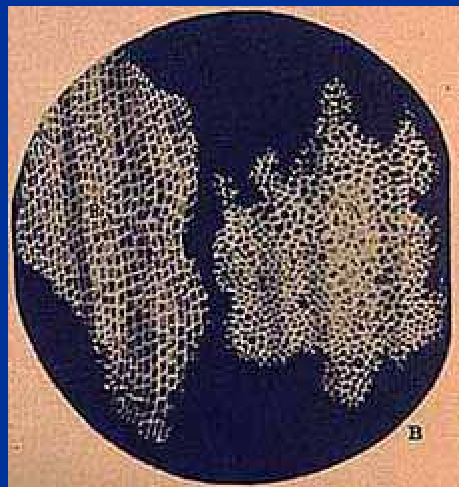
~1670: Antony van Leeuwenhoek, single-lens microscope, 200x, bright images. A great technologist and careful observer.

Hooke's Microscope

Hooke developed the compound microscope, with separate objective lens and eyepiece magnifier.







Hooke's *Micrographia*, 1665, excited people around the world.

Leeuwenhoek's Microscope

The lens has the form of a tiny oil drop. Hooke found Leeuwenhoek's microscope difficult to use, but the images obtained with it were fantastic for the day.

Single-lens image of unstained blood cells

Spiral bacteria

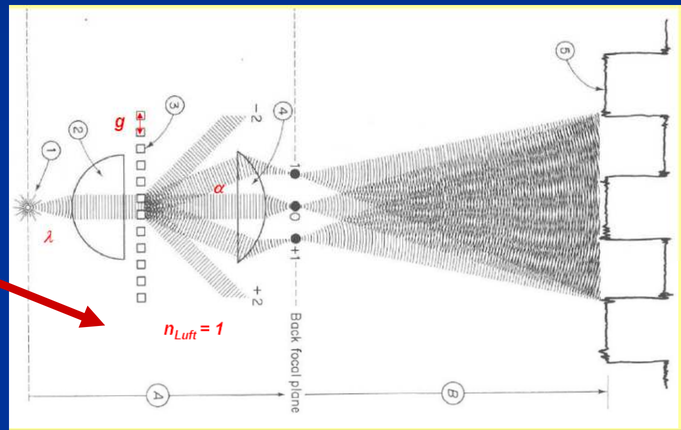
Replica Oil Drop Microscope

Courtesy James Mahaffee, Georgia Tech Research Institute

Leeuwenhoek kept one aspect of his work secret for some time: To reduce aberrations, he made the aperture smaller.

Not knowing his secret, many people questioned his work and doubted that he had actually seen those tiny “animals.”

Theoretical Developments



The development by Ernst Abbe in the 1870s of the diffraction theory of image formation in a microscope moved people away from “empty” magnification and in the direction of ever better microscope systems. Abbe worked for Carl Zeiss.

Abbe was a scientist, but even more a technology developer.

Ernst Abbe, 1840-1905

- Focometer
- Refractometer
- Spectrometer
- Apertometer
- Diffraction theory of image formation in a microscope
- Abbe number
- Sine condition
- Abbe condenser
- Eight-hour workday
- Staff pension fund
- Paid vacations
- Health insurance plan
- Sick pay
- Antidiscrimination policy

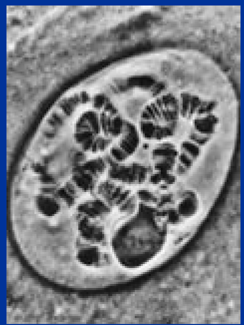
Phase Contrast Microscopy

Frits Zernike – 1953 Nobel Prize Winner

Zernike made significant contributions to coherence theory, ophthalmic optics, and clarified important conditions for illumination optics in microscopes.

Prototype of phase contrast microscope 1936

Allowed direct imaging in a microscope of phase objects, which previously could not be seen without staining



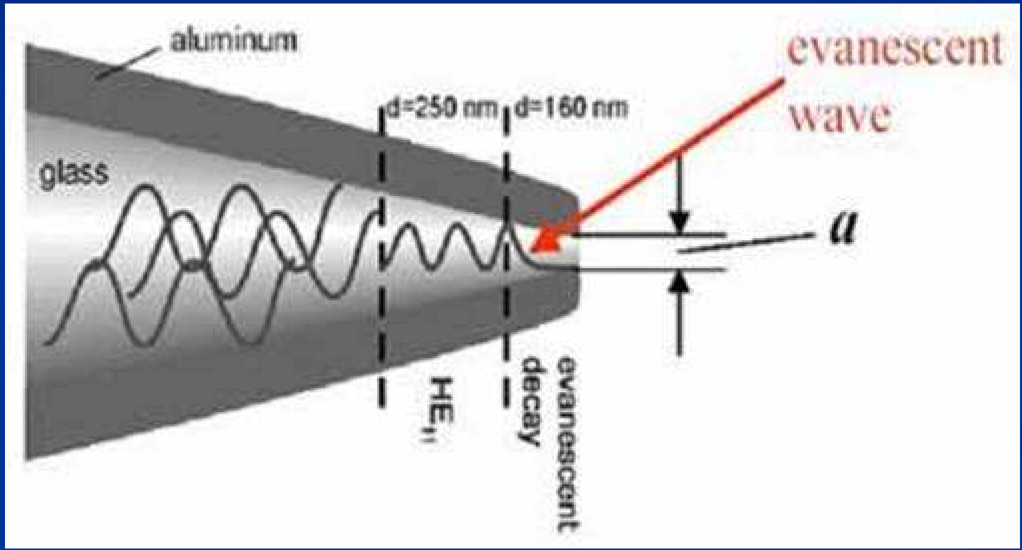
Nucleus of salivary gland 1941

From scientific concept to commercial products.

New additions

- Nomarski nterference contrast microscope provides new capabilities
- Scanning confocal microscope increases transverse resolution by the square root of two.

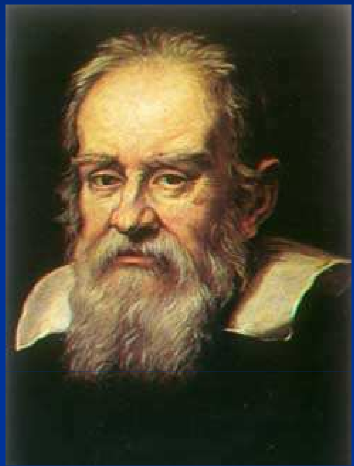
Scanning Near Field Optical Microscopy

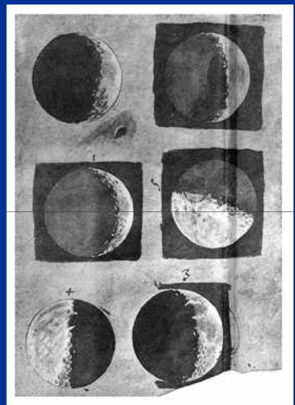


1990s

Light passes through a sub-wavelength diameter aperture and illuminates a sample at a distance much less than the wavelength of the light. Scattered light is measured by a detector in proximity to the sample. Critical for nanotechnology.

