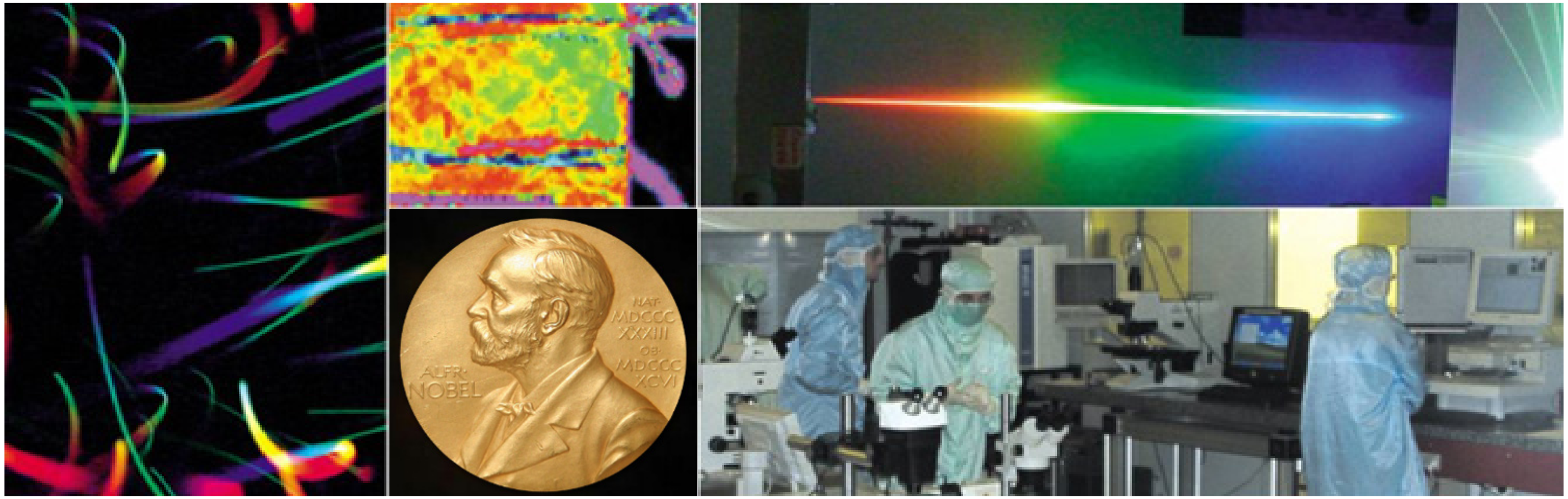
Unexpected connections in pure & applied research



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UNIVERSITé DE FRANCHE-COMTé

femto-st SCIENCES & TECHNOLOGIES

cnrs

United Nations Educational, Scientific and Cultural Organization

International Day of Light 16 May

What is the aim of this talk?

As a student, life is relatively simple!

As we study science at more advanced levels, we encounter the "ecosystem" of research organization & funding.

We also encounter an apparent "conflict" between the scientific community that generally wants to do curiosity-driven research, and funding agencies who increasingly support only applied objectives.

This talk gives some of the background history, and some examples of where applied research has led to very fundamental discoveries, and where fundamental research has led to completely unexpected applications.

Context – some definitions

Basic or Pure or Fundamental research is driven by *curiosity* in a scientific question.

The main motivation is to *expand knowledge*, not to invent something.
Potential commercial value is not a motivation.
It is usually long term (5 – 100+ years …).

Applied research is directed towards specific goals and solving practical problems.

There is no intention to acquire knowledge for knowledge's sake.
Applied research is often directly related to a commercial need.
It is usually short term (weeks to years).

Some scientists look negatively upon applied goal-driven research

Basic research with no practical goals in mind is often considered to be that which leads to the most important discoveries.

"We prided ourselves that the science we were doing could not, in any conceivable circumstances, have any practical use.

The more firmly one could make that claim, the more superior one felt "

- describing 1930s Cambridge

Photonics is a field where there are many examples of practical technologies that have arisen from both curiosity-driven research and industrial development.

As science is more in the spotlight, we need to know how to talk about this.

How solving an industrial & societal problem led to quantum mechanics

Quantum mechanics had its origins in the very practical question of comparing light emission from gas and electric light sources

europhysicsnews
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A TRIBUTE TO MAX PLANCK

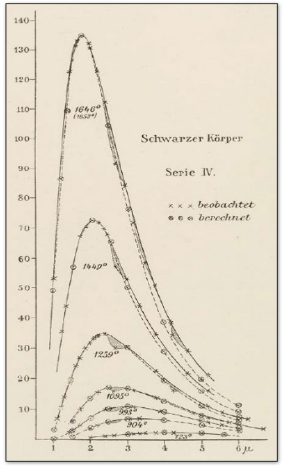
Henk Kubbinga – University of Groningen (The Netherlands) – DOI: https://doi.org/10.1051/epn/2018405

▲ PAGE 27

Tribute to Max Planck

Berlin: black body-radiation and statistics

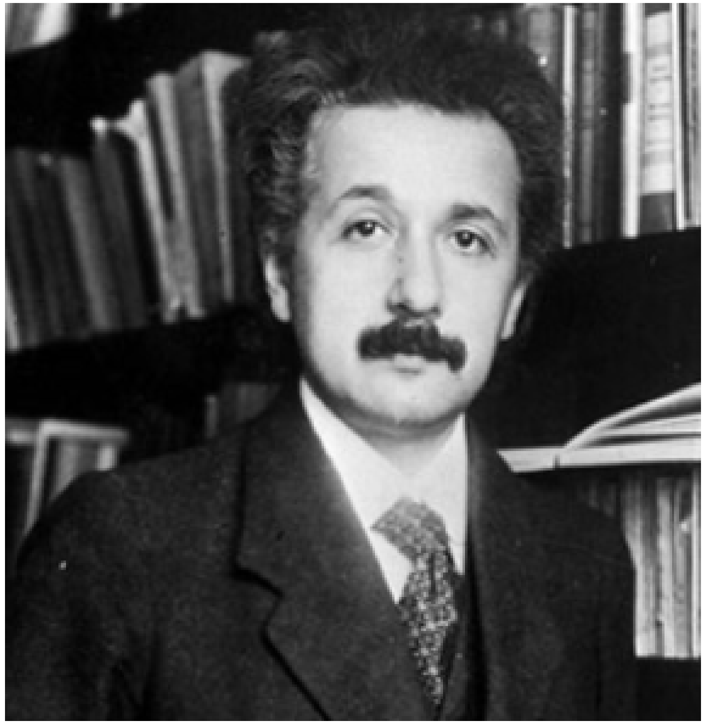
Kirchhoff's radiating 'schwarze Körper'—only radiation, perfect absorption—, initially a theoretical construct, became of practical importance when light sources had to be standardized at the P.-T.R., Berlin. The question to be answered: should the city of Berlin be illuminated by gas or electricity? If electricity, what kind of lamp was to be preferred ? Planck, a frequent visitor, got involved when the first high-precision radiation isotherms became available (Fig.3). Wilhelm

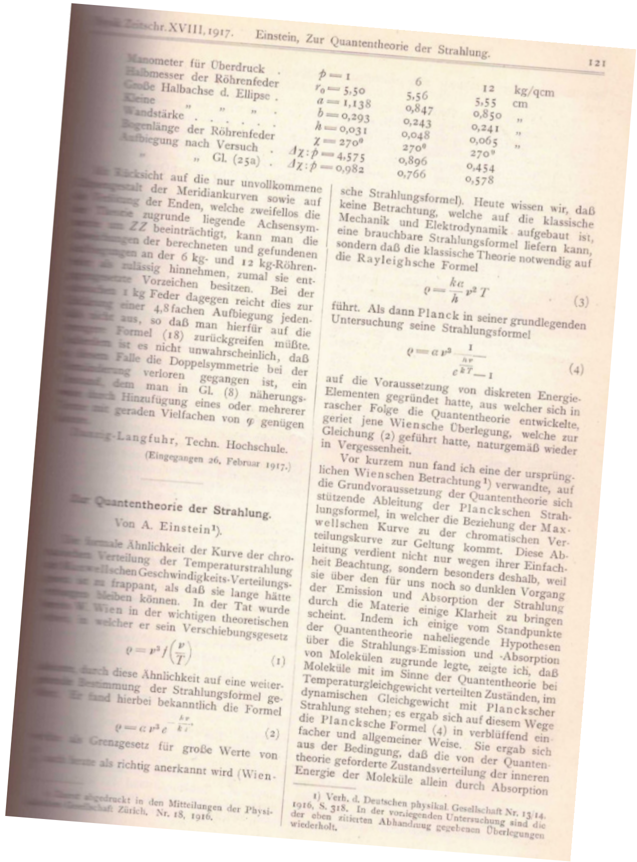


But critically, the scientific environment also strongly encouraged fundamental questions!

It took Einstein to see the possibility of stimulated emission

In 1916-1917 Einstein saw that the quantum nature of light implied that directional stimulated emission could occur when a photon was incident upon an excited atom





...Zeitschr. XVIII, 1917. Einstein, Zur Quantentheorie der Strahlung. 121

Manometer für Überdruck .	$p = 1$	6	12	kg/qcm
Halbmesser der Röhrenfeder	$r_0 = 5{,}50$	5,56	5,55	cm
Große Halbachse d. Ellipse .	$a = 1{,}138$	0,847	0,850	"
Kleine " " " .	$b = 0{,}293$	0,243	0,241	"
Wandstärke	$h = 0{,}031$	0,048	0,065	"
Bogenlänge der Röhrenfeder	$\chi = 270^0$	270^0	270^0	
Aufbiegung nach Versuch .	$\Delta\chi : p = 4{,}575$	0,896	0,454	
" " Gl. (25a) .	$\Delta\chi : p = 0{,}982$	0,766	0,578	

...Rücksicht auf die nur unvollkommene ...gestalt der Meridiankurven sowie auf ... der Enden, welche zweifellos die ... zugrunde liegende Achsensym... $= ZZ$ beeinträchtigt, kann man die ...gen der berechneten und gefundenen ...gen an der 6 kg- und 12 kg-Röhren... zulässig hinnehmen, zumal sie ent... Vorzeichen besitzen. Bei der ... 1 kg Feder dagegen reicht dies zur ... einer 4,8fachen Aufbiegung jeden... aus, so daß man hierfür auf die ... Formel (18) zurückgreifen müßte. ... ist es nicht unwahrscheinlich, daß ... Falle die Doppelsymmetrie bei der ... verloren gegangen ist, ein ..., dem man in Gl. (8) näherungs... Hinzufügung eines oder mehrerer ... geraden Vielfachen von φ genügen ...

...-Langfuhr, Techn. Hochschule.

(Eingegangen 26. Februar 1917.)

...Quantentheorie der Strahlung.

Von A. Einstein[1]).

...formale Ähnlichkeit der Kurve der chro... Verteilung der Temperaturstrahlung ...wellschen Geschwindigkeits-Verteilungs... zu frappant, als daß sie lange hätte ... bleiben können. In der Tat wurde ... W. Wien in der wichtigen theoretischen ... welcher er sein Verschiebungsgesetz

$$\varrho = \nu^3 f\left(\frac{\nu}{T}\right) \qquad (1)$$

... durch diese Ähnlichkeit auf eine weiter... Bestimmung der Strahlungsformel ge... Er fand hierbei bekanntlich die Formel

$$\varrho = \alpha \nu^3 e^{-\frac{h\nu}{kT}} \qquad (2)$$

... als Grenzgesetz für große Werte von ... als richtig anerkannt wird (Wien-sche Strahlungsformel). Heute wissen wir, daß keine Betrachtung, welche auf die klassische Mechanik und Elektrodynamik aufgebaut ist, eine brauchbare Strahlungsformel liefern kann, sondern daß die klassische Theorie notwendig auf die Rayleighsche Formel

$$\varrho = \frac{k\alpha}{h} \nu^2 T \qquad (3)$$

führt. Als dann Planck in seiner grundlegenden Untersuchung seine Strahlungsformel

$$\varrho = \alpha \nu^3 \frac{1}{e^{\frac{h\nu}{kT}} - 1} \qquad (4)$$

auf die Voraussetzung von diskreten Energie-Elementen gegründet hatte, aus welcher sich in rascher Folge die Quantentheorie entwickelte, geriet jene Wiensche Überlegung, welche zur Gleichung (2) geführt hatte, naturgemäß wieder in Vergessenheit.

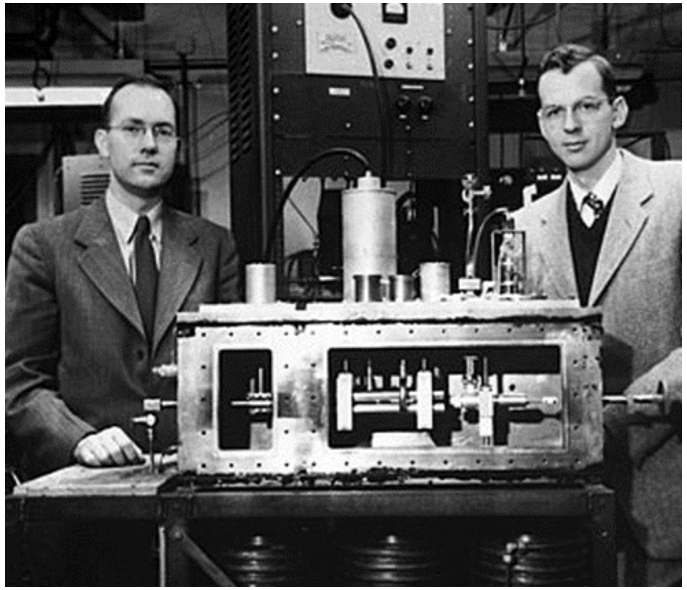
Vor kurzem nun fand ich eine der ursprünglichen Wienschen Betrachtung[1]) verwandte, auf die Grundvoraussetzung der Quantentheorie sich stützende Ableitung der Planckschen Strahlungsformel, in welcher die Beziehung der Maxwellschen Kurve zu der chromatischen Verteilungskurve zur Geltung kommt. Diese Ableitung verdient nicht nur wegen ihrer Einfachheit Beachtung, sondern besonders deshalb, weil sie über den für uns noch so dunklen Vorgang der Emission und Absorption der Strahlung durch die Materie einige Klarheit zu bringen scheint. Indem ich einige vom Standpunkte der Quantentheorie naheliegende Hypothesen über die Strahlungs-Emission und -Absorption von Molekülen zugrunde legte, zeigte ich, daß Moleküle mit im Sinne der Quantentheorie bei Temperaturgleichgewicht verteilten Zuständen, im dynamischen Gleichgewicht mit Planckscher Strahlung stehen; es ergab sich auf diesem Wege die Plancksche Formel (4) in verblüffend einfacher und allgemeiner Weise. Sie ergab sich aus der Bedingung, daß die von der Quantentheorie geforderte Zustandsverteilung der inneren Energie der Moleküle allein durch Absorption

1) ...abgedruckt in den Mitteilungen der Physi... Gesellschaft Zürich, Nr. 18, 1916.

1) Verh. d. Deutschen physikal. Gesellschaft Nr. 13/14, 1916, S. 318. In der vorliegenden Untersuchung sind die der eben zitierten Abhandlung gegebenen Überlegungen wiederholt.

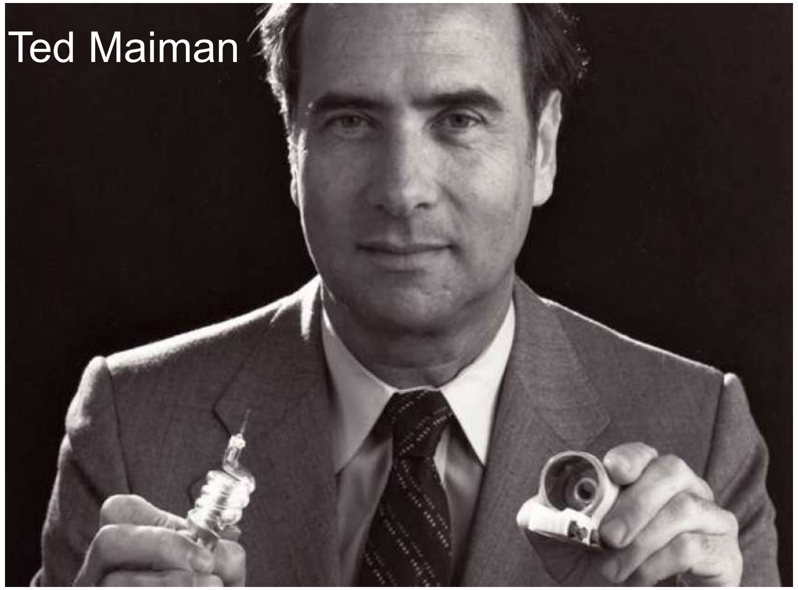
Developing the maser and laser along different lines

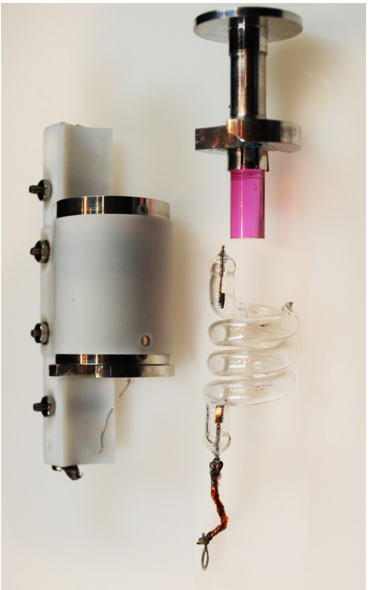
In 1953, Townes & Gordon developed the maser – **m**icrowave **a**mplification by **s**timulated **e**mission of **r**adiation



Charles Townes Jim Gordon

In 1960, Maiman built the first working laser, using very pragmatic principles of engineering





"I was obsessed with simplicity. I was adamant about avoiding cryogenics"

Also: Fabrikant, Purcell, Pound, Zeiger, Weber, Bloembergen, Feher, Kikuchi, Schawlow, Gould, Javan …

The maser and laser were rapidly recognized with Nobel Prizes

The Nobel Prize in Physics 1964

Photo from the Nobel Foundation archive.

Charles Hard Townes

Prize share: 1/2

Photo from the Nobel Foundation archive.

Nicolay Gennadiyevich Basov

Prize share: 1/4

Photo from the Nobel Foundation archive.

Aleksandr Mikhailovich Prokhorov

Prize share: 1/4

The Nobel Prize in Physics 1964 was divided, one half awarded to Charles Hard Townes, the other half jointly to Nicolay Gennadiyevich Basov and Aleksandr Mikhailovich Prokhorov "for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle."

The Nobel Prize in Physics 1966

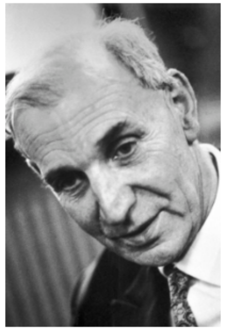


Photo from the Nobel Foundation archive.

Alfred Kastler

Prize share: 1/1

The Nobel Prize in Physics 1966 was awarded to Alfred Kastler "for the discovery and development of optical methods for studying Hertzian resonances in atoms."

The Nobel Prize in Physics 1981

Photo from the Nobel Foundation archive.

Nicolaas Bloembergen

Prize share: 1/4

Photo from the Nobel Foundation archive.

Arthur Leonard Schawlow

Prize share: 1/4

Photo from the Nobel Foundation archive.

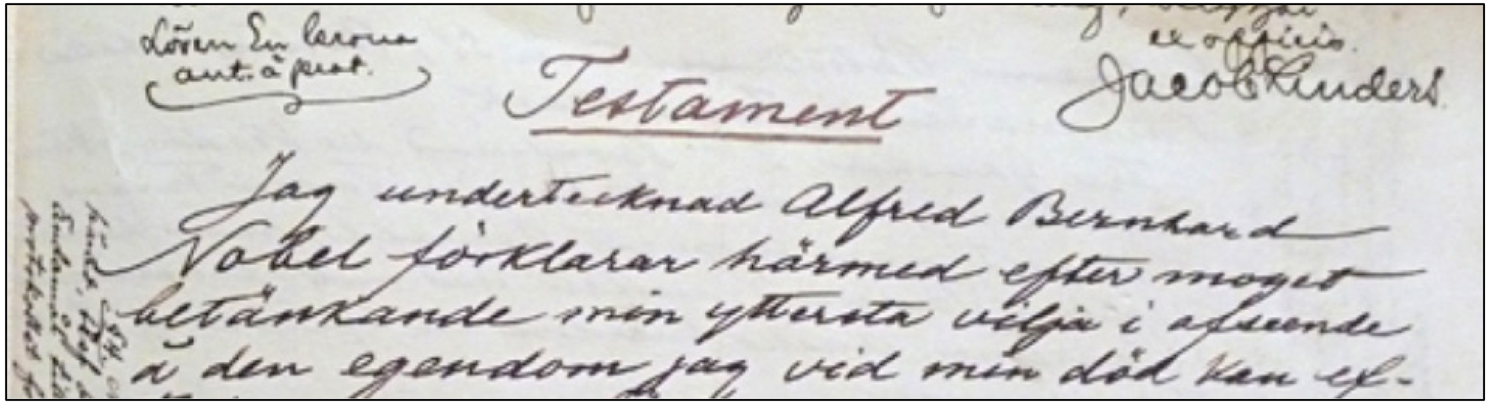
Kai M. Siegbahn

Prize share: 1/2

The Nobel Prize in Physics 1981 was divided, one half jointly to Nicolaas Bloembergen and Arthur Leonard Schawlow "for their contribution to the development of laser spectroscopy" and the other half to Kai M. Siegbahn "for his contribution to the development of high-resolution electron spectroscopy."

Alfred Nobel's will

" prizes to those who, during the preceding year, have conferred the **greatest benefit to humankind.**"

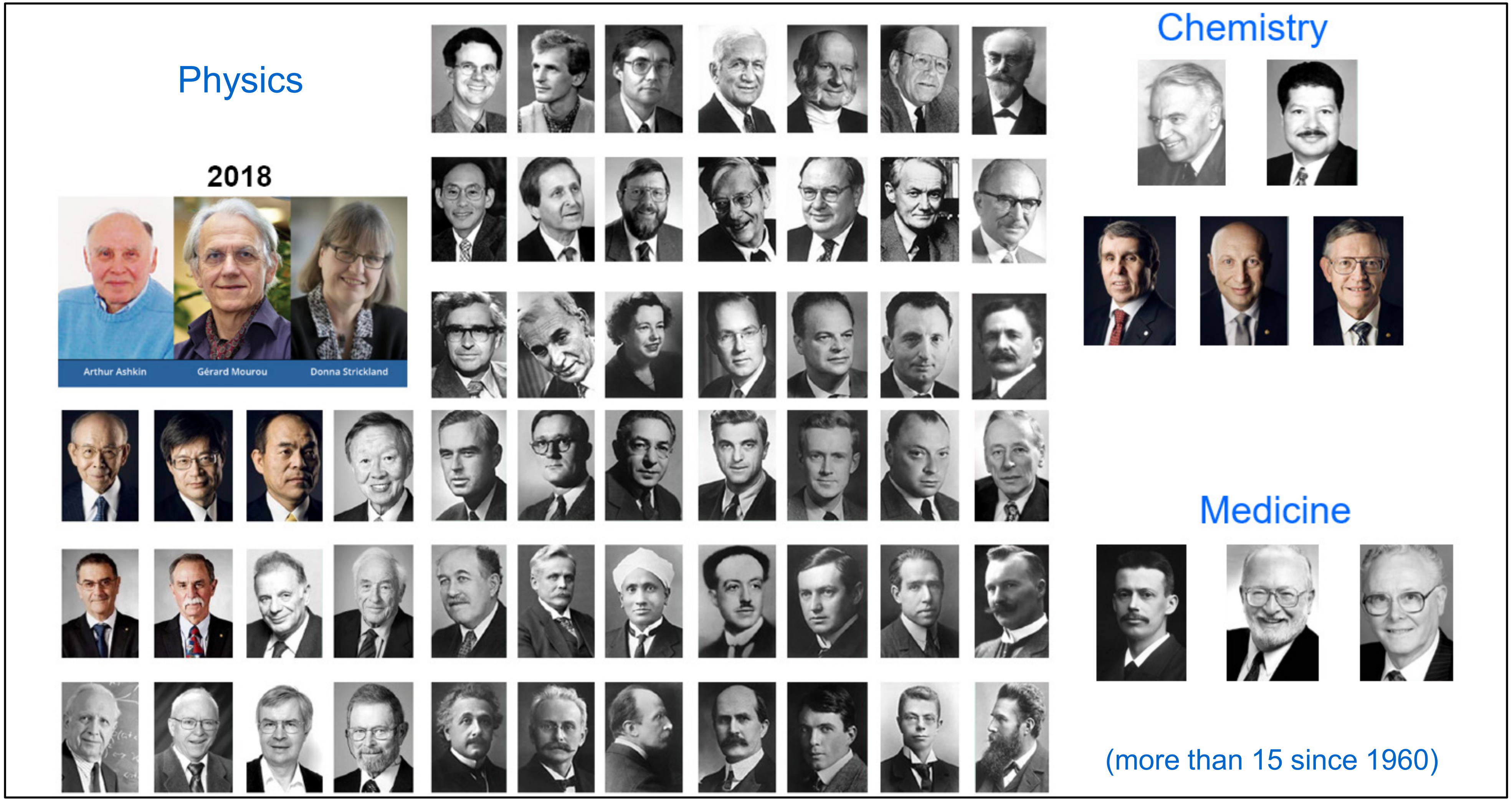


Testament

Jag undertecknad Alfred Bernhard Nobel förklarar härmed efter moget betänkande min yttersta vilja i afseende å den egendom jag vid min död kan ef-

Physics:	The most important **discovery or invention** in the field of physics
Chemistry:	The most important chemical **discovery or improvement**
Physiology or Medicine:	The most important **discovery** in physiology or medicine
Literature:	The most outstanding literary work in **an idealistic direction**
Peace:	The most or best to **advance fellowship among nations**

Over 35 Nobel Prizes associated with light



Nobel prizes associated with masers, lasers, and nonlinear optics

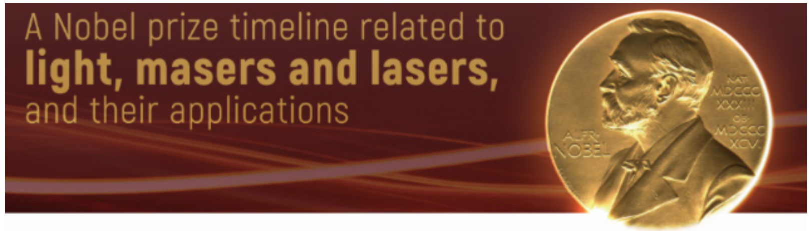
COMMENTARY

Light, Lasers, and the Nobel Prize

Advanced Photonics 2, 050501 (2020)

John M. Dudley

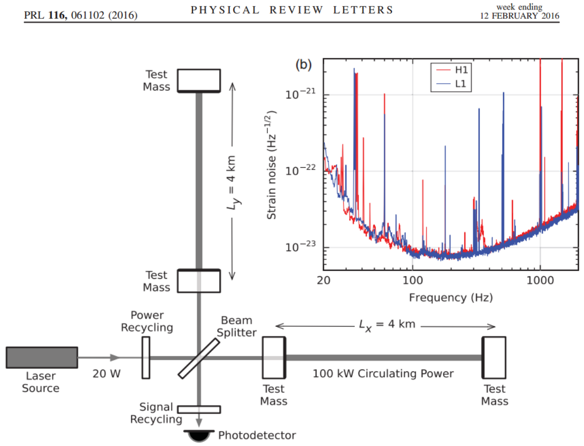
Fig. 1 (Left to right) James P. Gordon, Nikolai Basov, Herbert Zeiger, Alexander Prokhorov and Charles Hard Townes at the First Quantum Electronics Conference, Shawanga Lodge, September 14–16, 1959. Photo courtesy of The Regents of the University of California, Lawrence Berkeley National Laboratory.



1902 — Physics — **Lorentz and Zeeman** — The Zeeman Effect, Electron Oscillator Model
1903 — Physiology or Medicine — **Finsen** — Phototherapy-Use Of UV Light To Treat Lupus
1907 — Physics — **Michelson** — The Michelson Interferometer & Precision Measurements
1908 — Physics — **Lippmann** — Colour Photography Based On Interference
1911 — Physiology or Medicine — **Gullstrand** — Description Of The Refractive Optics Of The Eye
1912 — Physics — **Dalén** — Solar-Based Regulator For Buoys And Lighthouses
1918 — Physics — **Planck** — Energy Quanta
1919 — Physics — **Stark** — The Stark Effect
1921 — Physics — **Einstein** — Photoelectric Effect & Services To Theoretical Physics
1922 — Physics — **Bohr** — Atomic Structure And The Nature Of Radiation
1923 — Physics — **Millikan** — Elementary Charge And The Photoelectric Effect
1927 — Physics — **Compton** — The Compton Effect
1930 — Physics — **Raman** — Raman Scattering
1932 — Physics — **Heisenberg** — Creation Of Quantum Mechanics
1933 — Physics — **Schrodinger and Dirac** — New Productive Forms Of Atomic Theory
1945 — Physics — **Pauli** — Pauli Exclusion Principle
1953 — Physics — **Zernike** — Phase Contrast Microscope
1954 — Physics — **Born** — Statistical Interpretation Of The Wavefunction
1955 — Physics — **Lamb** — Fine Structure Of The H.Spectrum (Lamb Shift, QED)
1964 — Physics — **Townes, Basov, and Prokhorov** — Maser-Laser Principle
1966 — Physics — **Kastler** — Precision Studies Of Optical Resonances
1967 — Physiology or Medicine — **Granit, Hartline, and Wald** — Physiological And Chemical Visual Processes In The Eye
1967 — Chemistry — **Eigen, Norrish, and Porter** — Flashlamp Pump-Probe Studies Of Chemical Reactions (µs)
1971 — Physics — **Gabor** — Holography
1981 — Physics — **Bloembergen and Schawlow** — Laser Spectroscopy
1981 — Physiology and Medicine — **Hubel and Wiesel** — Information Processing In The Visual System
1989 — Physics — **Ramsey, Dehmelt, and Paul** — Atomic Clocks, The Ion Trap
1997 — Physics — **Chu, Cohen-Tannoudji, and Phillips** — Laser Cooling and Trapping
1999 — Chemistry — **Zewail** — Femtochemistry
2000 — Physics — **Alferov and Kroemer** — Optoelectronics, Semiconductor Heterostructures
2001 — Physics — **Cornell, Ketterle, and Wieman** — Bose Einstein Condensation
2005 — Physics — **Glauber, Hall, and Haensch** — Quantum Optics, Spectroscopy, Optical Frequency Comb
2008 — Chemistry — **Shimomura, Chalfie, and Tsien** — Green Fluorescent Protein GFP
2009 — Physics — **Kao, Boyle, and Smith** — Optical Fiber Communications; Imaging And The CCD
2012 — Physics — **Haroche and Wineland** — Individual Quantum Systems
2014 — Physics — **Akasaki, Amano, and Nakamura** — The Blue LED And Energy-Saving White Light Sources
2014 — Chemistry — **Betzig, Hell, and Moerner** — Super-Resolution Microscopy
2018 — Physics — **Ashkin, Mourou, and Strickland** — Optical Tweezers & Biophotonics; Chirped Pulse Amplification

Even more if you include applications in astrophysics

Laser interferometery to detect gravitational waves



The Nobel Prize in Physics 2017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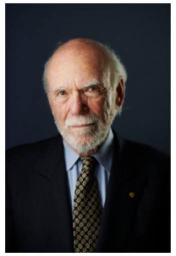
Rainer Weiss
Prize share: 1/2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Barry C. Barish
Prize share: 1/4


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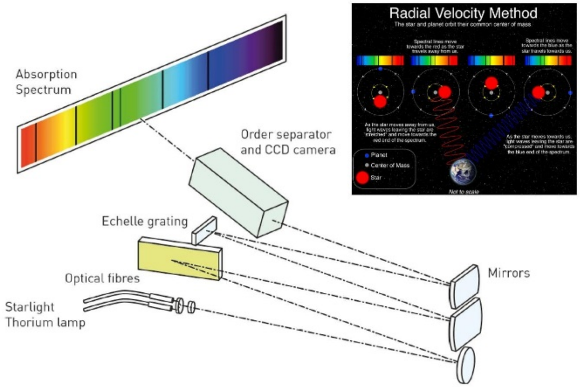
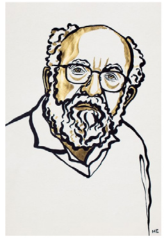
Kip S. Thorne
Prize share: 1/4

Precision spectroscopy for exoplanet discovery



The Nobel Prize in Physics 2019


Ill. Niklas Elmehed. © Nobel Media.
James Peebles
Prize share: 1/2


Ill. Niklas Elmehed. © Nobel Media.
Michel Mayor
Prize share: 1/4


Ill. Niklas Elmehed. © Nobel Media.
Didier Queloz
Prize share: 1/4

Laser guide stars to image black holes

The Nobel Prize in Physics 2020


Ill. Niklas Elmehed. © Nobel Media.
Roger Penrose


Ill. Niklas Elmehed. © Nobel Media.
Reinhard Genzel


Ill. Niklas Elmehed. © Nobel Media.
Andrea Ghez

Not to mention particle physics: APDs & PMTs used at CERN, Super-K etc.

We tend to forget about the maser, but …

Penzias and Wilson used masers to detect the cosmic microwave background

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE
AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964–April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.

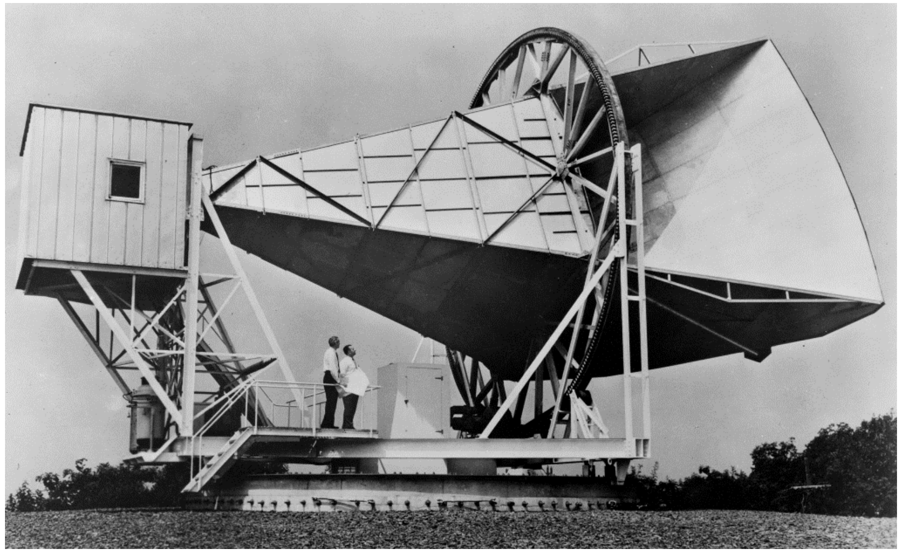
The total antenna temperature measured at the zenith is 6.7° K of which 2.3° K is due to atmospheric absorption. The calculated contribution due to ohmic losses in the antenna and back-lobe response is 0.9° K.

The radiometer used in this investigation has been described elsewhere (Penzias and Wilson 1965). It employs a traveling-wave maser, a low-loss (0.027-db) comparison switch, and a liquid helium–cooled reference termination (Penzias 1965). Measurements were made by switching manually between the antenna input and the reference termina-

free from seasonal variations (July, 1964–April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.

A. A. Penzias
R. W. Wilson

May 13, 1965
Bell Telephone Laboratories, Inc
Crawford Hill, Holmdel, New Jersey



Basic research and instrumentation enable discovery!