Telescopes





Galileo Galilei, 1564 – 1642.

Galileo advanced telescope technology 1606-1610: 10X, 3” of arc, 0.1” resolution

Produced many telescopes to sell and give away.

Entrepreneur and politically shrewd individual.

A scientist who was also a *technologist*.

Contended with poor optical quality glass, which presented the principal limitation to telescope performance.

Glass-Making Technology
(for centuries an important industry)

October 1547 edict from the Venetian Council of Ten
"If a [glassmaking] workman transport his art into a foreign country to the injury of the republic, a message shall be sent to him to return; if he does not obey, the persons most nearly related to him shall be put into prison. If, notwithstanding the imprisonment of his relatives, he persists in remaining abroad, an emissary shall be commissioned to put him to death."

- Glassmaking widespread in pre-Christian era
- Optical instrument quality dependent on the quality of the glass and the ability to shape it properly.
- 1674 English glassmaker George Ravenscroft patents new lead crystal glass (crown glass)
- 1733 Hall, compound achromat principle (contrary to Newton)

Hans Lippershey in Holland was issued a patent by his government in 1608, with many important commercial developments following.

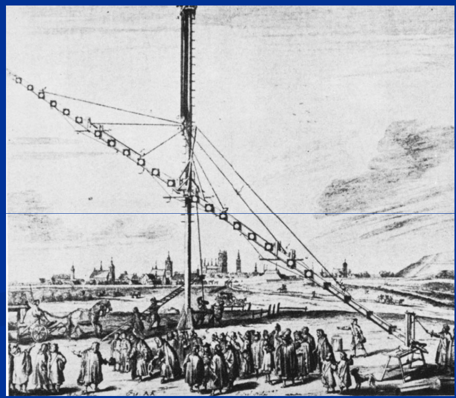
Newton demonstrated his reflector telescope before the Royal Academy in London in 1672. Disappointed members told him to return with a better demonstration model.

The reflector eliminated the chromatic aberrations characteristic of refractors and allowed for the manufacture of much smaller telescopes.

More on Telescopes

Astronomical telescopes were improved over centuries, but until quite recently the changes were primarily evolutionary.

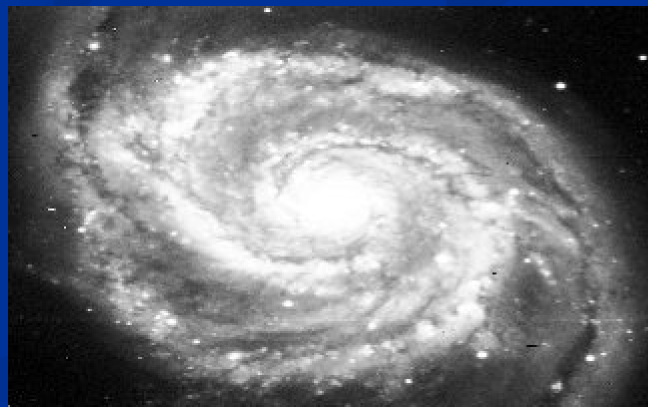
45m focal length telescope Hevelius in 1673 (a long focal length increases magnification and minimizes the effect of defects)



The Birr telescope in Ireland, first operating in 1845, was the largest telescope in the world for 70 years. The 72” mirror was of metal. Large glass mirrors came later.

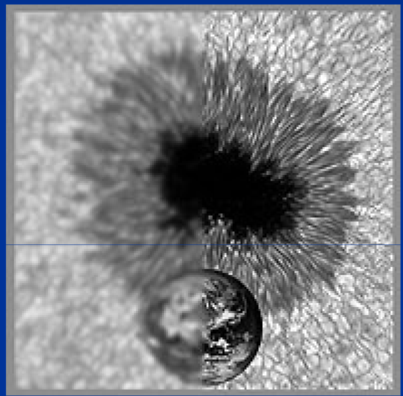
Big Birr

First observations of spiral galaxies.



Adaptive Optics Telescopes

New technology improves images - 1980's through today



Adaptive-optics "rubber-mirror" telescopes can compensate for atmospheric turbulence by feedback-controlled deformation of the telescope mirror surface by high-speed actuators.

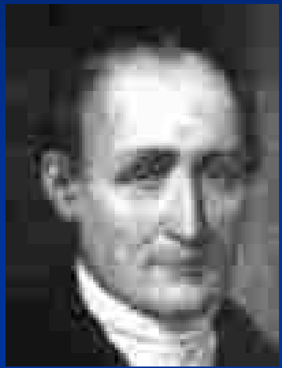
Images of sunspot and earth: left without adaptive correction, right with. Sunspot size compared with size of earth.

Early research connected with "Star Wars" missile defense program. Commercial applications now being developed in areas other than astronomy.

Beyond the Original Three

- Photography
- Holography
- Image Transmission

Recording the Image: The Birth of Photography



Joseph Nicephore Niépce
after 30 years of trying

First “heliograph” (eight-hour exposure) 1827

Partnered with Louis Daguerre in 1829. Daguerre was famous for his dioramas, which he hoped to improve through the use of the new photographic process.

Daguerre dioramas c. 1825

The Ruins of Holyrood Chapel.

The Effect of Fog and Snow Seen through a Ruined Gothic Colonnade

The Daguerreotype led the Revolution

Daguerreotype

Perfected by Louis Daguerre in 1839. Rights purchased by the French Government.

Beautiful, but cannot make copies.

Many subsequent inventions followed, improving and simplifying, but all based on the same principle and operating with silver halides.

In 1939, Neblette, in his book *Photographic Principles,* described more than 30 methods for recording color photographs…and Kodachrome had just been developed!

Positive-Negative Process

- The Calotype, invented by William Henry Fox Talbot around 1840, allowed the production of many positive prints from a single paper negative. The technique was later improved when photographic emulsions were put on glass.

Print made by Talbot, c. 1840

Commercial Impact!