This is a remarkable circle involving blackbody radiation

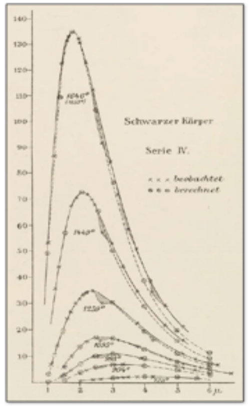
1900

A TRIBUTE TO MAX PLANCK

Henk Kubbinga – University of Groningen (The Netherlands) – DOI: https://doi.org/10.1051/epn/2018405

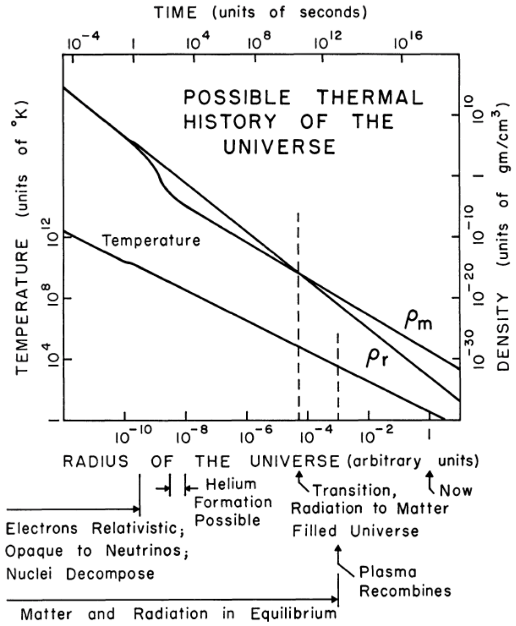
Berlin: black body-radiation and statistics

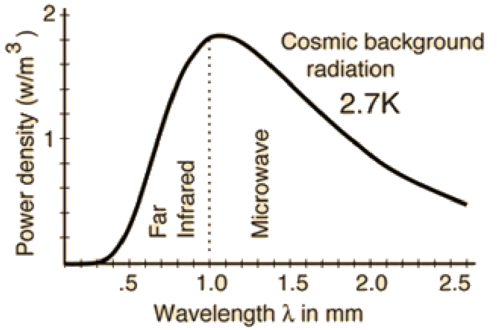
Kirchhoff's radiating 'schwarze Körper'—only radiation, perfect absorption—, initially a theoretical construct, became of practical importance when light sources had to be standardized at the P.-T.R., Berlin. The question to be answered: should the city of Berlin be illuminated by gas or electricity? If electricity, what kind of lamp was to be preferred ? Planck, a frequent visitor, got involved when the first high-precision radiation isotherms became available (Fig.3). Wilhelm



1965

COSMIC BLACK-BODY RADIATION*





R. H. Dicke
P. J. E. Peebles
P. G. Roll
D. T. Wilkinson

May 7, 1965
Palmer Physical Laboratory
Princeton, New Jersey

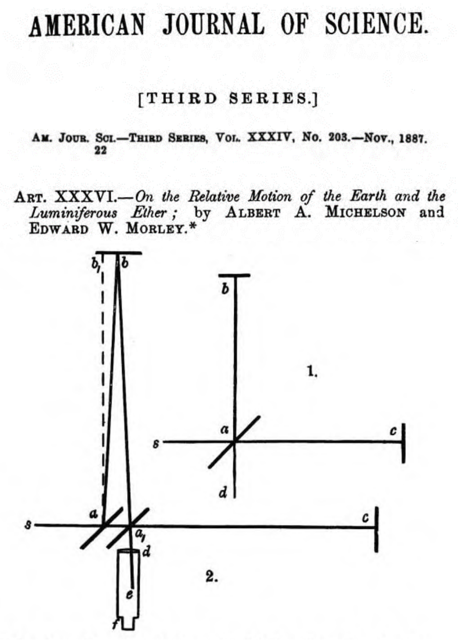
The Nobel Prize in Physics 2019

James Peebles, Prize share: 1/2 — Michel Mayor, Prize share: 1/4 — Didier Queloz, Prize share: 1/4

Lighting → Black body → Quanta → Stimulated emission → MASER → Black Body → Cosmology

Instrumentation enables discovery!

Special Relativity 1887



AMERICAN JOURNAL OF SCIENCE.

[THIRD SERIES.]

AM. JOUR. SCI.—THIRD SERIES, VOL. XXXIV, No. 203.—NOV., 1887.
22

ART. XXXVI.—*On the Relative Motion of the Earth and the Luminiferous Ether*; by ALBERT A. MICHELSON and EDWARD W. MORLEY.*

The Nobel Prize in Physics 1907

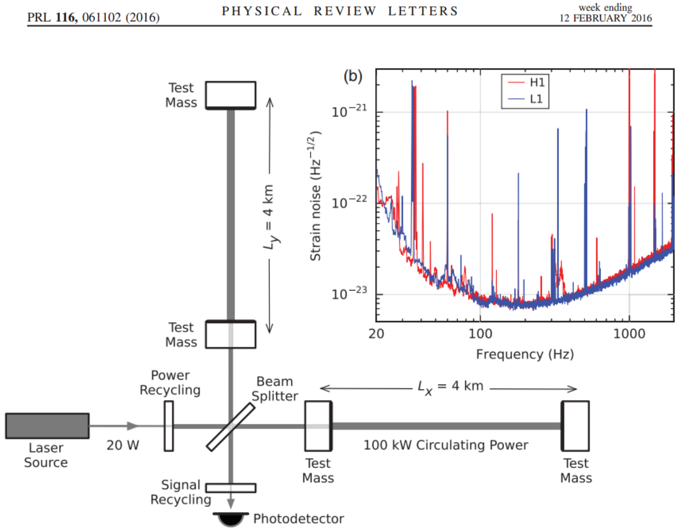
Photo from the Nobel Foundation archive.

Albert Abraham Michelson

Prize share: 1/1

The Nobel Prize in Physics 1907 was awarded to Albert Abraham Michelson "for his optical precision instruments and the spectroscopic and metrological investigations carried out with their aid."

General Relativity 2016



The Nobel Prize in Physics 2017

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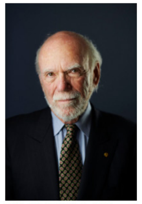
Rainer Weiss

Prize share: 1/2



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Barry C. Barish

Prize share: 1/4

© Nobel Media AB. Photo: A.Mahmoud

Kip S. Thorne

Prize share: 1/4

The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne "for decisive contributions to the LIGO detector and the observation of gravitational waves."

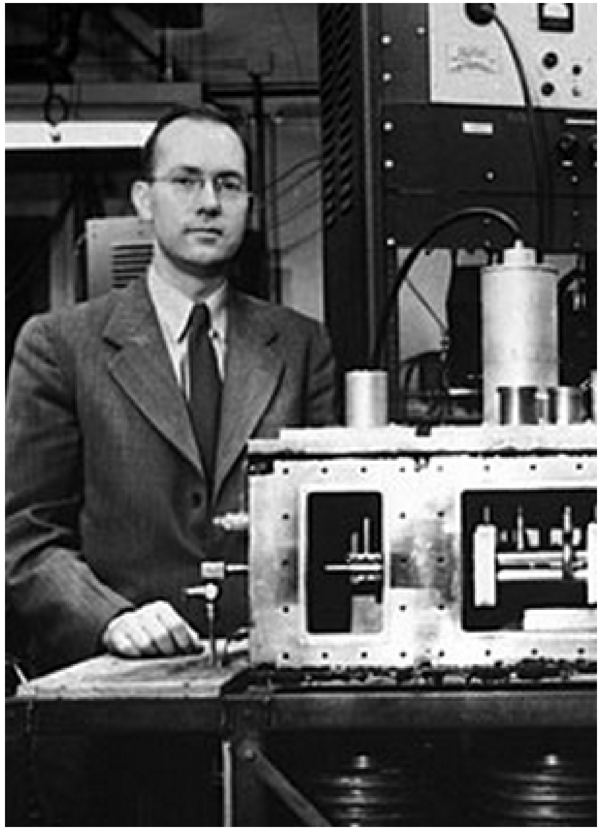
Humbling Nobel comparisons …

YEAR	LAUREATES	TOPIC	
1904	Pavlov	Digestion (behavioral conditioning in dogs)	Physiology or Medicine
1945	Fleming, Florey, Chain	Discovery of Antibiotics	Physiology or Medicine
1948	Muller	Pesticides & DDT (control of Typhus in WW2)	Physiology or Medicine
1949	Moniz	Therapeutic Brain Surgery – Lobotomy	Physiology or Medicine
1962	Watson, Crick, Wilkins	Molecular Structure of DNA	Physiology or Medicine
1966	Huggins	Hormone treatment of Prostate Cancer	Physiology or Medicine
1968	Holley, Khorana, Nirenberg	Interpretation of the Genetic Code & Protein Synthesis	Physiology or Medicine
1972	Frisch, Lorenz, Tinbergen	Animal (Insects, Fishes, Birds) Behaviour Patterns Imprinting, Social Communication	Physiology or Medicine
1981	Sperry	Specialization of the Cerebral Hemispheres	Physiology or Medicine
1990	Murray & Thomas	Organ Transplantation	Physiology or Medicine
2004	Axel & Buck	Functioning of the Olfactory System	Physiology or Medicine
2008	Hausen Barré-Sinoussi, Montagnier	Discovery of HPV that causes cervical cancer Discovery of HIV	Physiology or Medicine
2010	Edwards	Development of IVF	Physiology or Medicine
2018	Allison & Honjo	Immunotherapy Cancer Treatment	Physiology or Medicine

YEAR	LAUREATES	TOPIC	
1964	Martin Luther King	For Civil Rights and Social Justice	Peace
1971	Willy Brandt	Post-WW2 reconstruction and peace in Europe	Peace
1983	Lech Walesa	Freedom of Organization behind the Iron Curtain	Peace
1984	Desmond Tutu	Opposition to apartheid	Peace
1986	Elie Wiesel	Holocaust remembrance	Peace
1990	Mikhail Gorbachev	Leading radical change in East-West relations	Peace
1993	Mandela & de Klerk	Peaceful termination of apartheid & democratic South Africa	Peace
1998	Hume & Trimble	Resolution of Northern Ireland Conflict	Peace
2007	IPCC and Al Gore	Awareness of Anthropomorphic Climate Change	Peace
2014	Malala Yousafzai	The right of children to education	Peace

Some important words from Charles Townes

Charles Townes



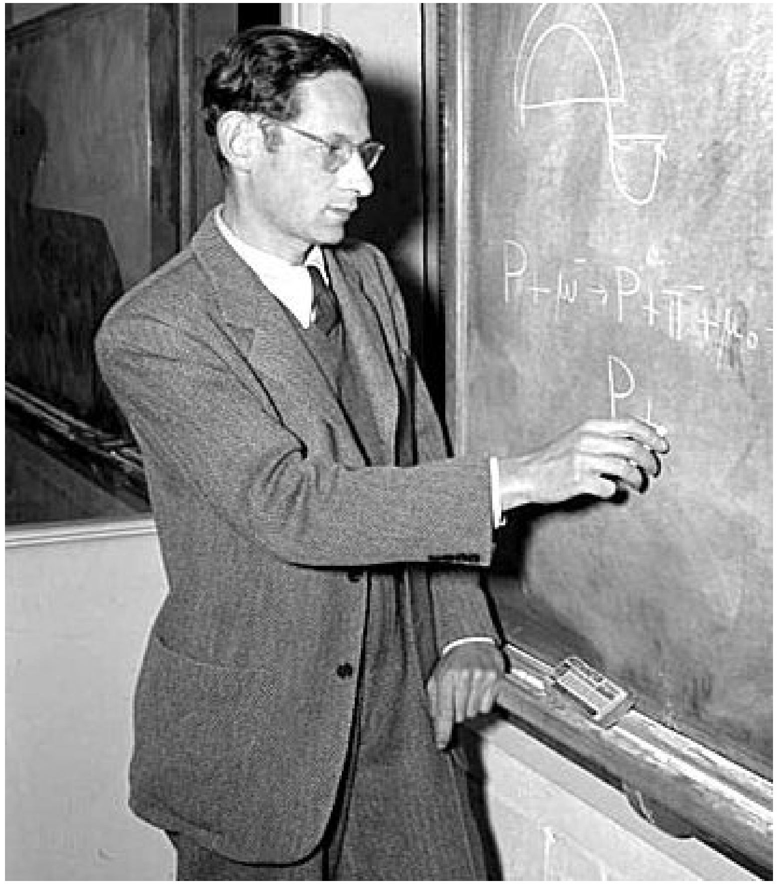
"What industrialist, looking for new cutting and welding devices, or what doctor, wanting a new surgical tool as the laser has turned out to be, would have urged the study of microwave spectroscopy?

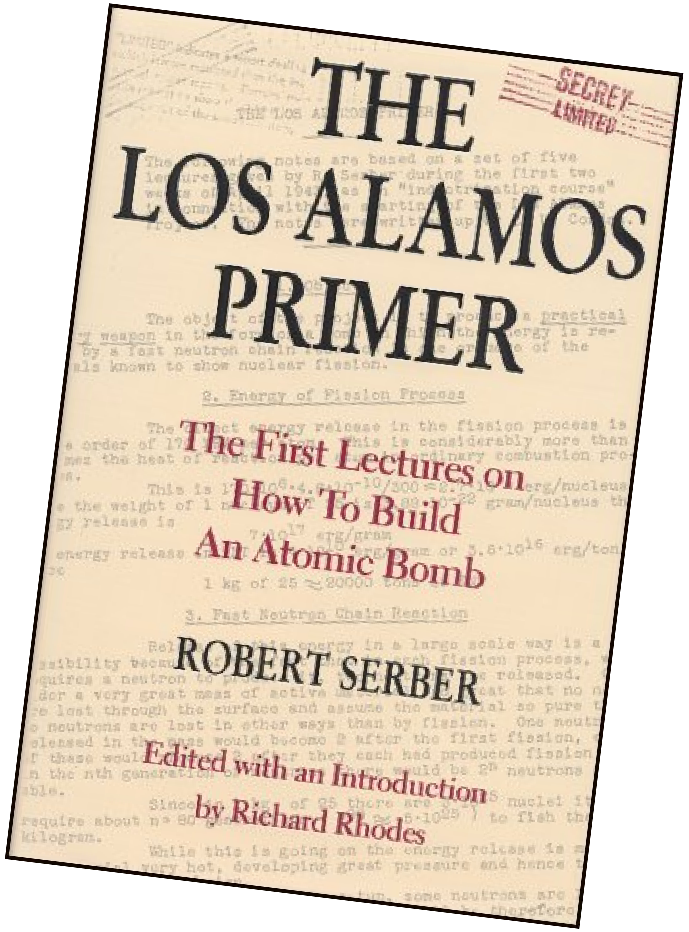
The whole field of quantum electronics is almost a textbook example of broadly applicable technology growing unexpectedly out of basic research."

Townes, C. H. *How the Laser Happened: Adventures of a Scientist.* Oxford University Press (1999)

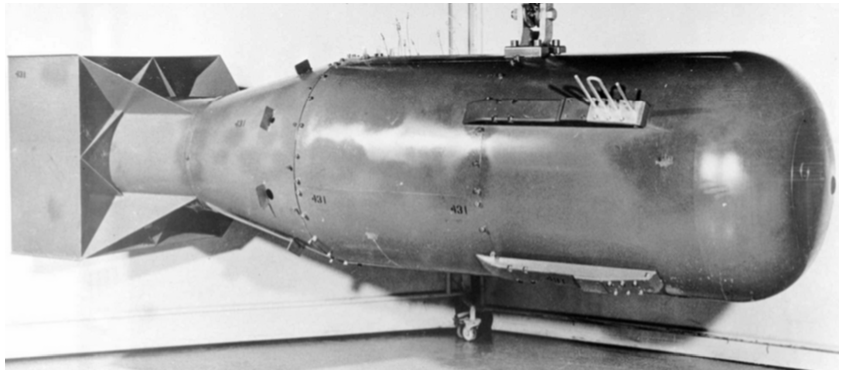
War is probably the most well-known example of "goal-driven" research

"The aim of this project is to produce a practical military weapon"

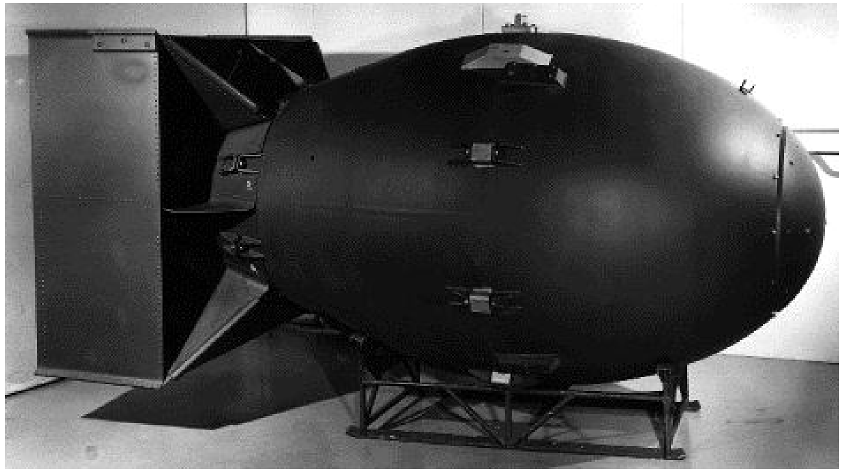




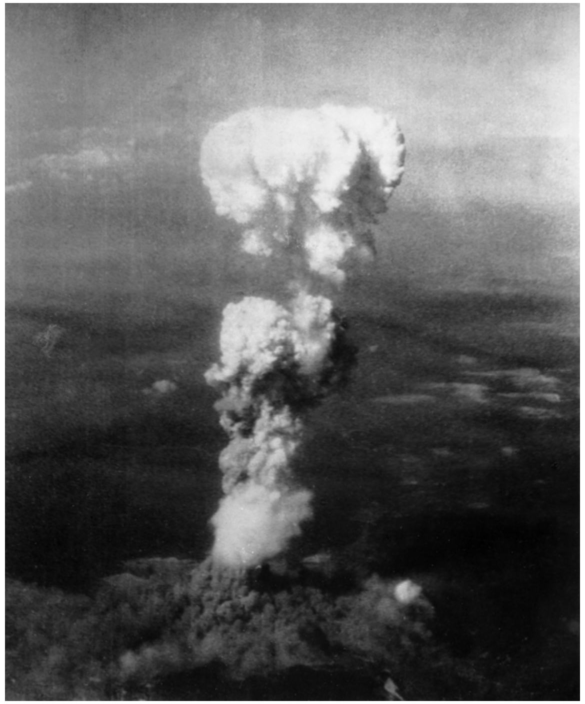
Science and technology accelerated by war …



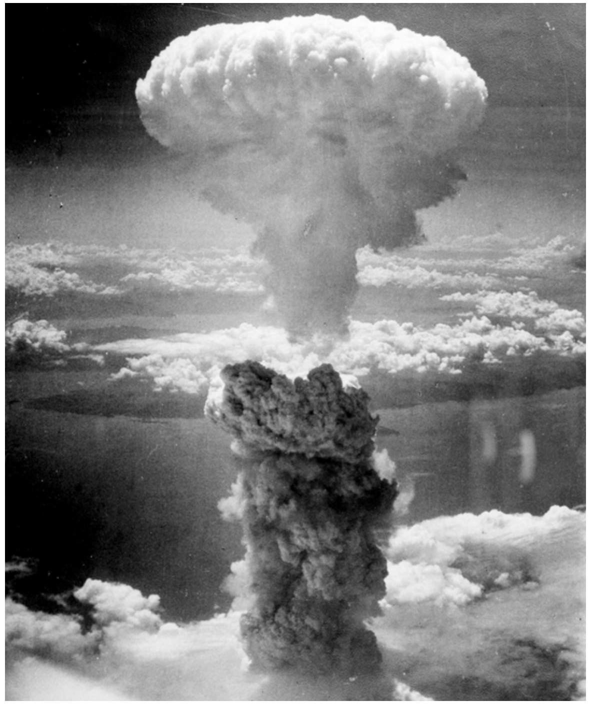
Little Boy (Hiroshima, August 6 1945)



Fat Man (Nagasaki, August 9 1945)



Hiroshima



Nagasaki

The Press seemed to like the idea of "goal driven research"

"All the News That's Fit to Print"

The New York Times.

LATE CITY EDITION

Partly cloudy, less humid today. Cloudy and warm tomorrow.

Temperatures Yesterday—Max., 72; Min., 66

Sunrise today, 5:57 A. M.; Sunset, 8:06 P. M.

VOL. XCIV..No. 31.972. Entered as Second-Class Matter, Postoffice, New York, N. Y. NEW YORK, TUESDAY, AUGUST 7, 1945. THREE CENTS NEW YORK CITY

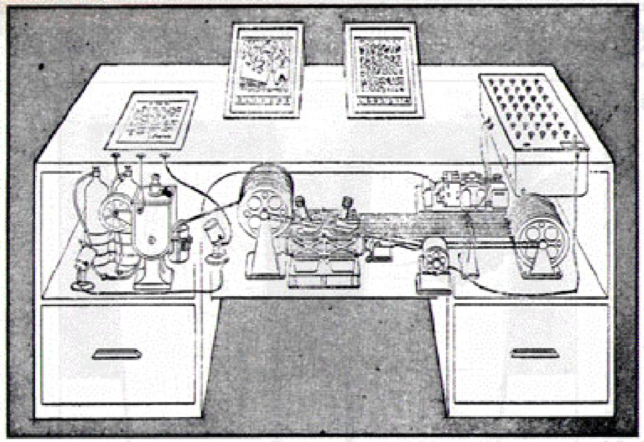
SCIENCE AND THE BOMB.

University professors who are opposed to organizing, planning and directing research after the manner of industrial laboratories because in their opinion fundamental research is based on "curiosity" and because great scientific minds must be left to themselves have something to think about. A most important piece of research was conducted on behalf of the Army by precisely the means adopted in industrial laboratories. And the result? An invention is given to the world in three years which it would have taken perhaps half a century to develop if we had to rely on prima donna research scientists who work alone. The internal logical necessities of atomic physics and the war led to the bomb. A problem was stated. It was solved by team work, by planning, by competent direction and not by a mere desire to satisfy curiosity.

One of the most important people you have likely never heard of

Vannevar Bush 1890-1974
Initial manager of the Manhattan Project until 1943
Bits of information; Shannon (1936)

In a 1945 article As we May Think, he anticipated the World Wide Web via the Memex (Memory Extender)

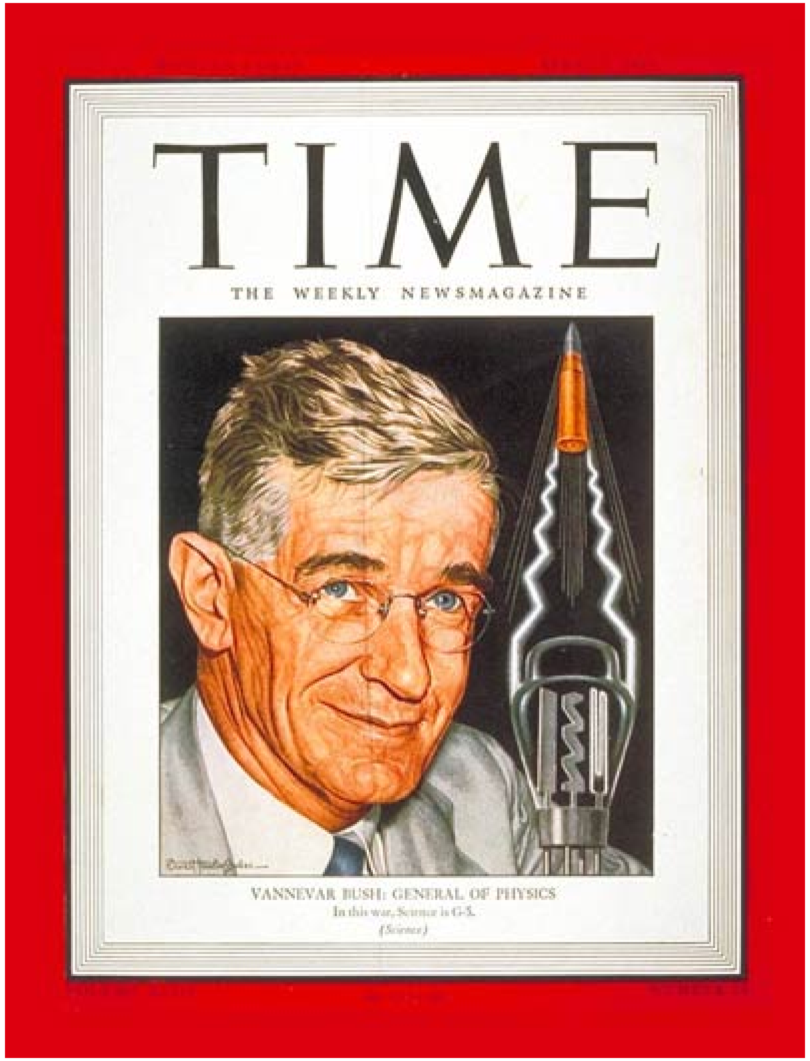


Memex in the form of a desk would instantly bring files and material on any subject to the operator's fingertips. Slanting translucent viewing screens magnify supermicrofilm filed by code numbers. At left is a mechanism which automatically photographs longhand notes, pictures and letters, then files them in the desk for future reference (*LIFE 19*(11), p. 123).

A memex is a device in which an individual stores all his books, records, and communications, and which is mechanized so that it may be consulted with exceeding speed and flexibility.

The essential feature of the memex [is] the process of tying two items together…at any time, when one of these items is in view, the other can be instantly recalled merely by tapping a button

One of the most important people you have likely never heard of



Vannevar Bush 1890-1974
Initial manager of the Manhattan Project until 1943
Bits of information; Shannon (1936)

In a 1945 report *Science the Endless Frontier*, he created a funding system for scientific research and the structure of research organisation.

"Basic research is the pacemaker of technological progress"

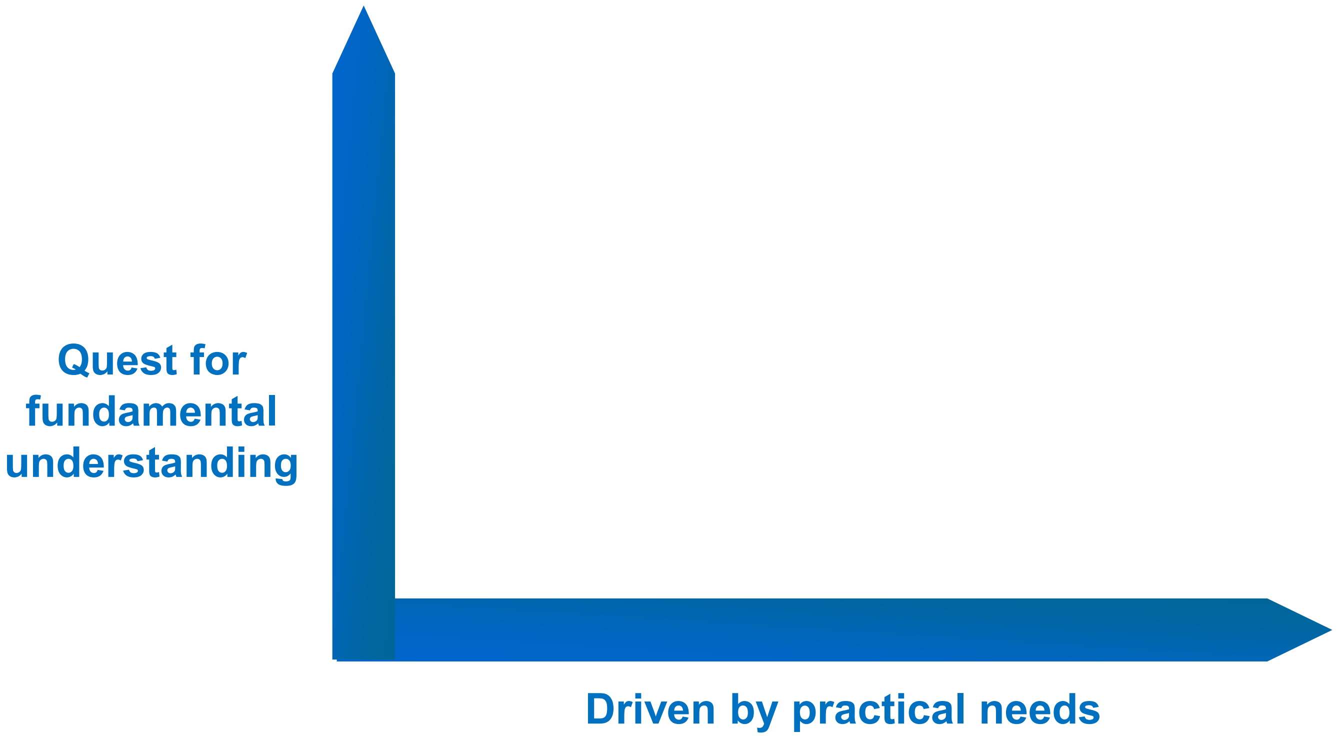
Basic Research → Applied Research → Development → Production

This idea which we take for granted was first written down in 1945

www.nsf.gov/about/history/nsf50/vbush1945.jsp

But this approach does not describe the two way flow of ideas

A more useful approach adds another dimension to describe how pure and applied research interact



Donald E. Stokes 1928-1997
Political Scientist, NSF Advisor

1997: *Pasteur's Quadrant - Basic Science & Technological Innovation*

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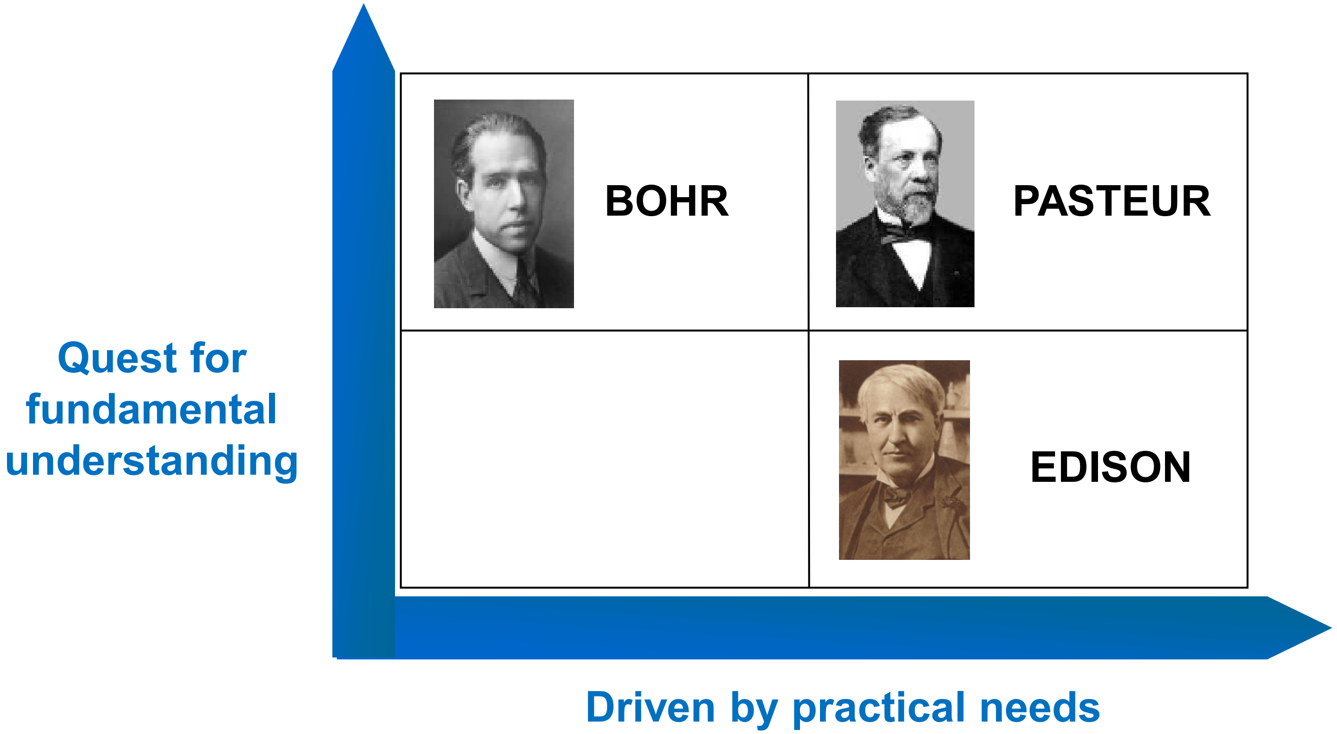
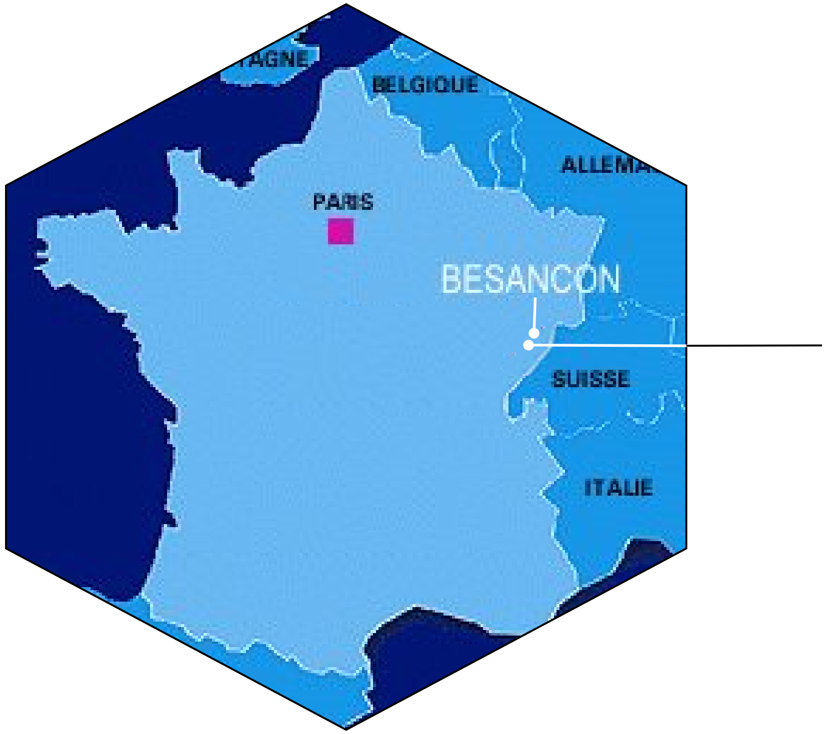