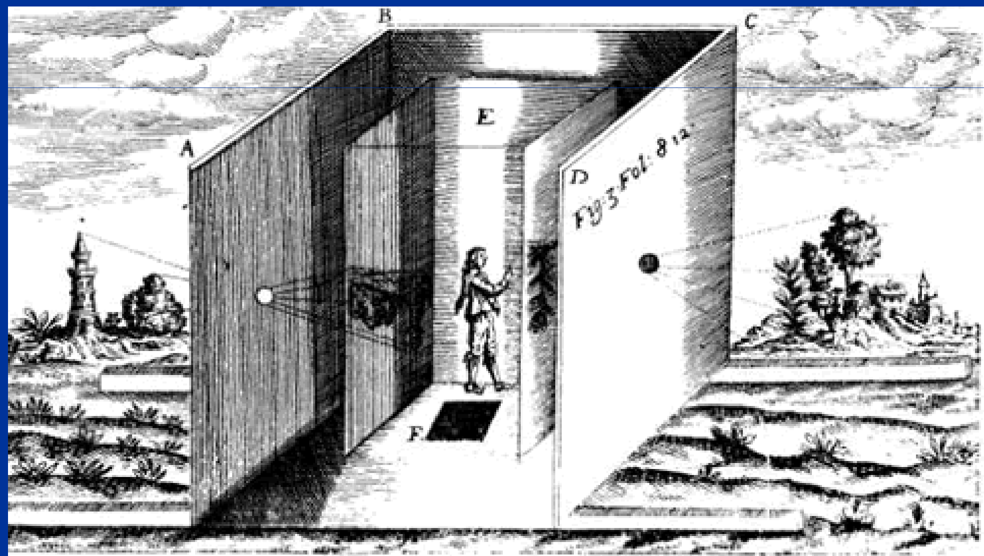
In 1850 there were 77 photographic galleries in New York City…*before* the development of the important collodion process that greatly facilitated production!

And in 1900 George Eastman's Brownie camera brought photography to the masses.

Quiz question: How many cameras are there now in the world?

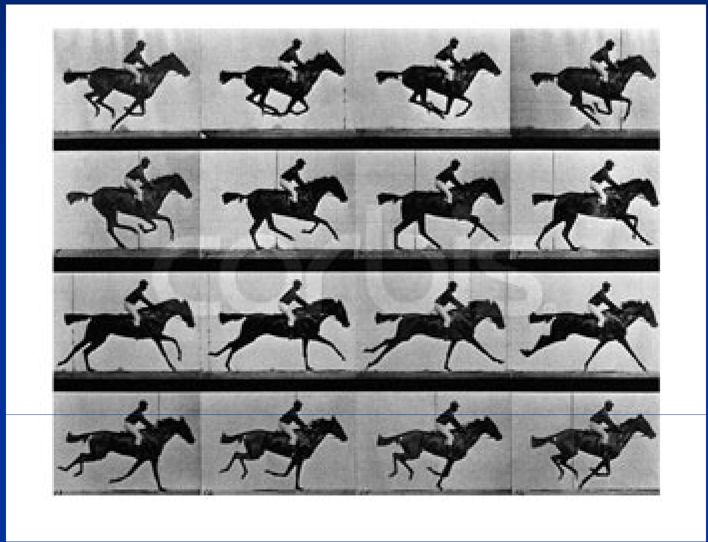
Why the Delay?

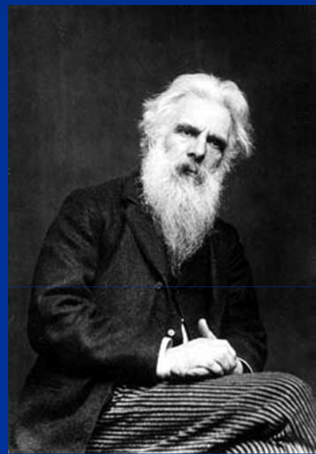
- Silver Nitrate's photochemical properties known in 1500s, rediscovered in early 1600s
- The camera obscura was studied by Aristotle, Alhazan, and Da Vinci.
- Lenses were incorporated in the camera obscura in the 1600s for better image quality.



Answer: No one had found a way to "fix" the image.

Motion Pictures



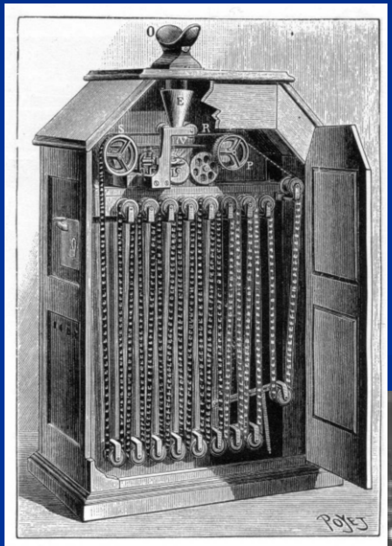


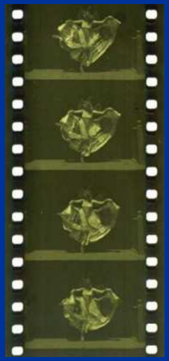
In 1872, Eadweard Muybridge used 12 separately-triggered cameras to photograph a horse in full gallop.

Shortly before taking these pictures, Muybridge was jailed for shooting his wife's lover. His release was obtained by railroad builder and university founder Leland Stanford.

Thomas Edison was inspired by a meeting with Muybridge and put his laboratory to work on the predecessor to the movie projector.

The kinetoscope was popular in the 1890s. Theater projectors were developed only later, because the kenetoscope was so successful commercially.