Donald E. Stokes 1928-1997
Political Scientist, NSF Advisor

1997: *Pasteur's Quadrant - Basic Science & Technological Innovation*

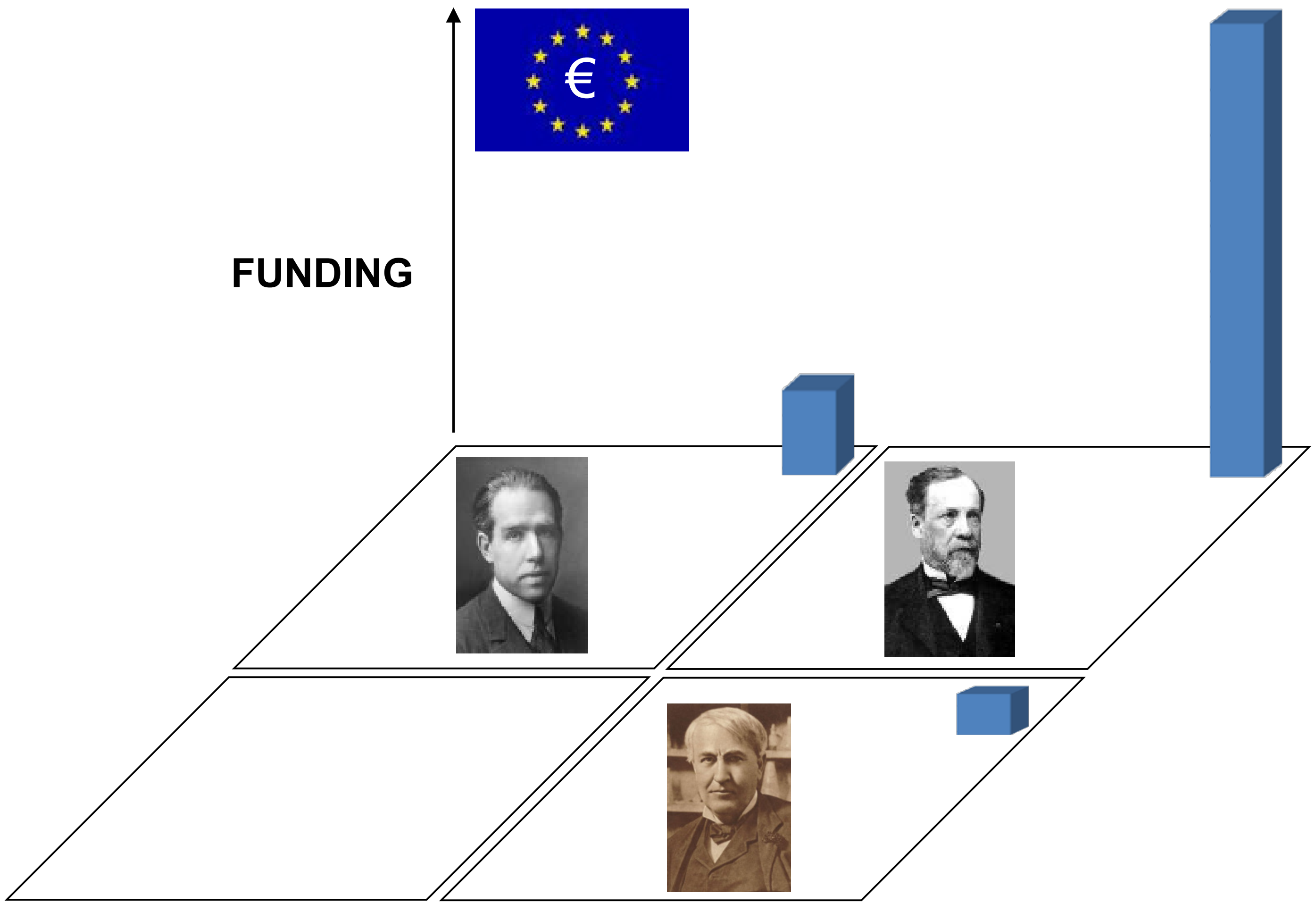
Pasteur – science inspired by need



Motivation : spoilage, disease …

Results : microbiology, germ theory of disease …

Pasteur's quadrant and modern university funding

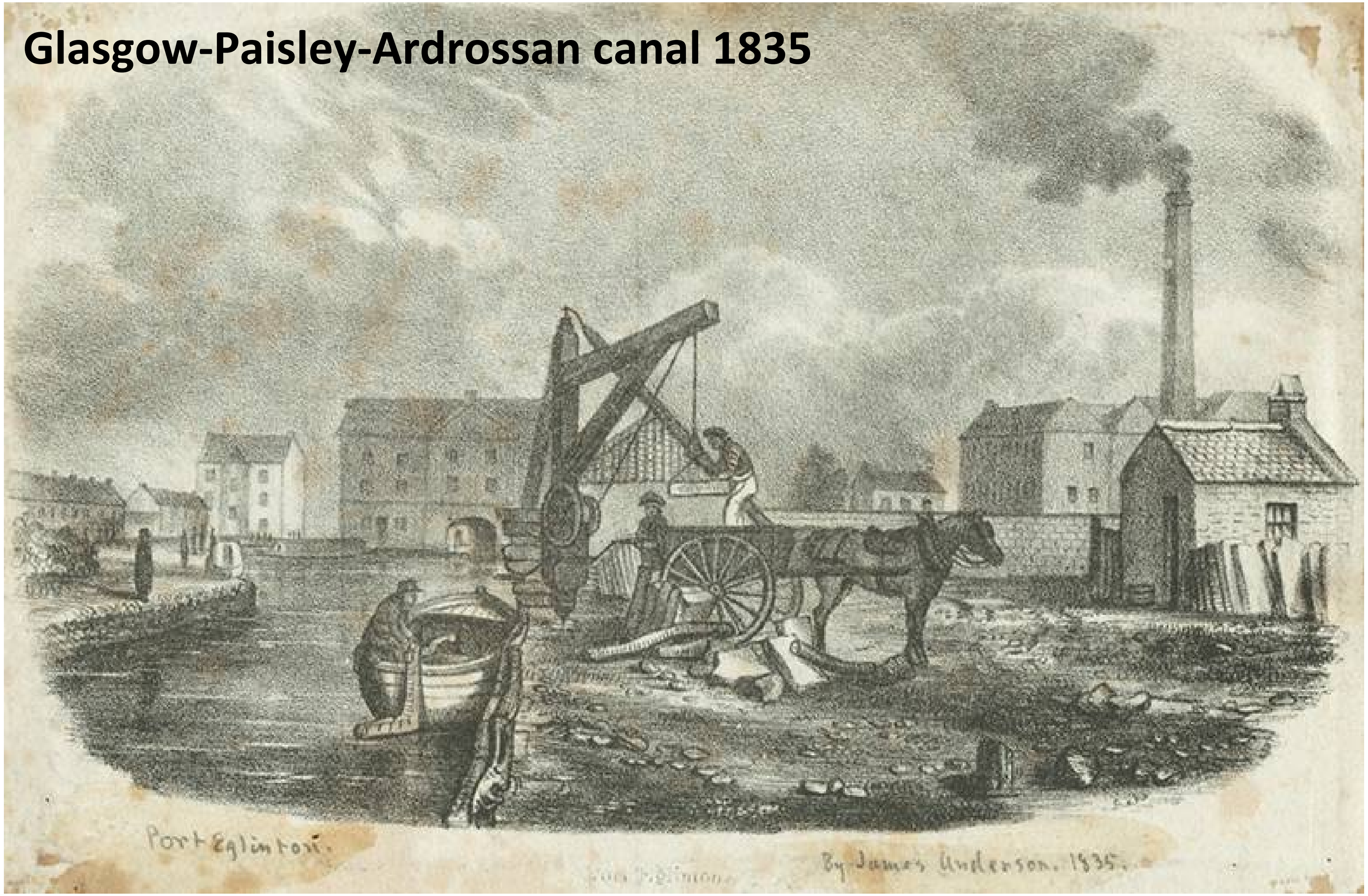


This may seem restrictive, but there are many examples of fundamental research concepts being developed from goal-driven objectives

However, it is of course essential that there is always the freedom (and time) to be able to follow up any new ideas

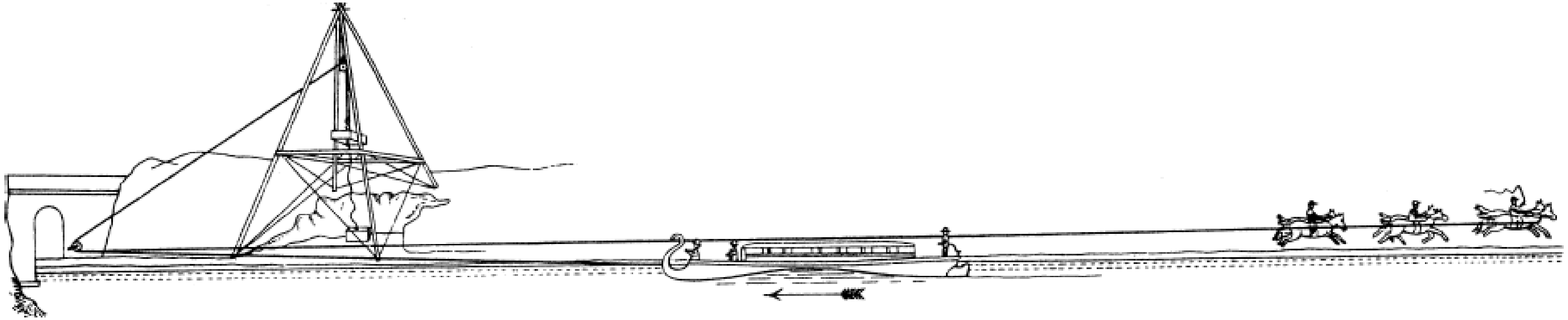
We now look at some stories from nonlinear science and nonlinear fibre optics

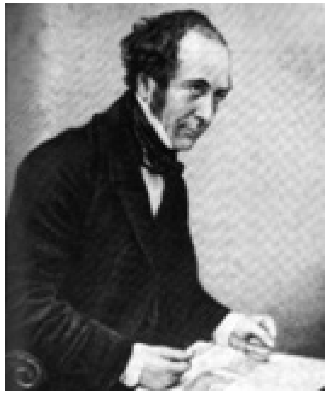
The practical origins of the science of nonlinear waves



The 1830's – the curious history of the soliton

In August 1834, Russell was studying how canal boat speed depends on hull shape when a rope in the towing apparatus broke, resulting in the unexpected propagation of a solitary wave over 4 km in the canal.

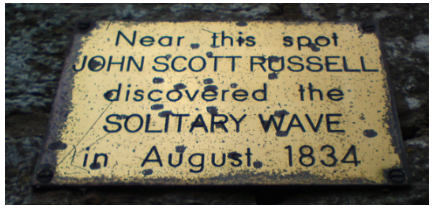




John Scott Russell
(1808-1882)

the boat suddenly stopped – not so the mass of water in the channel which it had put in motion ... assuming the form of a large solitary elevation …

Bridge 11,
Hermiston Walk,
Heriot Watt University



Russell : British Association for the Advancement of Science, Annual reports 1837, 1839, 1844

Developing theories of nonlinear wave equations

Confirmation and theory

1865: Henri Bazin (Canal de Bourgogne)
1871: Joseph Boussinesq
1895: Korteweg – de Vries

KdV shallow water wave equation

Korteweg and de Vries succeeded in deducing the following non-linear equation for the change in height, denoted by η, above the original (and final) depth of water, denoted by h

$$\frac{\partial \eta}{\partial t} = \frac{3}{2}\sqrt{\frac{g}{h}}\left[\frac{2}{3}\,\alpha\,\frac{\partial \eta}{\partial x} + \eta\,\frac{\partial \eta}{\partial x} + \frac{1}{3}\,\sigma\,\frac{\partial^3 \eta}{\partial x^3}\right]. \qquad (1)$$

Here $\sigma = h^3/3 - Th/\rho g$, where ρ is the density and T is the surface tension. The constant quantity α is small compared with h and is closely related to the amplitude of the wave.

Canal de Bourgogne

J. E. Allen, The Early History of Solitons (Solitary Waves) Phys. Scr. **57** 436 (1998)

The Korteweg – de Vries solution was a PhD problem

The solitary wave was studied by Diederik Korteweg (1848–1941) from the University of Amsterdam who proposed its study **to his student** Gustav de Vries (1866–1934) who started his Ph.D. in 1891.

De Vries's initial PhD thesis submission was rejected by Korteweg in a letter of October 1893

To my regret I am unable to accept your dissertation in its present form.

It is obviously a disappointment for you who must have deemed to have already almost completed your task, to discover that you have apparently only completed the preparatory work.

In the meantime do not be down-hearted. With pleasure I will do my best to help you mount the horse...

Nonlinear science became a focus with the development of computers

During the Manhattan Project, Fermi had wondered about the application of numerical techniques to explore the fundamental properties of coupled systems

STUDIES OF NON LINEAR PROBLEMS

E. FERMI, J. PASTA, and S. ULAM
Document LA-1940 (May 1955).

ABSTRACT.

A one-dimensional dynamical system of 64 particles with forces between neighbors containing nonlinear terms has been studied on the Los Alamos computer MANIAC I. The nonlinear terms considered are quadratic, cubic, and broken linear types. The results are analyzed into Fourier components and plotted as a function of time.

*We thank Miss Mary Tsingou for efficient coding of the problems and for running the computations on the Los Alamos MANIAC machine.

The first numerical experiment in nonlinear science - 1955

During the Manhattan Project, Fermi had wondered about the application of numerical techniques to explore the fundamental properties of coupled systems

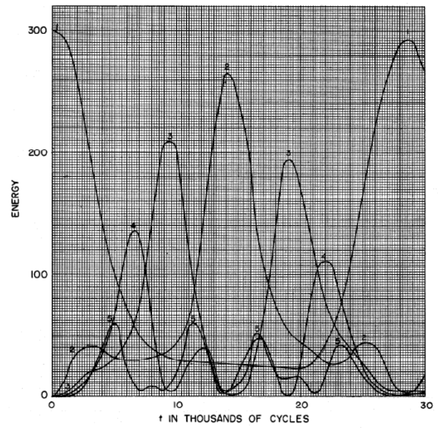


Fig. 1. The quantity plotted is the energy (kinetic plus potential in each of the first five modes). The units for energy are arbitrary. $N = 32$; $\alpha = 1/4$; $\delta t^2 = 1/8$. The initial form of the string was a single sine wave. The higher modes never exceeded in energy 20 of our units. About 30,000 computation cycles were calculated.

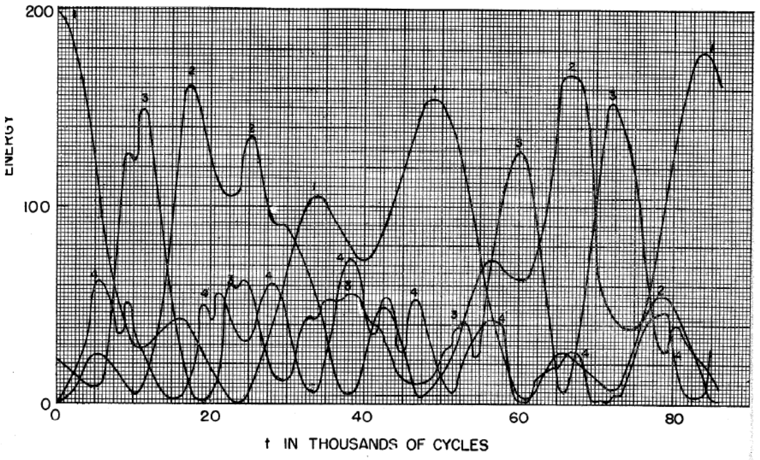
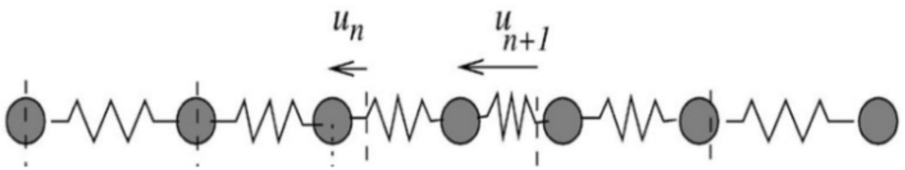


Fig. 3. Same conditions as in Fig. 1, but the initial configuration of the string was a "saw-tooth" triangular-shaped wave. Already at $t = 0$, therefore, energy was present in some modes other than 1. However, modes 5 and higher never exceeded 40 of our units.



It was expected that nonlinearity would couple energy from one initially excited mode into all the modes of the system.

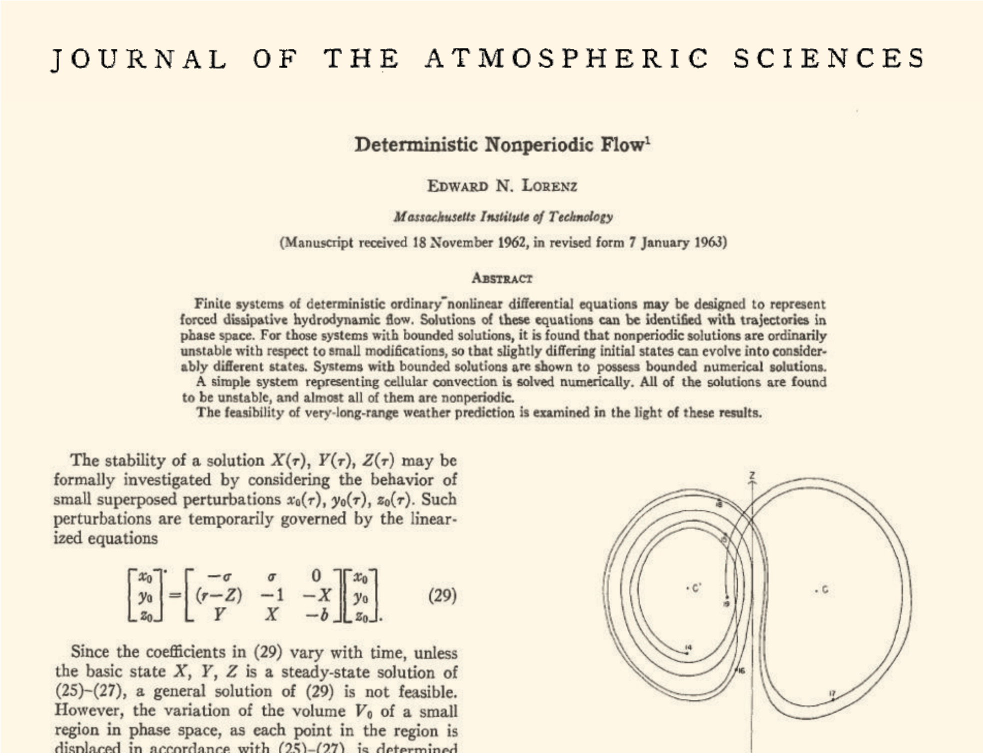
The "intuition" was that the initial energy would be distributed towards (thermodynamic) equipartition amongst the modes

What was observed was totally different !

> Let us say here that the results of our computations show features which were, from the beginning, surprising to us.

A slightly later numerical experiment in nonlinear science - 1962

Conrad Lorenz discovered chaos in atmospheric convection, opening up the domains of chaos, nonlinear science & complexity with impact in both basic and applied sciences



JOURNAL OF THE ATMOSPHERIC SCIENCES

Deterministic Nonperiodic Flow[1]

EDWARD N. LORENZ

Massachusetts Institute of Technology

(Manuscript received 18 November 1962, in revised form 7 January 1963)

ABSTRACT

Finite systems of deterministic ordinary nonlinear differential equations may be designed to represent forced dissipative hydrodynamic flow. Solutions of these equations can be identified with trajectories in phase space. For those systems with bounded solutions, it is found that nonperiodic solutions are ordinarily unstable with respect to small modifications, so that slightly differing initial states can evolve into considerably different states. Systems with bounded solutions are shown to possess bounded numerical solutions.

A simple system representing cellular convection is solved numerically. All of the solutions are found to be unstable, and almost all of them are nonperiodic.

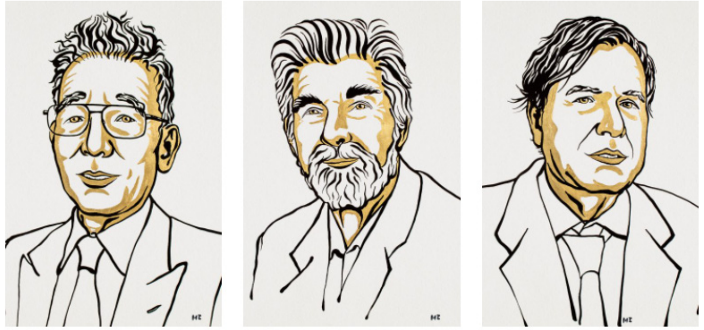
The feasibility of very-long-range weather prediction is examined in the light of these results.

The stability of a solution $X(\tau)$, $Y(\tau)$, $Z(\tau)$ may be formally investigated by considering the behavior of small superposed perturbations $x_0(\tau)$, $y_0(\tau)$, $z_0(\tau)$. Such perturbations are temporarily governed by the linearized equations

$$\begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix}^{\cdot} = \begin{bmatrix} -\sigma & \sigma & 0 \\ (r-Z) & -1 & -X \\ Y & X & -b \end{bmatrix} \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix}. \qquad (29)$$

Since the coefficients in (29) vary with time, unless the basic state X, Y, Z is a steady-state solution of (25)–(27), a general solution of (29) is not feasible. However, the variation of the volume V_0 of a small region in phase space, as each point in the region is displaced in accordance with (25)–(27), is determined

The Nobel Prize in Physics 2021



Ill. Niklas Elmehed © Nobel Prize Outreach
Syukuro Manabe
Prize share: 1/4

Ill. Niklas Elmehed © Nobel Prize Outreach
Klaus Hasselmann
Prize share: 1/4

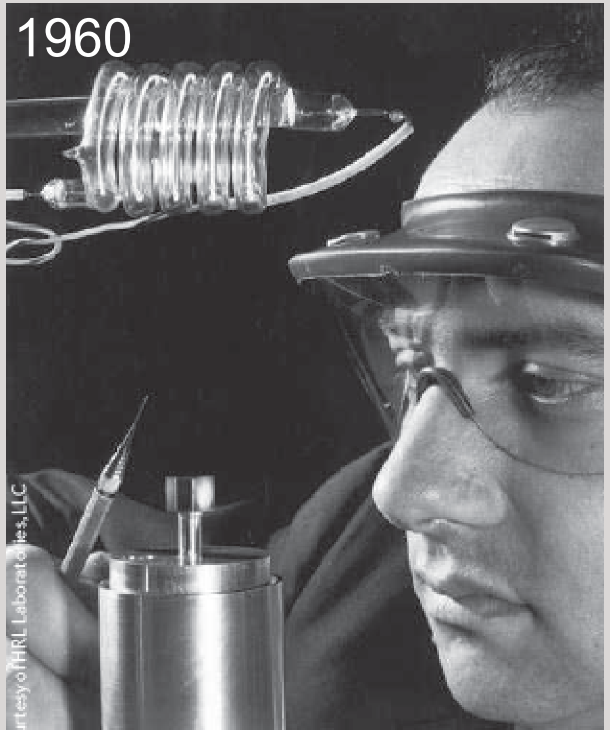
Ill. Niklas Elmehed © Nobel Prize Outreach
Giorgio Parisi
Prize share: 1/2

Syukuro Manabe and Klaus Hasselmann "for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming"

Giorgio Parisi "for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales."

Nonlinear optics with lasers - 1961

The power & spatial coherence of lasers enabled the study of the nonlinear response of matter to light

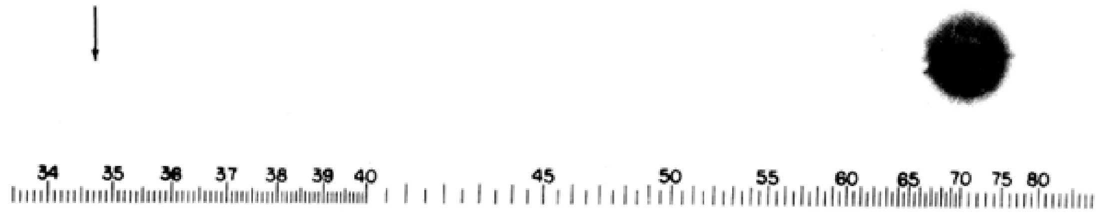


1961

VOLUME 7, NUMBER 4 PHYSICAL REVIEW LETTERS AUGUST 15, 1961

GENERATION OF OPTICAL HARMONICS*

P. A. Franken, A. E. Hill, C. W. Peters, and G. Weinreich
The Harrison M. Randall Laboratory of Physics, The University of Michigan, Ann Arbor, Michigan
(Received July 21, 1961)



In the experiments we have used a commercially available ruby optical maser[4] which produces approximately 3 joules of 6943A light in a one-millisecond pulse.

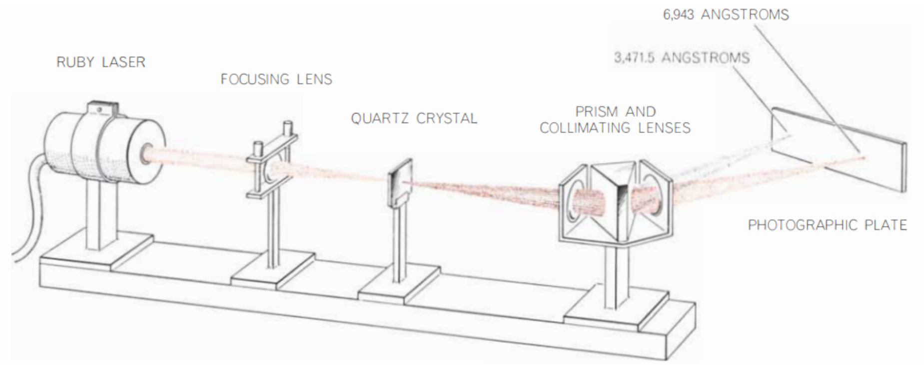
NATURE MILESTONES | PHOTONS www.nature.com/milestones/photons

(but the first evidence of the second harmonic was removed as a speck of dirt)

Luckily for us …

The Interaction of Light with Light

by J. A. Giordmaine



FIRST DEMONSTRATION that ultraviolet light could be generated by the intense flash of a ruby laser was made with this experimental arrangement in 1961 at the University of Michigan. The investigators were Peter A. Franken, Allen E. Hill, C. W. Peters and Gabriel Weinreich. The quartz crystal converted only a hundred-millionth of the incident light to ultraviolet light. On being passed through a prism the ultraviolet is bent more than the red laser light and the two can be photographed separately (*see below*).

FIRST PHOTOGRAPHS of second-harmonic ultraviolet light were made by Franken and his associates. In each case the amount of ultraviolet (*small spots at 3,471.5 angstroms*) is roughly proportional to the square of the amount of red light at 6,943 angstroms.

1963 – the mode-locked laser & birth of ultrafast optics

Zeitschrift für Physik 172, 163—171 (1963)

Aus dem Forschungslaboratorium der Siemens & Halske AG, München

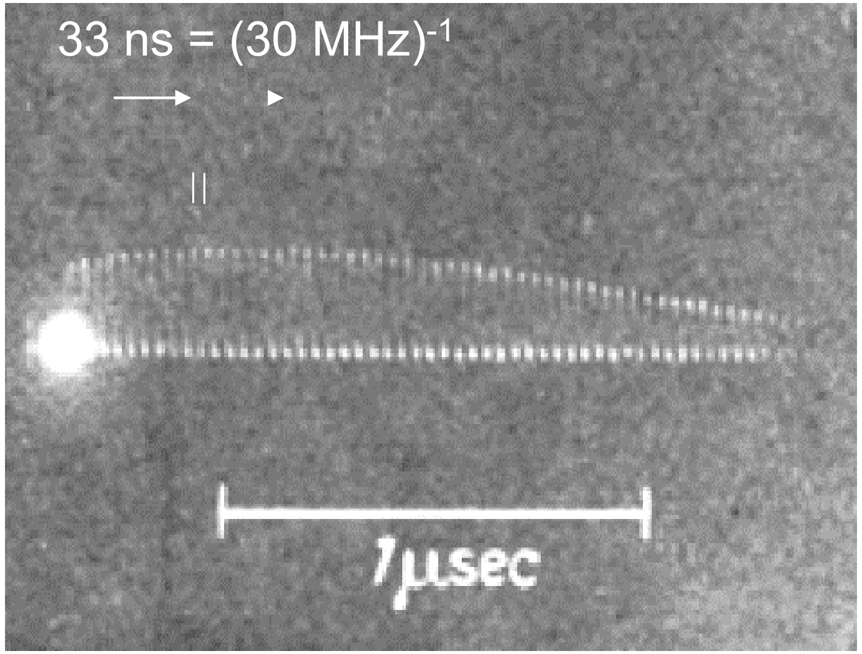
Innere Modulation von optischen Masern*

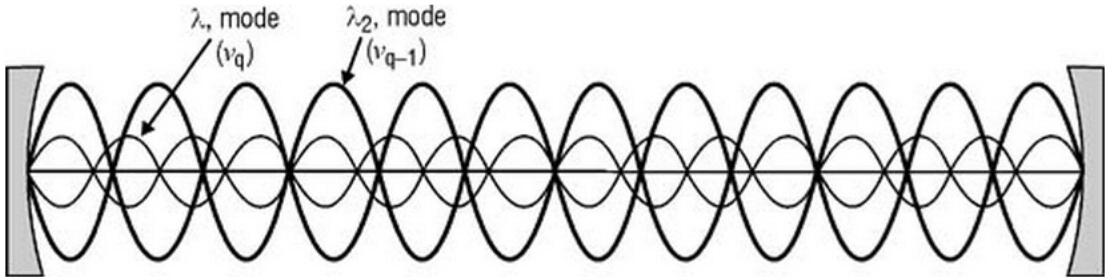
Von
KARL GÜRS

Mit 5 Figuren im Text

(Eingegangen am 5. Oktober 1962)

Fig. 5a–c. Modulation bei 30 MHz

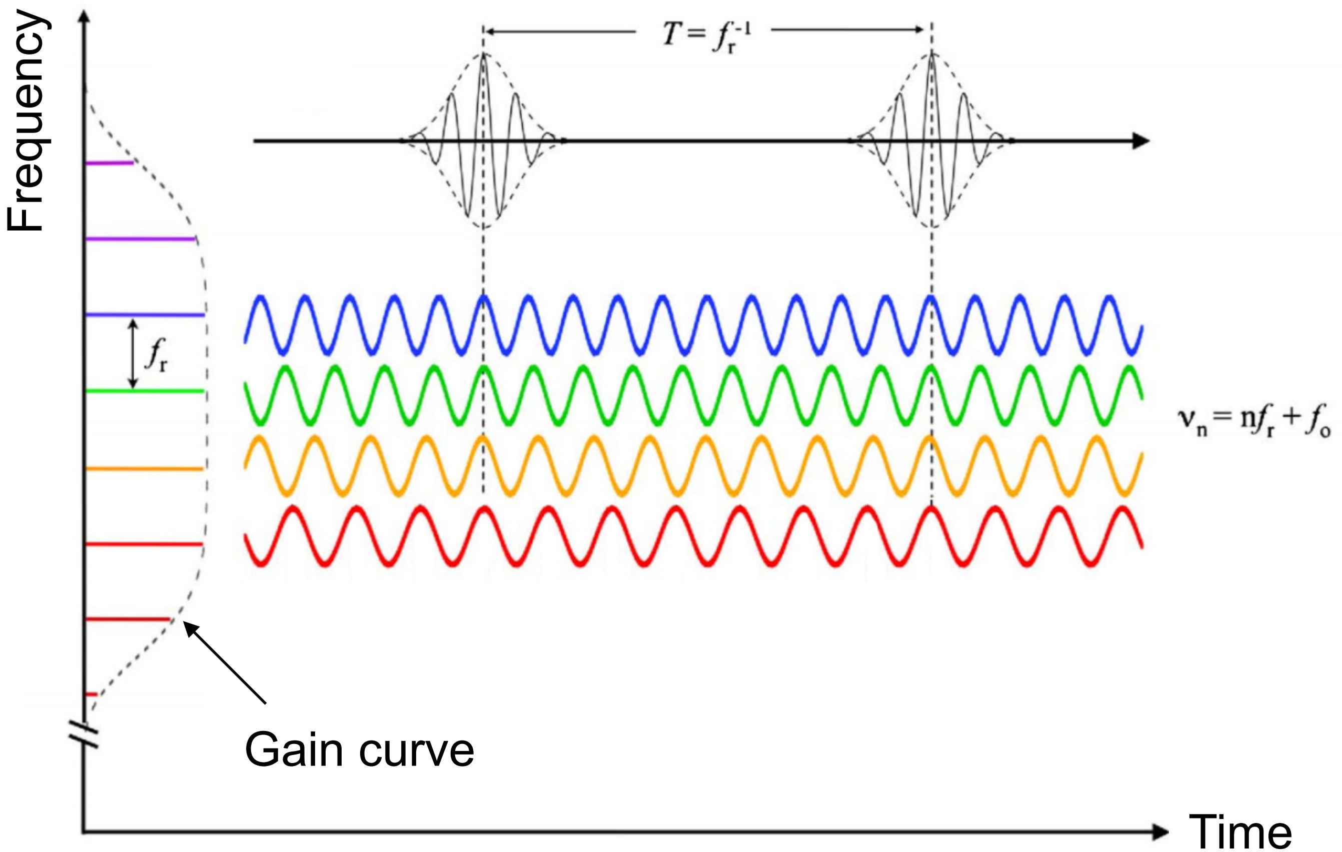




Phase-locked modes in a standing-wave optical cavity

1963 – the mode-locked laser & birth of ultrafast optics

Locking phases of the optical cavity modes oscillating beneath gain curve creates a train of ultrashort pulses



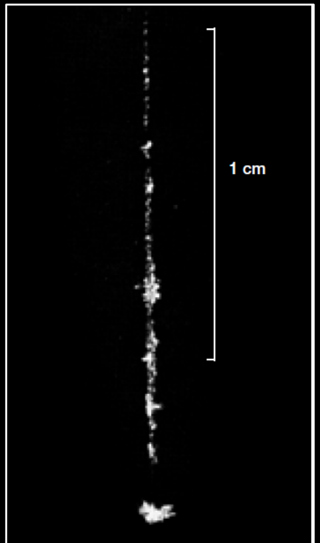
Karl Gürs, Innere Modulation von optischen Masern
Z. für Physik, **172**, 163 (1963)

1965 – Optical Solitons were first observed in the spatial domain

OPN Optics & Photonics News November 2010 |

How the Laser Launched Nonlinear Optics

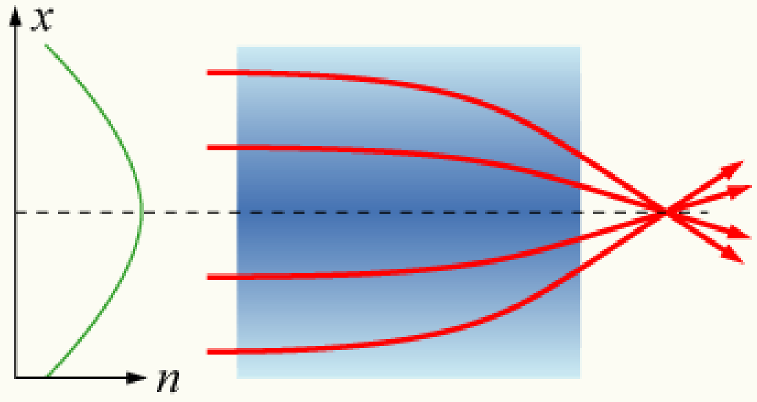
Jeff Hecht



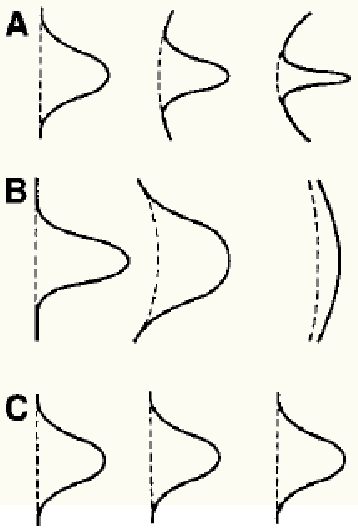
Firing a Q-switched ruby pulse through an f/20 lens produced a long, thin damage zone that revealed self-trapping.

Courtesy of Michael Hercher

The fact that the damaged zone was smaller than the focal spot—and that it did not increase as the beam passed through the glass—led Townes to suggest that optical nonlinearities were offsetting beam diffraction to cause self-trapping.



$$n = n_0 + n_2 \, I(x)$$



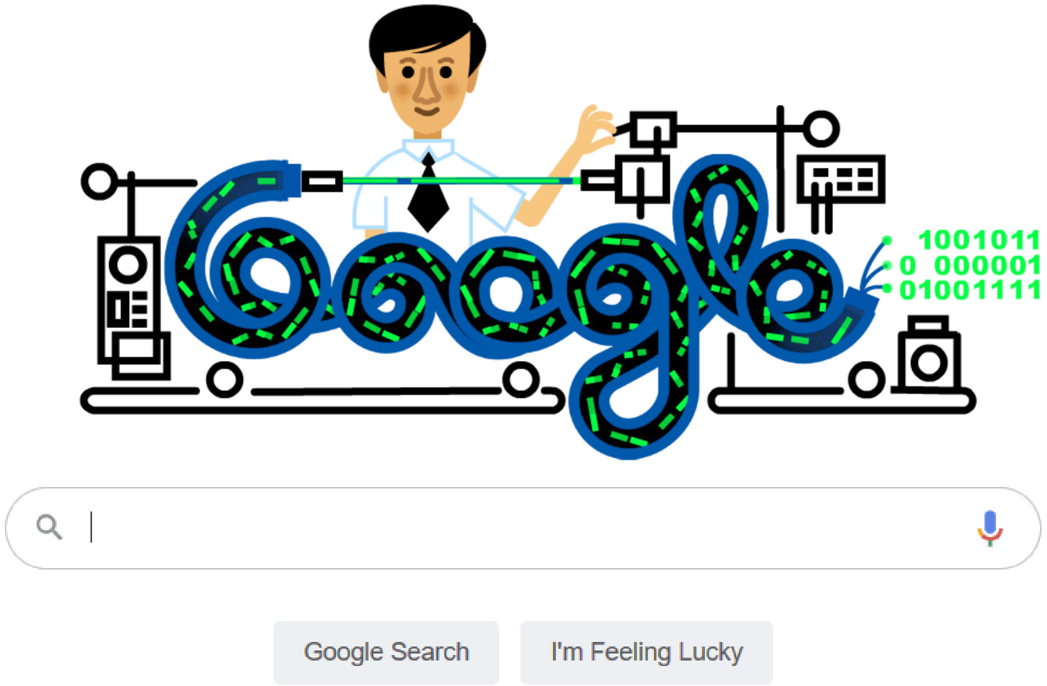
1966 - low-loss optical waveguide development

Reliable techniques for fabricating small-core waveguides yielded the birth of fibre optics

PROC. IEE, Vol. 113, No. 7, JULY 1966

Dielectric-fibre surface waveguides for optical frequencies

The Nobel Prize in Physics 2009



Details: (i) total internal reflection

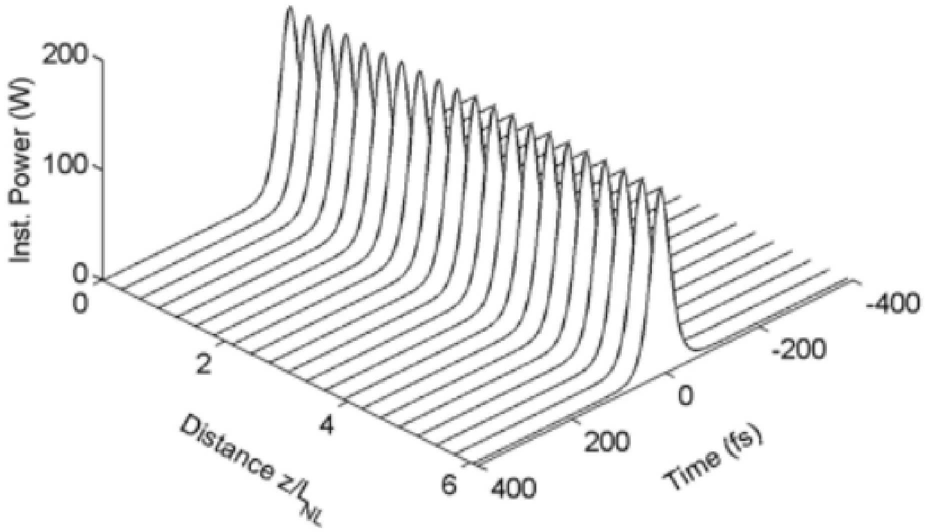
(ii) the binary sequences converted to ASCII spell K A O

1970s & 80s Temporal Solitons as invariant information carriers

Solitons in optical fibres

1973: Theory: Hasegawa & Tappert
(origin in plasma physics)

1980: Experiment: Mollenauer, Stolen, Gordon



Nonlinear Schrödinger equation

$$\mathrm{i}\frac{\partial A(z,T)}{\partial z} = \frac{\beta_2}{2}\frac{\partial^2 A(z,T)}{\partial T^2} - \gamma\,|A(z,T)|^2\,A(z,T)$$

co-moving time $T = t - z/v_g = t - \beta_1 z$

Kerr nonlinearity $\gamma = n_2\omega_0/cA_{eff}$

instantaneous power (W) $|A(z,T)|^2$

Stable propagation of temporal solitons from the balance between dispersion and self-phase modulation (temporal self-focussing)

1970s & 80s Temporal Solitons as invariant information carriers

Solitons in optical fibres

1973: Theory: Hasegawa & Tappert
(origin in plasma physics)

1980: Experiment: Mollenauer, Stolen, Gordon

Nonlinear Schrödinger equation

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co-moving time $T = t - z/v_g = t - \beta_1 z$

Kerr nonlinearity $\gamma = n_2\omega_0/cA_{eff}$

instantaneous power (W) $|A(z,T)|^2$

Linn Mollenauer 1937-2021

Solitons in mode-locked lasers - 1984

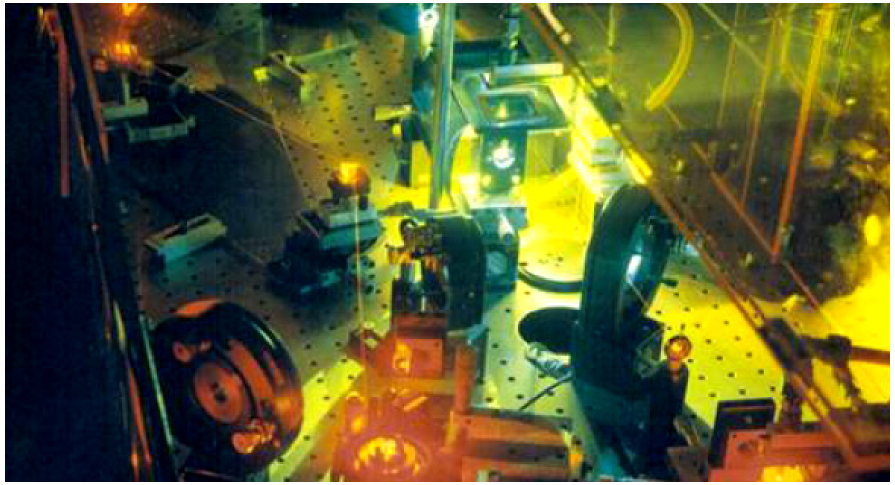
156 OPTICS LETTERS / Vol. 9, No. 5 / May 1984

Theory of passively mode-locked lasers including self-phase modulation and group-velocity dispersion

O. E. Martinez, R. L. Fork, and J. P. Gordon

AT&T Bell Laboratories, Holmdel, New Jersey 07733

Closed-form analytical solutions are obtained for a passively mode-locked laser for the case in which self-phase *modulation and group-velocity dispersion, in addition to the more conventional mechanisms of saturable absorption* and gain, shape the laser pulses. Provided that the self-phase modulation and group-velocity dispersion are related in a manner similar to that which causes soliton formation in optical fibers, this additional pulse shaping can reduce the pulse duration below the limit otherwise set by the laser bandwidth.