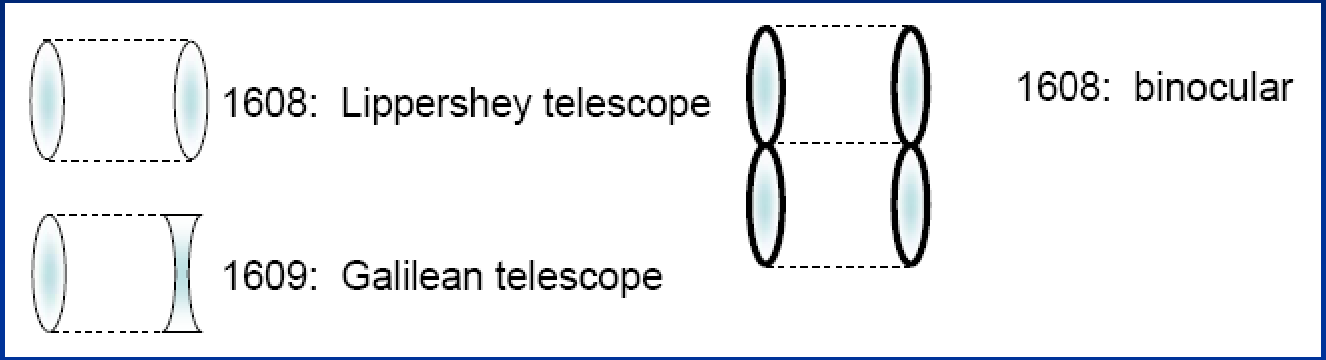




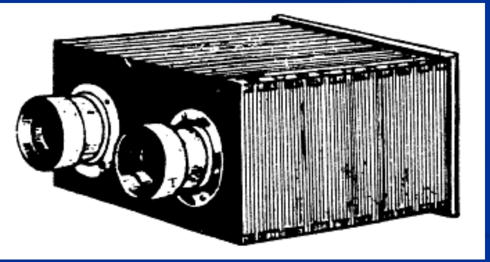
The 35mm film strip was introduced in 1895 by Edison.

Strong commercial motivation

Extension to 3-D



- Charles Wheatstone, first stereoscopic viewer, late 1830s (photographs)
- David Brewster's work resulted in well-designed stereo cameras
- Other contributions by Helmholtz and Pulfrich



Da Vinci sketched stereo pairs for viewing – no surprise!

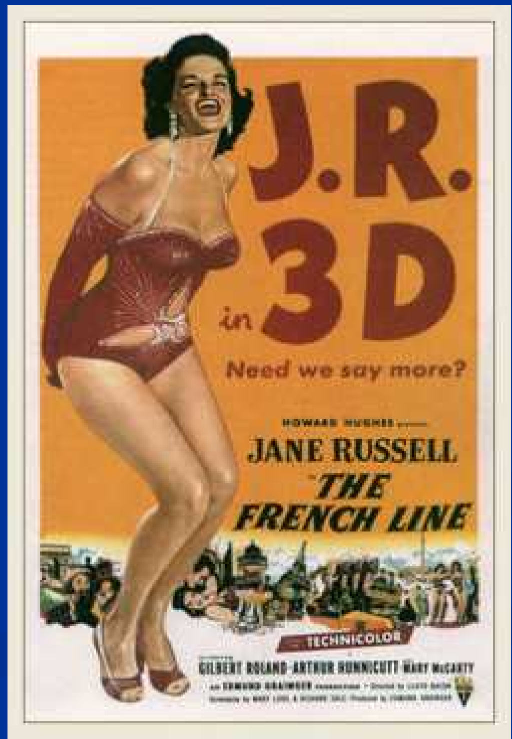
If you view the stereo pair crossing your eyes, the depth is reversed, with near objects moved back, far objects moved forward. The stereopticon viewer eliminates this problem, and does not make your eyes hurt!

3-D Movies

The development of polarizing filters in 1936 led to 3-D movies in the theaters, especially in the 1950s.

Today we see a resurgence in the popularity of 3-D cinema.

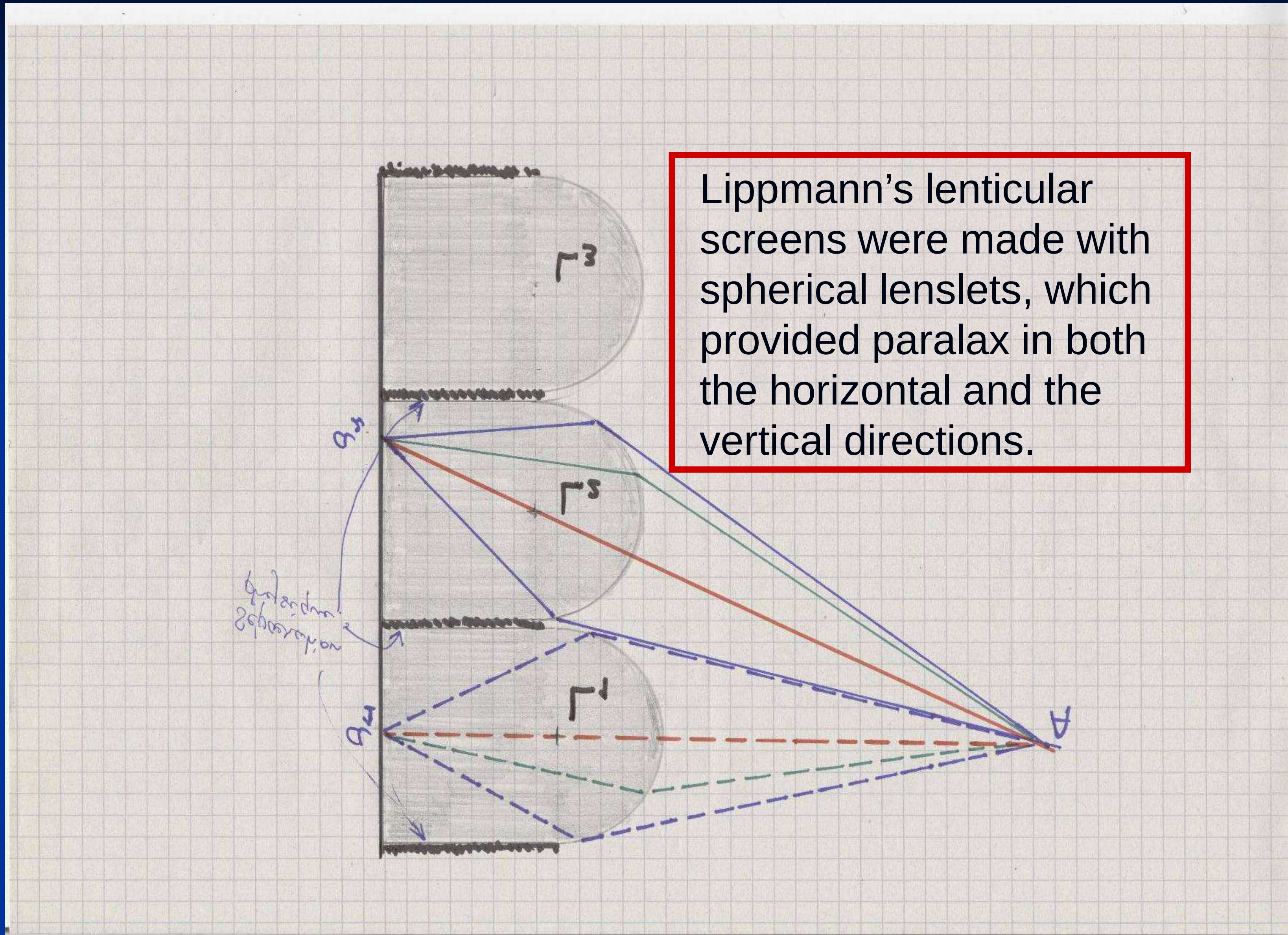
Why were 3-D movies so popular? You get an idea from magazine covers and posters from that time:



Lippmann invented the lenticular-screen 3-D image.