Fibre soliton concepts could be immediately applied to mode-locked laser design

Temporal & spatial solitons in a Kerr lens mode-locked (KLM) Ti:Sapphire

42 OPTICS LETTERS / Vol. 16, No. 1 / January 1, 1991

60-fsec pulse generation from a self-mode-locked Ti:sapphire laser

D. E. Spence, P. N. Kean, and W. Sibbett

This frequency chirp must originate from within the main laser cavity and is due primarily to the presence of self-phase modulation (SPM) and GVD within the Ti:Al_2O_3 gain medium.

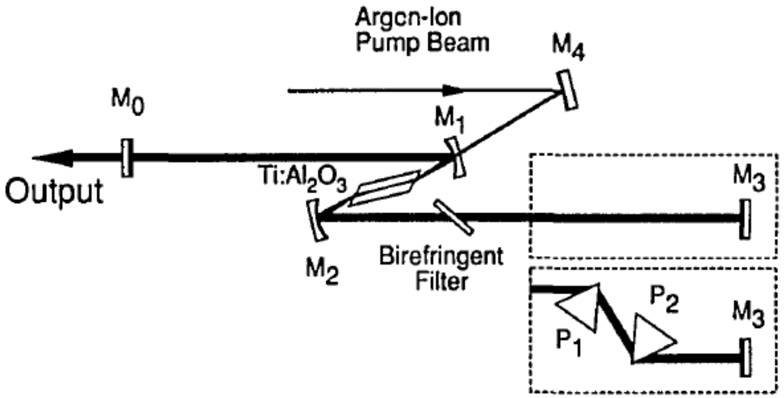
1022 OPTICS LETTERS / Vol. 16, No. 13 / July 1, 1991

Femtosecond pulses from a continuously self-starting passively mode-locked Ti:sapphire laser

U. Keller, G. W. 'tHooft,* W. H. Knox, and J. E. Cunningham

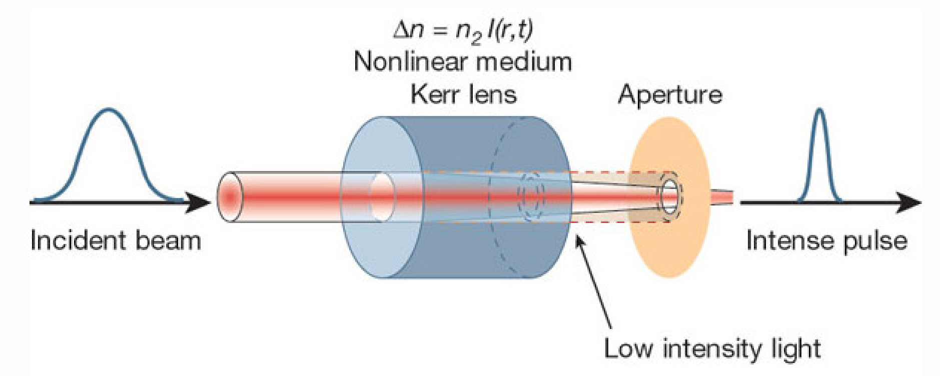
At high peak power a self-focusing effect inside the Ti:sapphire rod modifies the cavity mode in such a way that the beam waist at the aperture becomes smaller, which lowers losses in favor of a mode-locked operation.

Temporal & spatial solitons in a Kerr lens mode-locked (KLM) Ti:Sapphire



Temporal soliton dynamics

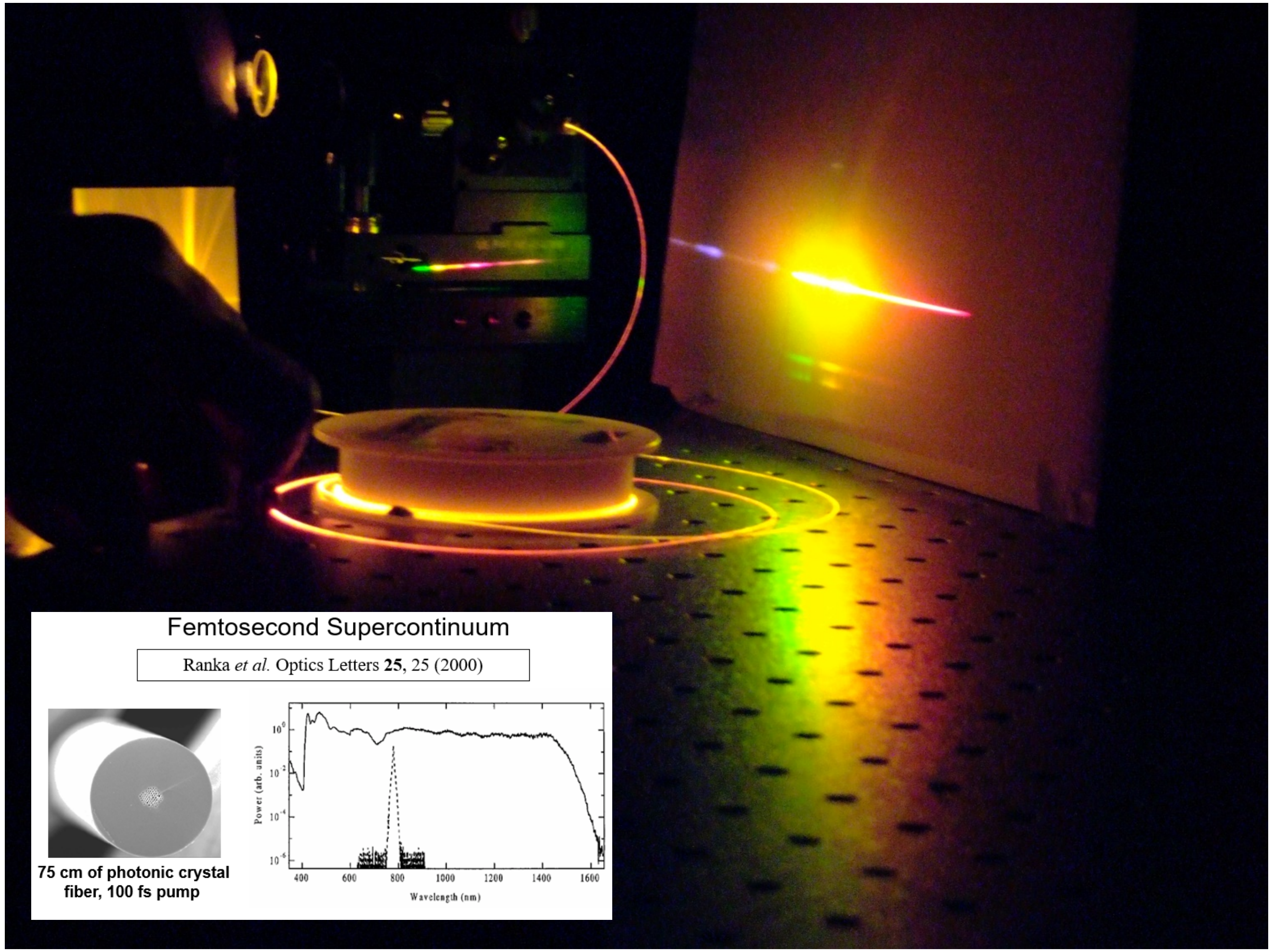
dispersion management

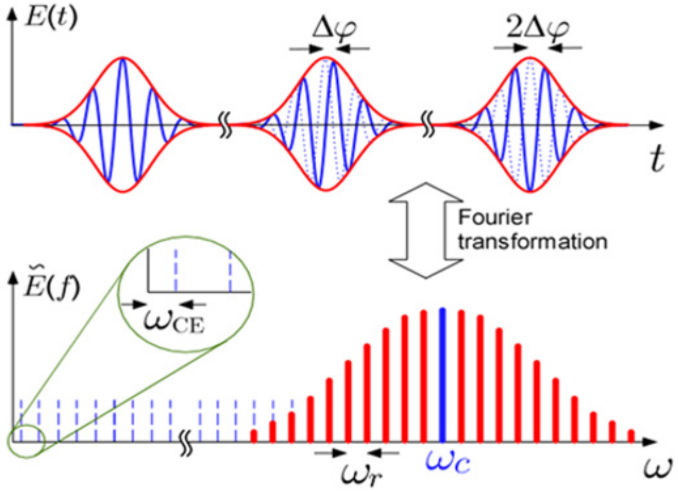


Spatial soliton dynamics

diffraction management

Nobel Prize 2005. A fs KLM laser + fibre solitons = a frequency comb





The Nobel Prize in Physics 2005

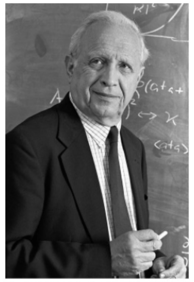


Photo: J.Reed

Roy J. Glauber

Prize share: 1/2

Photo: Sears.P.Studio

John L. Hall

Prize share: 1/4

Photo: F.M. Schmidt

Theodor W. Hänsch

Prize share: 1/4

High power lasers had problems though because of spatial self-focussing

Volume 56, number 3 OPTICS COMMUNICATIONS 1 December 1985

Donna STRICKLAND and Gerard MOUROU

Laboratory for Laser Energetics, University of Rochester, 250 East River Road, Rochester, NY 14623-1299, USA

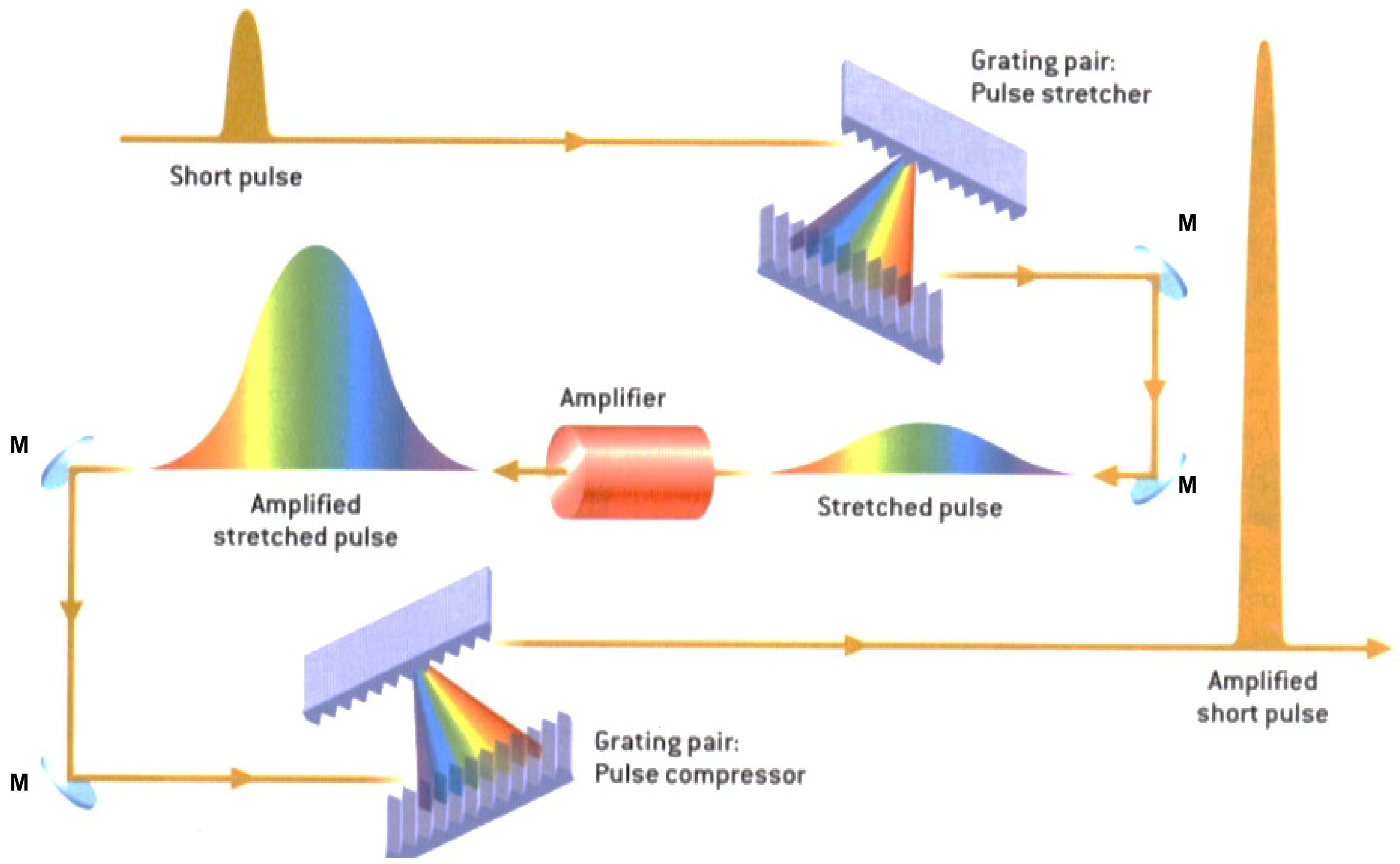
Received 5 July 1985

We have demonstrated the amplification and subsequent recompression of optical chirped pulses. A system which produces 1.06 μm laser pulses with pulse widths of 2 ps and energies at the millijoule level is presented.

The onset of self-focusing of intense light pulses limits the amplification of ultra-short laser pulses. A similar problem arises in radar because of the need for short, yet energetic pulses, without having circuits capable of handling the required peak powers. The solution for radar transmission is to stretch the pulse by passing it through a positively dispersive delay line before amplifying and transmitting the pulse. The echo is compressed to its original pulse shape by a negatively dispersive delay line [1].

We wish to report here a system which transposes the technique employed in radar to the optical regime, and that in principle should be capable of producing short ($\lesssim$1 ps) pulses with energies at the Joule level. A long pulse is deliberately produced by stretching a short, low-energy pulse in a single mode optical fiber. The pulse is linearly chirped in the fiber by the combination of group velocity dispersion and self-phase modulation [2]. The stretched pulse is amplified and then compressed by a double grating compressor [3].

The Chirped Pulse Amplifier System



The 2018 Nobel prize in physics – ultrafast lasers

The Nobel Prize in Physics 2018

Ill. Niklas Elmehed. © Nobel Media

Arthur Ashkin

Prize share: 1/2

Ill. Niklas Elmehed. © Nobel Media

Gérard Mourou

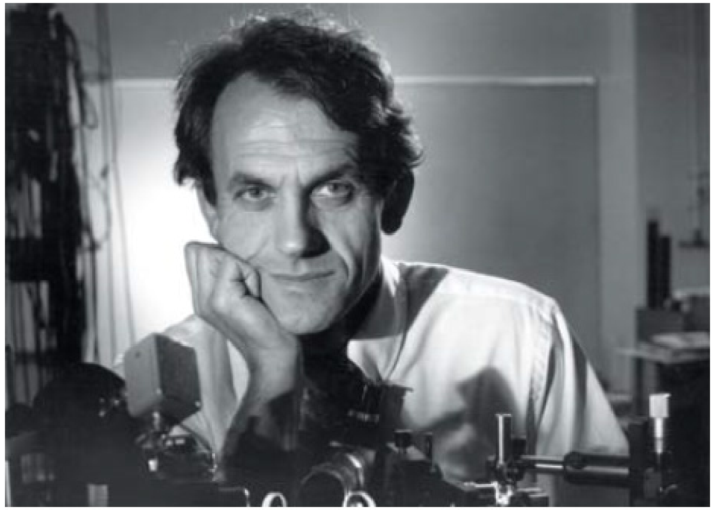
Prize share: 1/4

Ill. Niklas Elmehed. © Nobel Media

Donna Strickland

Prize share: 1/4

The Nobel Prize in Physics 2018 was awarded "for groundbreaking inventions in the field of laser physics" with one half to Arthur Ashkin "for the optical tweezers and their application to biological systems", the other half jointly to Gérard Mourou and Donna Strickland "for their method of generating high-intensity, ultra-short optical pulses."