Lippmann was a scientist, inventor, and technologist. But not a businessman.

Integral photography images can be viewed from different positions with a 3-D result. M. Bonnet produced integral photographs with horizontal parallax using cylindrical lenslets.



Lippmann's lenticular screens were made with spherical lenslets, which provided paralax in both the horizontal and the vertical directions.

Roger de Montebello replicated Lippmann’s integral photographs with spherical lenslet arrays

Roger de Montebello ~1960.

Parallax in two dimensions

Photographies obtenues en regardant de trois angles différents le même «Integram», réalisé par Roger de Montebello dans les années 1960. Dans l'Integram, de Montebello accole à une photographie intégrale une seconde couche de microlentilles pour améliorer la qualité de l'image. Pour prendre une photographie intégrale, on remplace l'appareil photographique classique par un «châssis intégral» *(à côté du titre)*, constitué d'une multitude de microlentilles juxtaposées, derrière lesquelles on dépose une émulsion photosensible.

Lippmann Photography

Although this looks like a poor photograph, it in fact allows us to measure today the spectral distribution of light in the Swiss alps at the end of the 19th century, and over the *entire* visible spectrum.

Gabriel Lippman

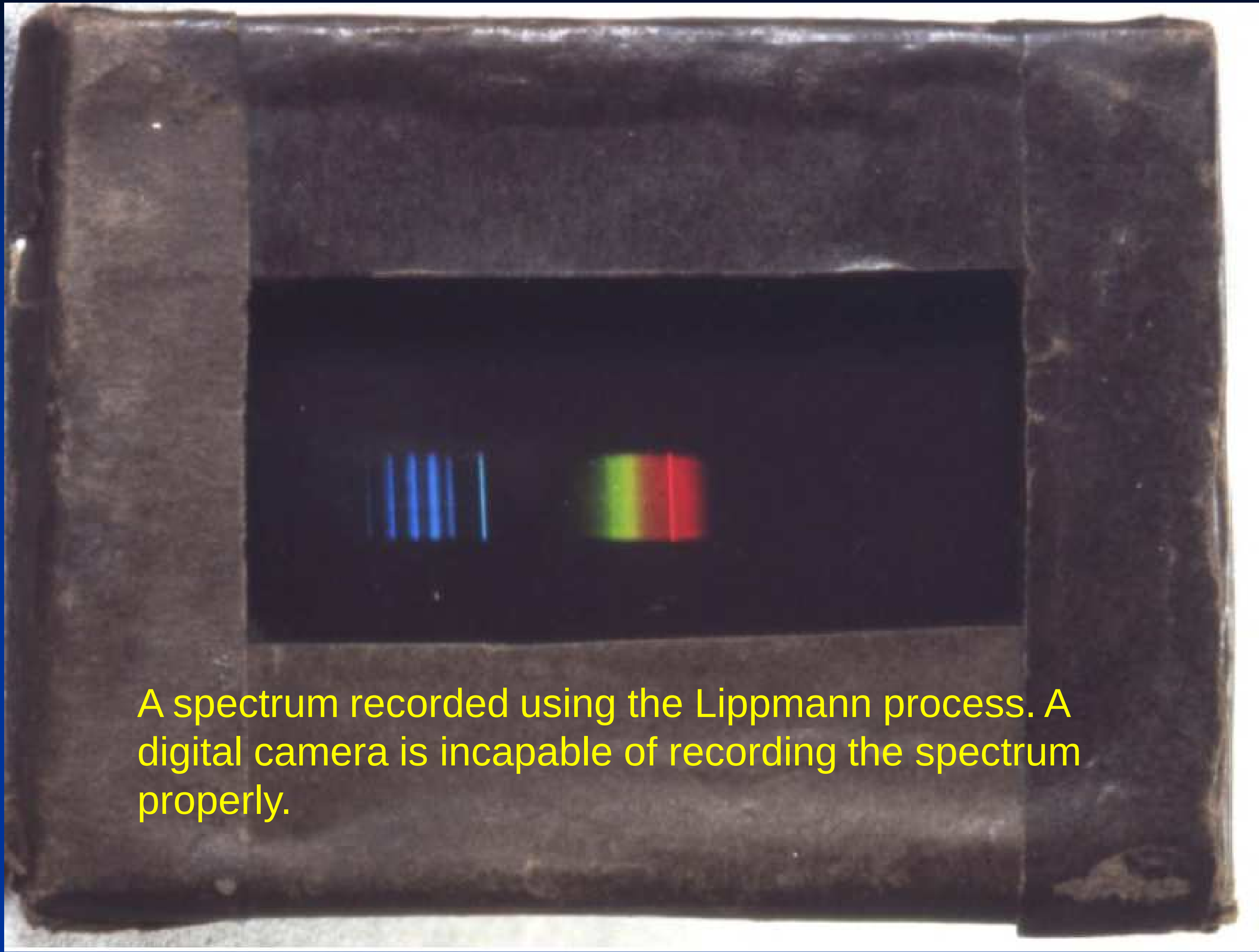
Contemporary of and inspired by James Clerk Maxwell

Published paper on interferometric photography in 1894

> G. LIPPMANN, *Sur la théorie de la photographie des couleurs simples et composées par la méthode interférentielle*, in *Journal de Physique*, 3ᵉ série, tome III, p. 97, 1894.

See J.-M. Fournier and P.L. Burnett, *Color Rendition and Archival properties of Lippmann Photographs,* in *J. Imag. Sc. Tech.*, vol. 38, no. 6, p. 507, 1994

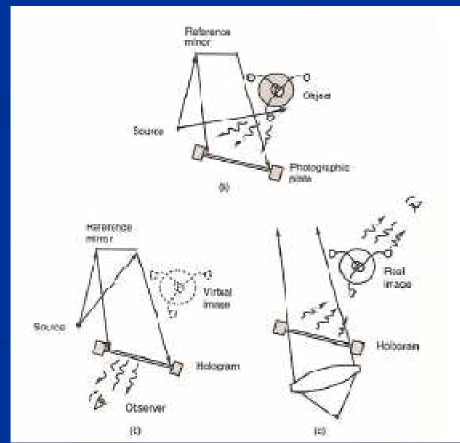
Technology inspired by science.