The 2018 Nobel prize in physics – ultrafast lasers

The Nobel Prize in Physics 2018

Ill. Niklas Elmehed. © Nobel Media

Arthur Ashkin

Prize share: 1/2

Ill. Niklas Elmehed. © Nobel Media

Gérard Mourou

Prize share: 1/4

Ill. Niklas Elmehed. © Nobel Media

Donna Strickland

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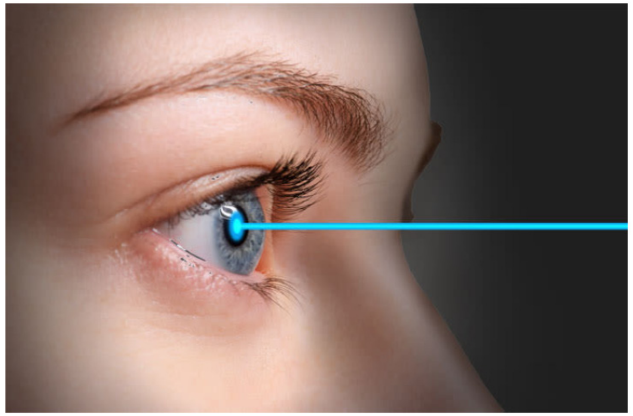
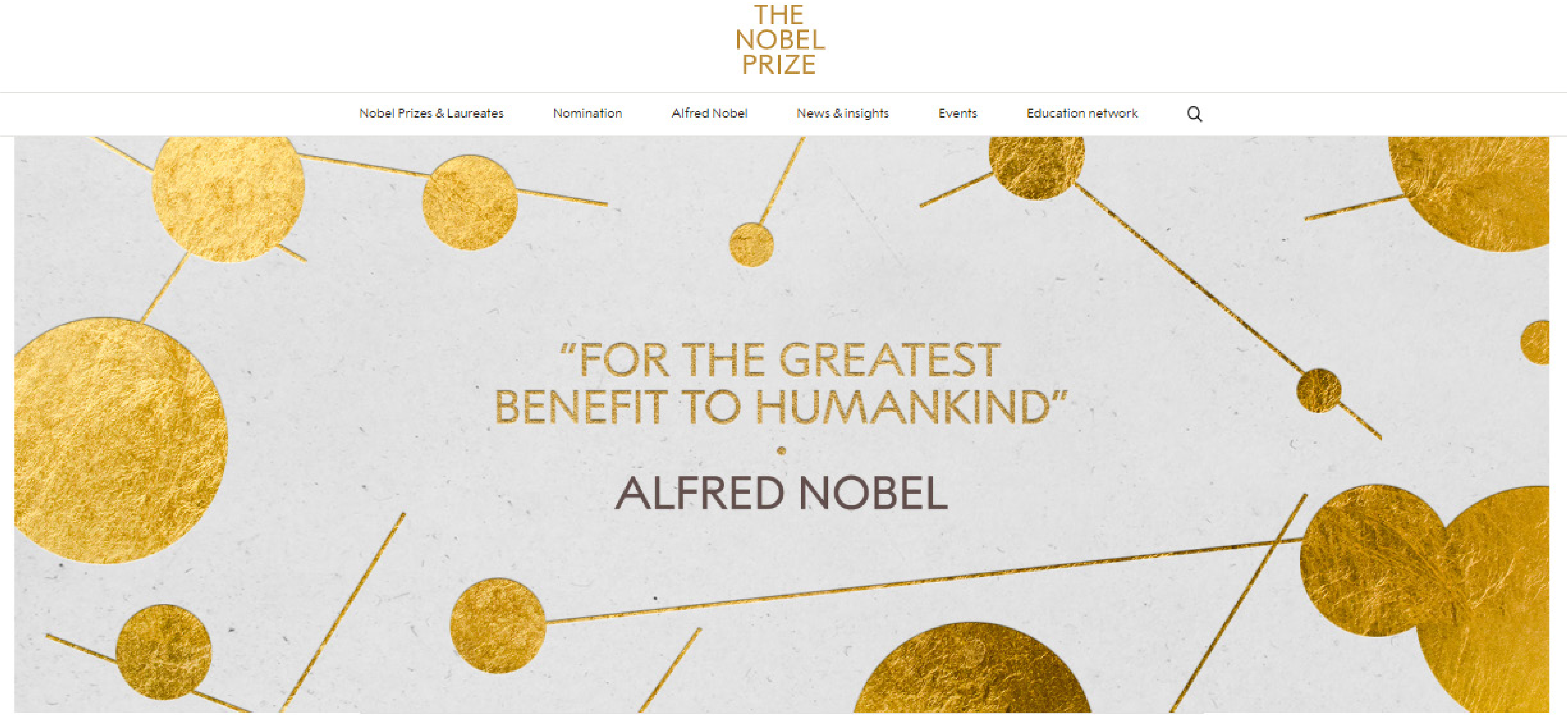
Femtosecond lasers for unmatched micromachining of medical devices

Bladeless LASIK: Femtosecond laser eases LASIK fears

Reviewed by Vance Thompson, MD



Many recent Nobel Prizes stress applications of basic research



Think about what we use in our PCs and phones for example …

The Nobel Prize in Physics 1956

Photo from the Nobel Foundation archive.

William Bradford Shockley

Prize share: 1/3

John Bardeen

Prize share: 1/3

Photo from the Nobel Foundation archive.

Walter Houser Brattain

Prize share: 1/3

The Nobel Prize in Physics 1956 was awarded jointly to William Bradford Shockley, John Bardeen and Walter Houser Brattain "for their researches on semiconductors and their discovery of the transistor effect."

Transistors

Think about what we use in our PCs and phones for example …

The Nobel Prize in Physics 2000

Photo from the Nobel Foundation archive.

Zhores I. Alferov

Prize share: 1/4

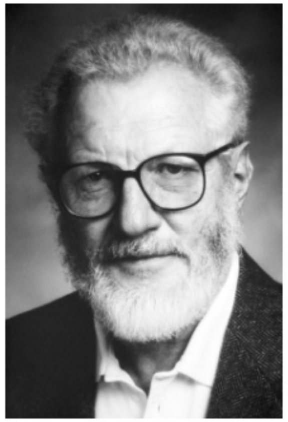


Photo from the Nobel Foundation archive.

Herbert Kroemer

Prize share: 1/4

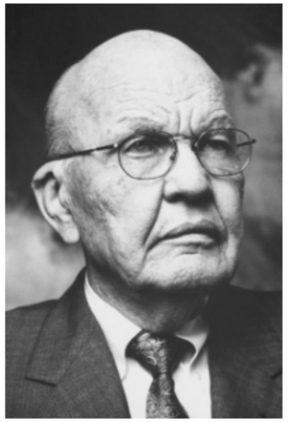


Photo from the Nobel Foundation archive.

Jack S. Kilby

Prize share: 1/2

The Nobel Prize in Physics 2000 was awarded "for basic work on information and communication technology" with one half jointly to Zhores I. Alferov and Herbert Kroemer "for developing semiconductor heterostructures used in high-speed- and opto-electronics" and the other half to Jack S. Kilby "for his part in the invention of the integrated circuit."

Optoelectronics and the Integrated Circuit

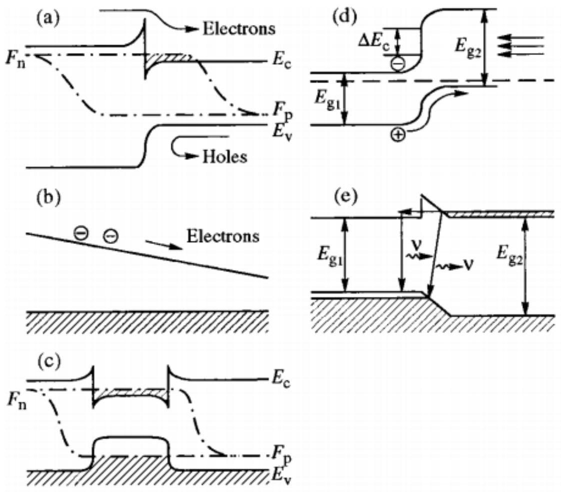
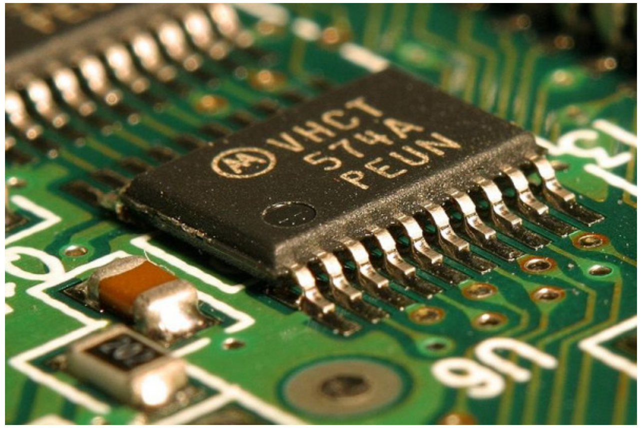


FIG. 1. Main physical phenomena in classical heterostructures: (a) One-side injection and superinjection; (b) diffusion in built-in quasielectric field; (c) electron and optical confinement; (d) wide-gap window effect; (e) diagonal tunneling through a heterostructure interface.



Think about what we use in our PCs and phones for example …

The Nobel Prize in Physics 2007

© The Nobel Foundation. Photo: U. Montan

Albert Fert

Prize share: 1/2

© The Nobel Foundation. Photo: U. Montan

Peter Grünberg

Prize share: 1/2

The Nobel Prize in Physics 2007 was awarded jointly to Albert Fert and Peter Grünberg "for the discovery of Giant Magnetoresistance."

The Hard Drive

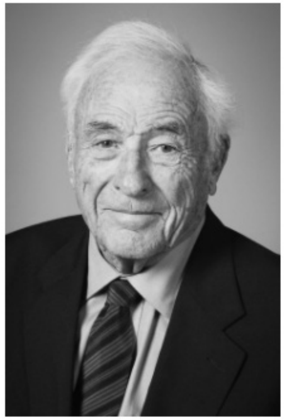
Think about what we use in our PCs and phones for example …

The Nobel Prize in Physics 2009

© The Nobel Foundation. Photo: U. Montan

Charles Kuen Kao

Prize share: 1/2



© The Nobel Foundation. Photo: U. Montan

Willard S. Boyle

Prize share: 1/4

© The Nobel Foundation. Photo: U. Montan

George E. Smith

Prize share: 1/4

The Nobel Prize in Physics 2009 was divided, one half awarded to Charles Kuen Kao "for groundbreaking achievements concerning the transmission of light in fibers for optical communication", the other half jointly to Willard S. Boyle and George E. Smith "for the invention of an imaging semiconductor circuit - the CCD sensor."

Fibre Communications

CCD sensor & digital photography

Think about what we use in our PCs and phones for example …

The Nobel Prize in Physics 2014

© Nobel Media AB. Photo: A. Mahmoud

Isamu Akasaki

Prize share: 1/3

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Hiroshi Amano

Prize share: 1/3

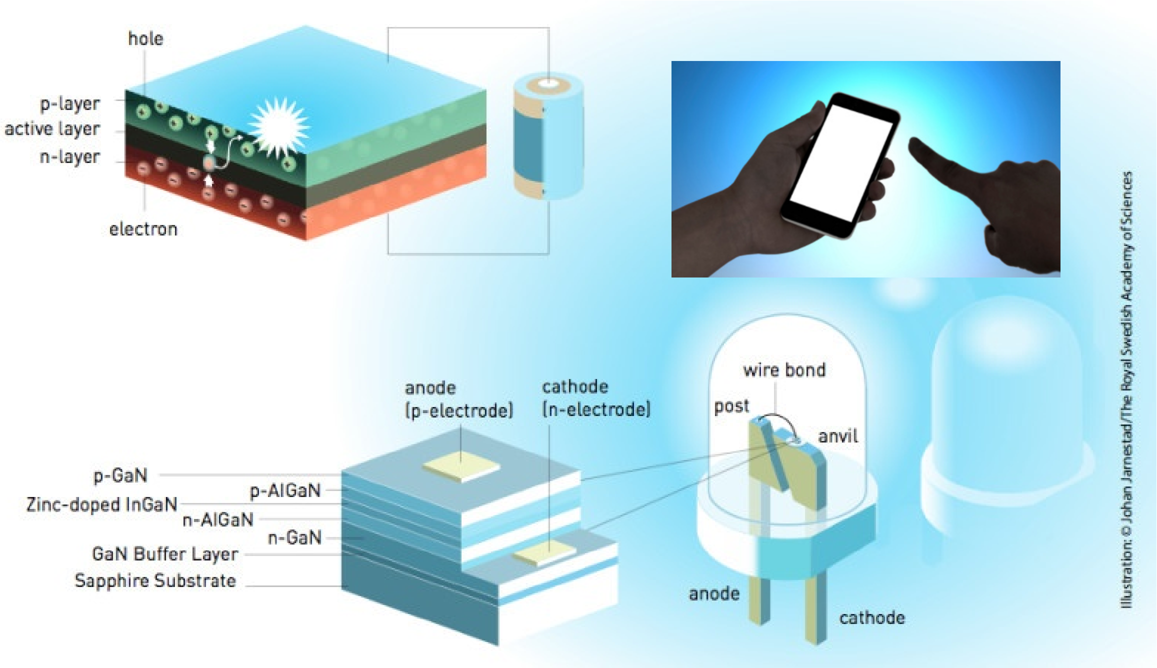
© Nobel Media AB. Photo: A. Mahmoud

Shuji Nakamura

Prize share: 1/3

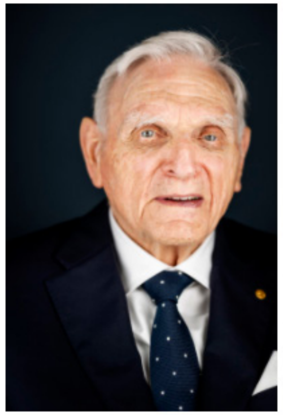
The Nobel Prize in Physics 2014 was awarded jointly to Isamu Akasaki, Hiroshi Amano and Shuji Nakamura "for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources."

Blue LEDS, Flat Panel Displays



Think about what we use in our PCs and phones for example …

The Nobel Prize in Chemistry 2019



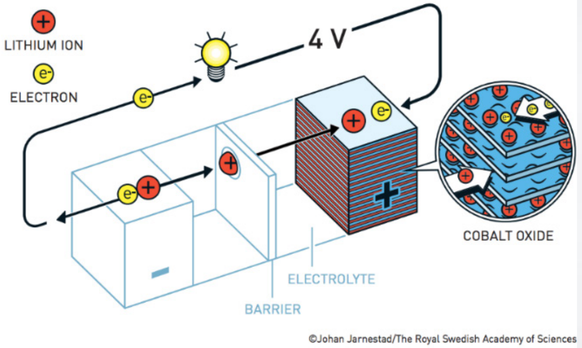
© Nobel Media. Photo: A. Mahmoud
John B. Goodenough
Prize share: 1/3

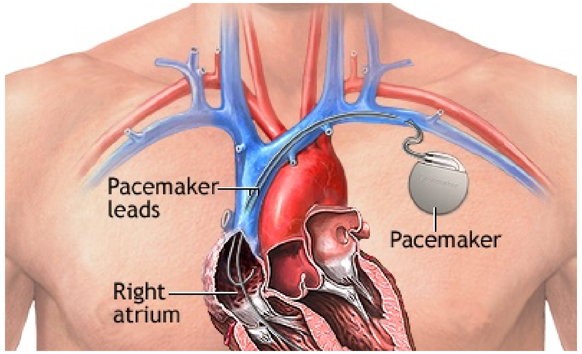
© Nobel Media. Photo: A. Mahmoud
M. Stanley Whittingham
Prize share: 1/3

© Nobel Media. Photo: A. Mahmoud
Akira Yoshino
Prize share: 1/3

The Nobel Prize in Chemistry 2019 was awarded jointly to John B. Goodenough, M. Stanley Whittingham and Akira Yoshino "for the development of lithium-ion batteries."

Lithium-ion batteries



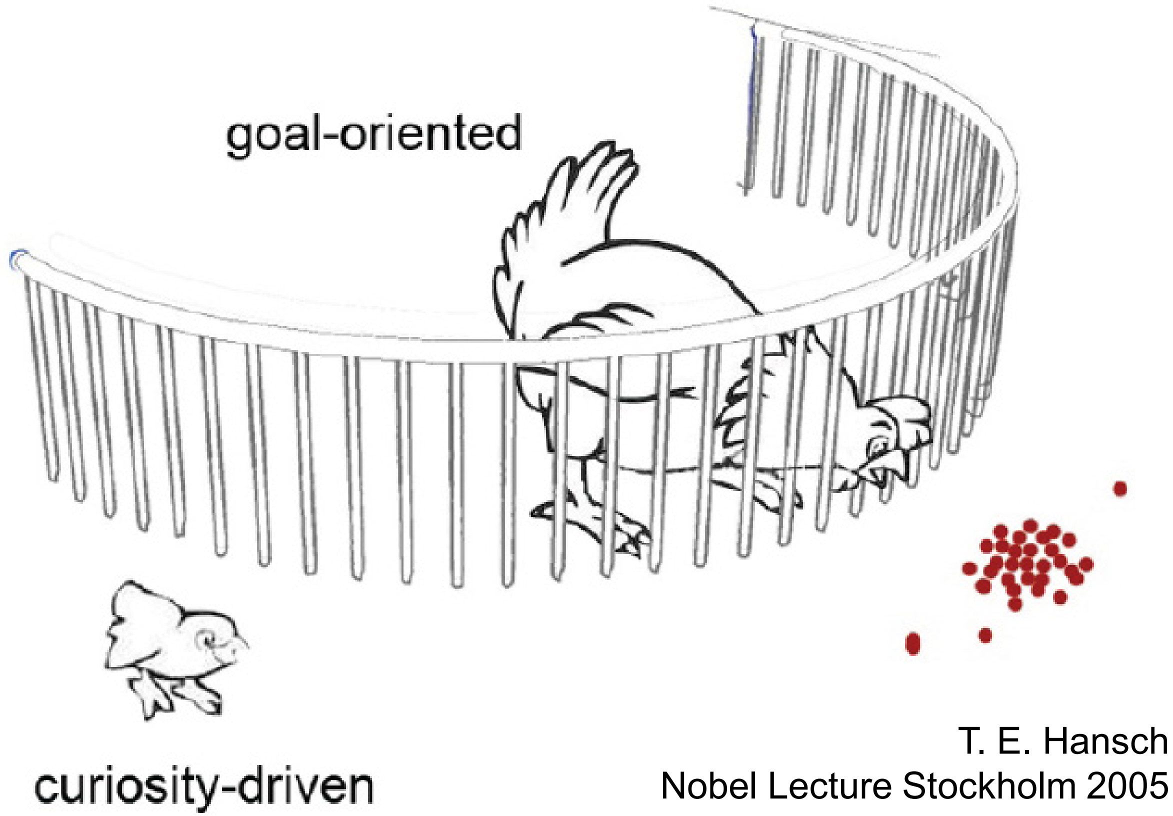


The main points of this talk

1. Fundamental and applied research have a long history of co-existence
2. Examples from the history of nonlinear physics illustrate how this leads to unexpected connections of tremendous benefit
3. Recent developments in photonics show that such connections continue to occur
4. It is vital that even if we are doing applied research, our “systems” allow us the time to follow up fundamental directions of research

Above all …

It is vital that even if we are doing applied research, our "systems" allow us the time to follow up fundamental directions of interest. Sometimes a pre-defined project approach to achieving a goal imposes constraints that could be removed if we looked in another direction.



T. E. Hansch
Nobel Lecture Stockholm 2005