A spectrum recorded using the Lippmann process. A digital camera is incapable of recording the spectrum properly.

Holography

Holography was a Nobel prize winning invention for Dennis Gabor, one of the few true technologists to receive this award*.



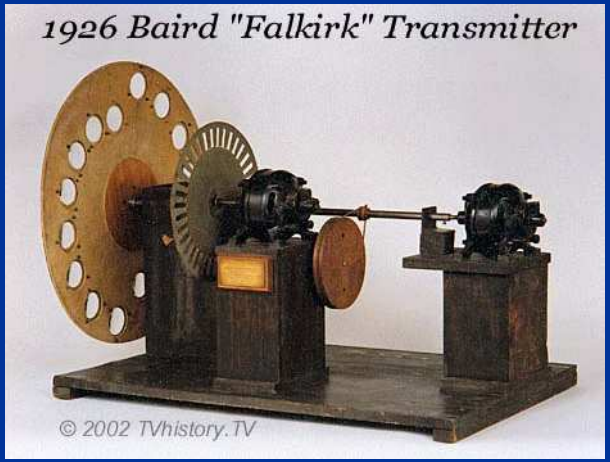
* In fact, because Gabor was viewed by many scientists as being more engineer than scientist, he almost did not receive the award.

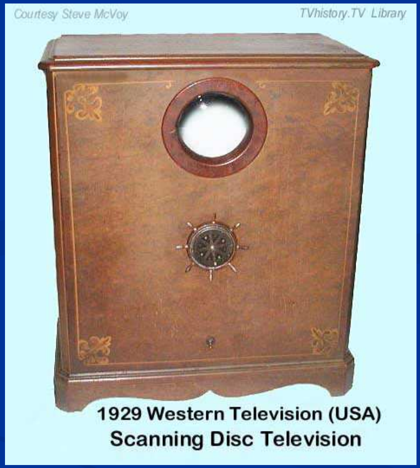
In order to make holograms, people used photographic materials that were made with Lippmann's special high-resolution emulsion.

But low economic impact!

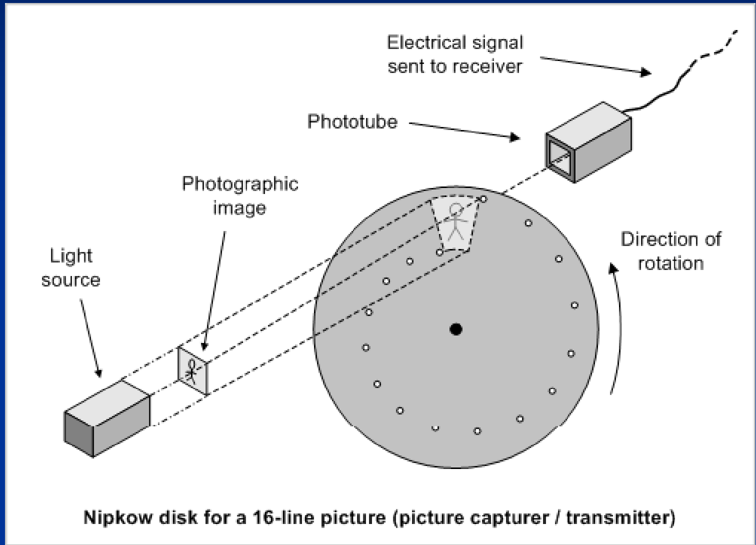
Image Transmission

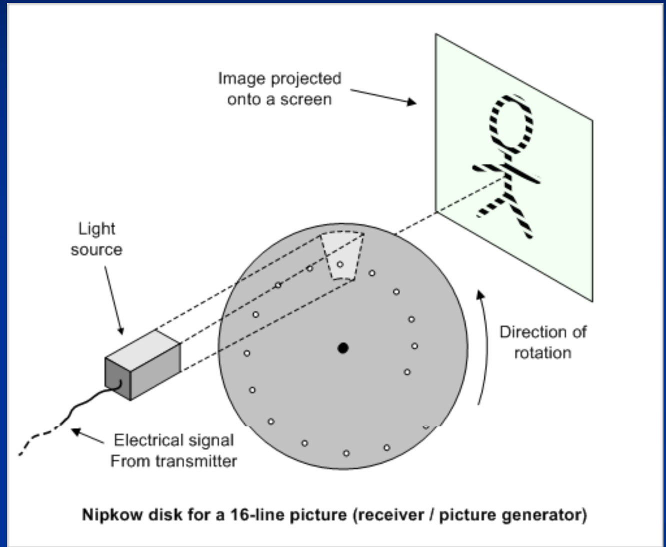
Early televisions were based on opto-mechanical scanners. The real revolution came with the development of the image orthocon, vidicon, and cathode ray tube (CRT). Strong economic motivation and impact. Almost exclusively by technologists.

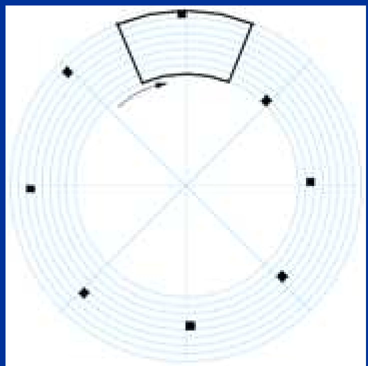




Nipkov Disk

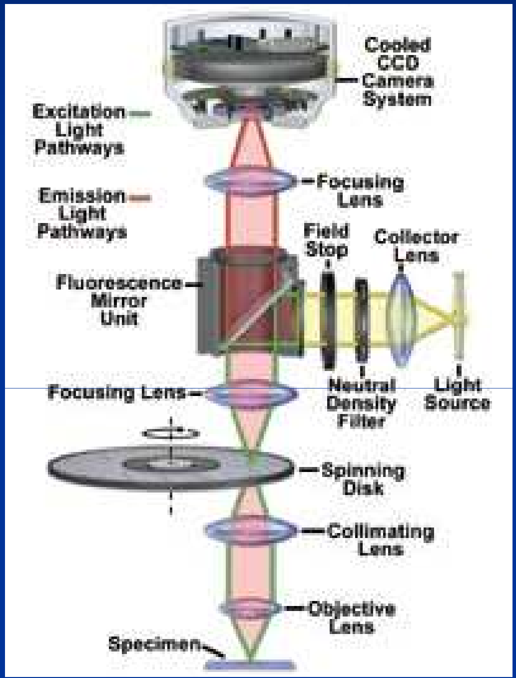






Paul Gottlieb Nipkow (1860-1940) – Mechanical Television. Small images, ~100 lines or fewer. Nipkov disks used today in high-quality confocal scanning optical microscopes. No economic impact on TV but great impact on microscopy.

Scanning Confocal Microscopy

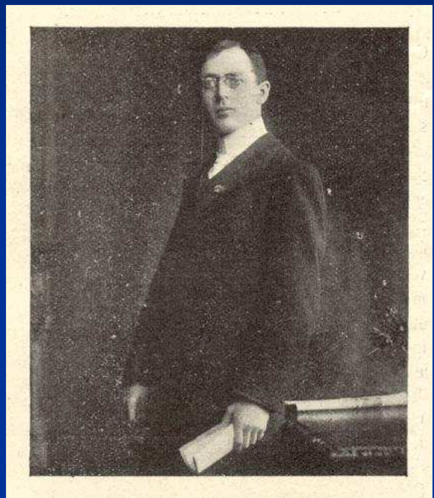


The Nipkov disk is used today in state-of-the-art scanning confocal microscopes, which are capable of providing higher-resolution imagery than conventional microscopes.

Other Early Television

E. E. Fournier d' Albe

Fournier d'Albe transmitted each pixel of a scene by the modulation of a separate audio-frequency carrier using frequency-division multiplexing (1925).



MR. E.-E. FOURNIER D'ALBE.

Not economically sound, but reinvented by Gabor and by Zenith researchers many years later.

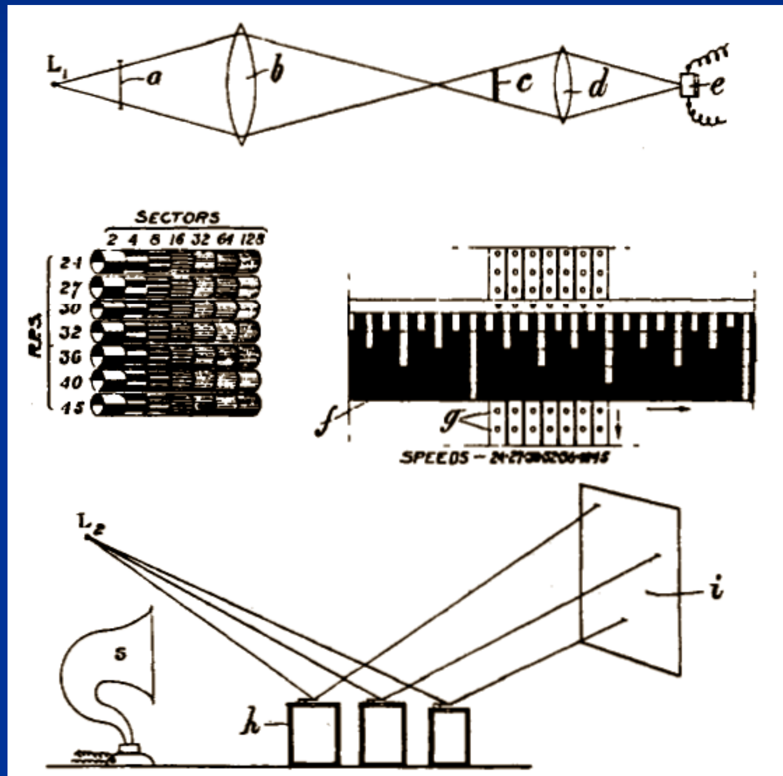


Fig. 1. Frequency domain display after Fournier D'Albe.

Video Recorders

The thermoplastic video recorder was invented by William E. Glenn in 1960 at the General Electric Research Laboratory.

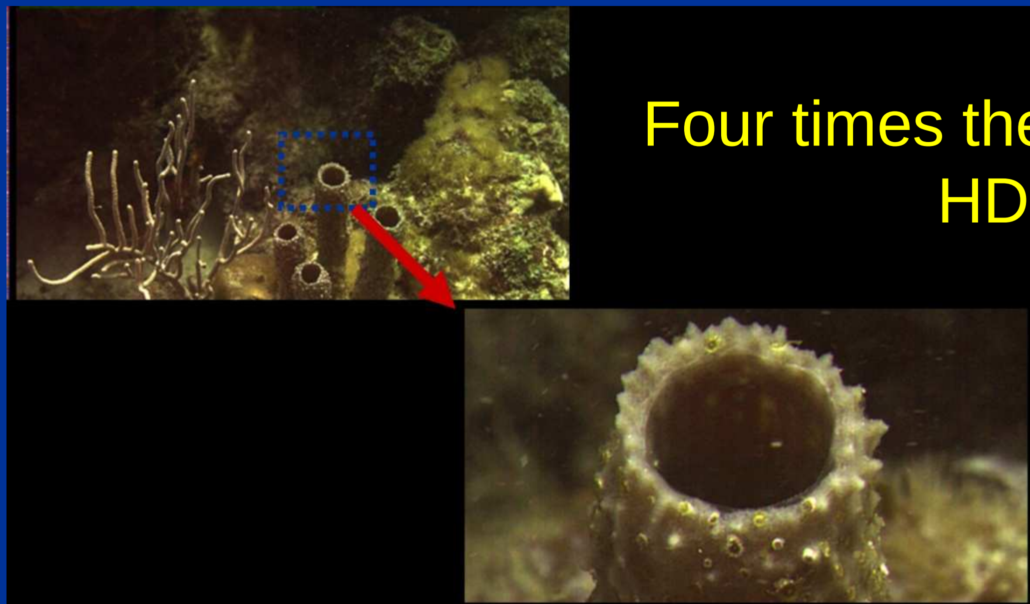
Glenn later became Director of the CBS Laboratories.

One of his employees was Dennis Gabor.

Until last 2008 he directed Florida Atlantic University's Imaging Technology Center.

FAU Imaging Technology Center

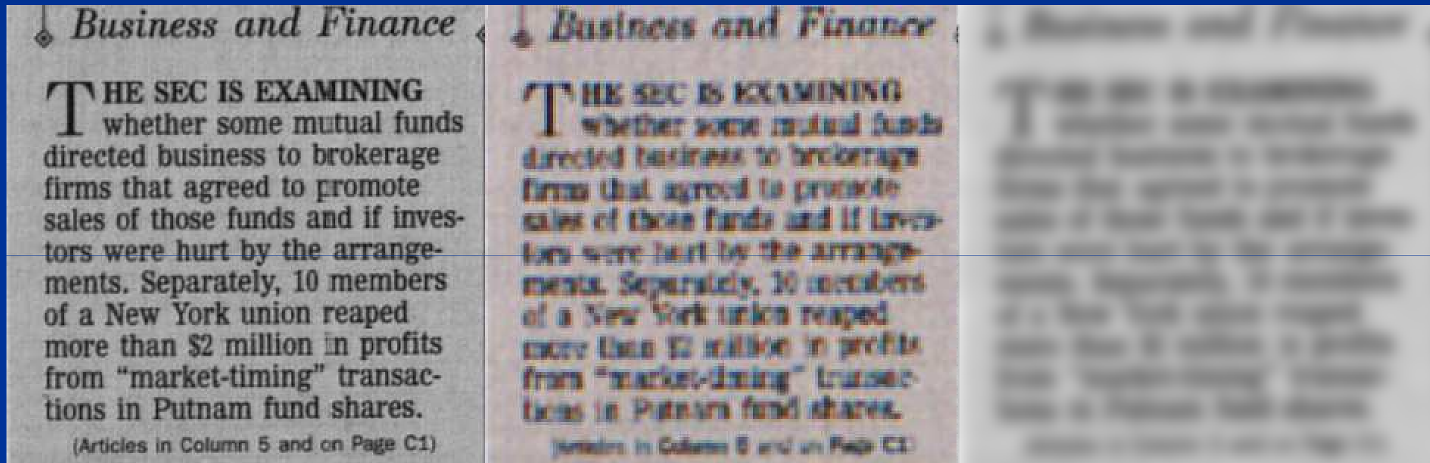
The Florida Atlantic University HDMAX video camera: 3840x2160 pixels at TV frame rates.



Four times the resolution of HDTV.

Resolution Comparison

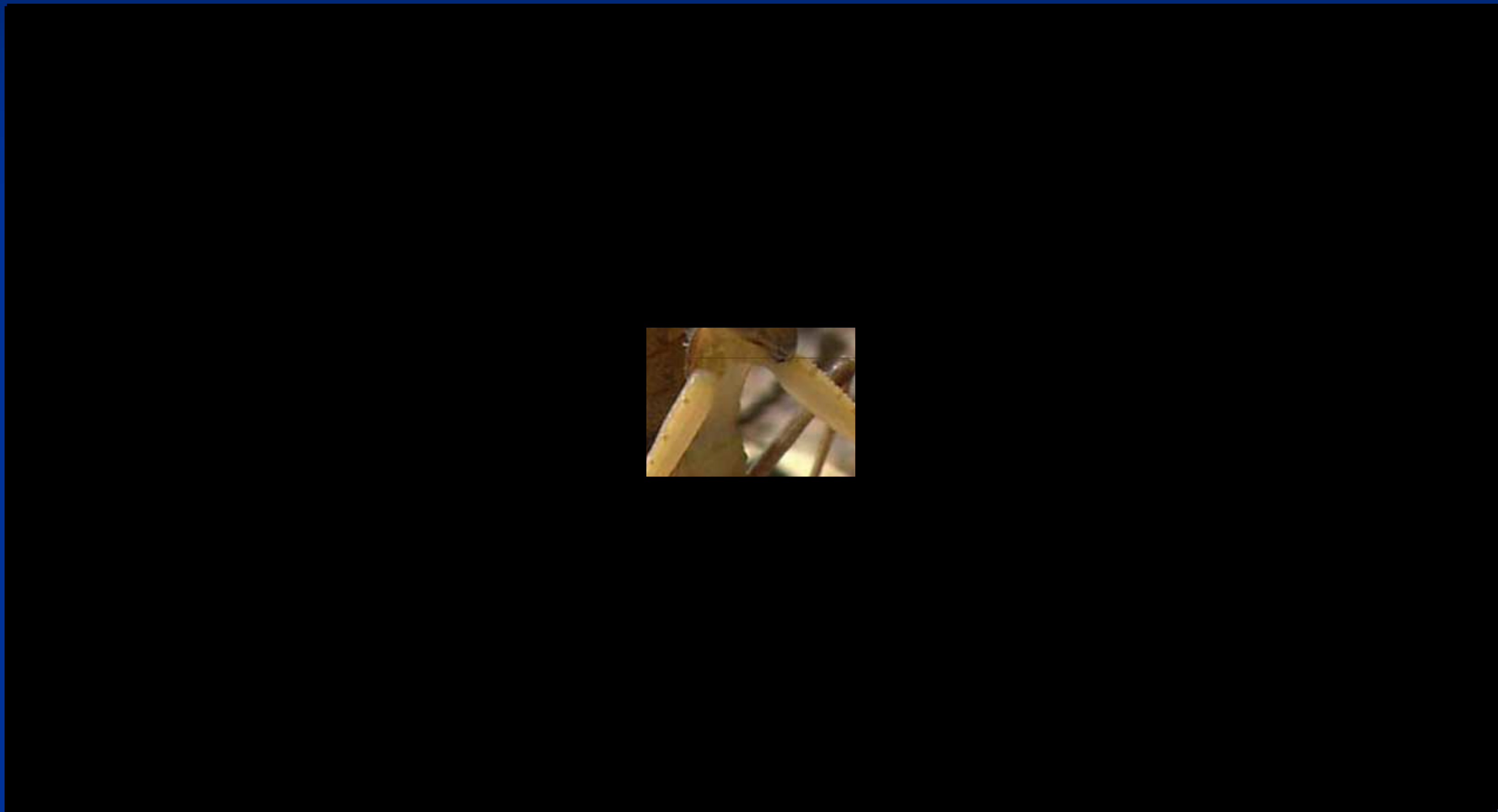
HDMAX 2160 lines   HDTV 1080 lines   NTSC 480 lines


Business and Finance

THE SEC IS EXAMINING whether some mutual funds directed business to brokerage firms that agreed to promote sales of those funds and if investors were hurt by the arrangements. Separately, 10 members of a New York union reaped more than $2 million in profits from "market-timing" transactions in Putnam fund shares.

(Articles in Column 5 and on Page C1)

Florida Atlantic University's ultra-HD video camera



Standard TV, HDTV, and Quad-TV compared.

- All of this has been about past developments.

- What about the present and the future?

- The present and the future are the subject of this Winter College on Optics.