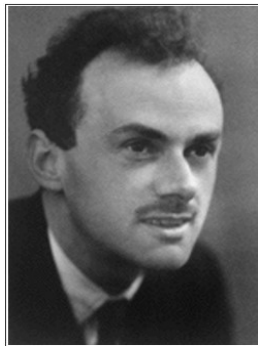
NMR history: analytical technique with several Nobel laureates!

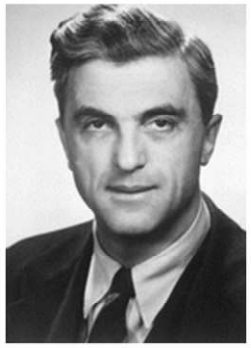


Paul Dirac
1902-1984
Nobel Prize 1933
(Physics)

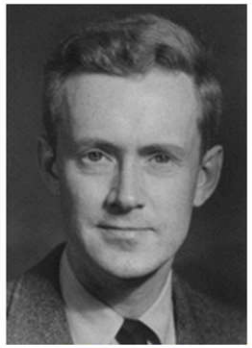
Otto Stern
1888 - 1969
Nobel Prize 1943
(Physics)

Wolfgang Pauli
1900 - 1958
Nobel Prize 1945
(Physics)

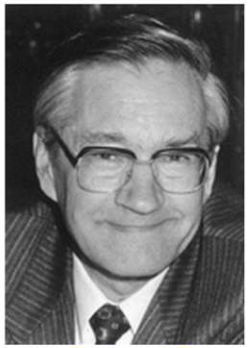
Isidor Isaac Rabi
1898 - 1988
Nobel Prize 1944
(Physics)



Felix Bloch
1905 - 1983
Nobel Prize 1955
(Physics)



Edward Purcell
1912 - 1997
Nobel Prize 195
(Physics)



Richard Ernst
1933-
Nobel Prize 1991
(Chemistry)

Kurt Wüthrich

1938-

Nobel Prize 2002

(Chemistry)

Paul Lauterbur
1929 – 2007
Nobel Prize 2003
(Medicine and
Physiology)

Peter Mansfield
1933 –
Nobel Prize 2003
(Medicine and
Physiology)

Dr. Dirac: 1933 Nobel Prize in physics with Erwin Schrödinger "for the discovery of new productive forms of atomic theory"!

Dirac equation

From Wikipedia, the free encyclopedia

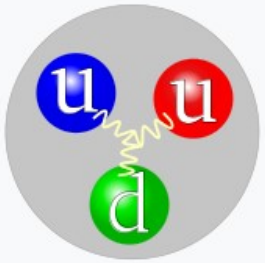
In particle physics, the **Dirac equation** is a relativistic wave equation derived by British physicist Paul Dirac in 1928. In its free form, or including electromagnetic interactions, it describes all spin-$\frac{1}{2}$ massive particles such as electrons and quarks for which parity is a symmetry. It is consistent with both the principles of quantum mechanics and the theory of special relativity,[1] and was the first theory to account fully for special relativity in the context of quantum mechanics. It was validated by accounting for the fine details of the hydrogen spectrum in a completely rigorous way.

The equation also implied the existence of a new form of matter, *antimatter*, previously unsuspected and unobserved and which was experimentally confirmed several years later. It also provided a *theoretical* justification for the introduction of several component wave functions in Pauli's phenomenological theory of spin; the wave functions in the Dirac theory are vectors of four complex numbers (known as bispinors), two of which resemble the Pauli wavefunction in the non-relativistic limit, in contrast to the Schrödinger equation which described wave functions of only one complex value. Moreover, in the limit of zero mass, the Dirac equation reduces to the Weyl equation.

Although Dirac did not at first fully appreciate the importance of his results, the entailed explanation of spin as a consequence of the union of quantum mechanics and relativity—and the eventual discovery of the positron—represents one of the great triumphs of theoretical physics. This accomplishment has been described as fully on a par with the works of Newton, Maxwell, and Einstein before him.[2] In the context of quantum field theory, the Dirac equation is reinterpreted to describe quantum fields corresponding to spin-$\frac{1}{2}$ particles.

NMR basics: properties of quarks and some nuclei!

Quark



A proton is composed of two up quarks, one down quark, and the gluons that mediate the forces "binding" them together. The color assignment of individual quarks is arbitrary, but all three colors must be present.

Composition	Elementary particle
Statistics	Fermionic
Generation	1st, 2nd, 3rd
Interactions	Electromagnetism, gravitation, strong, weak
Symbol	q
Antiparticle	Antiquark ($\bar{q}$)
Theorized	Murray Gell-Mann (1964) George Zweig (1964)
Discovered	SLAC (c. 1968)
Types	6 (up, down, strange, charm, bottom, and top)
Electric charge	$+\frac{2}{3}$ e, $-\frac{1}{3}$ e
Color charge	Yes
Spin	$\frac{1}{2}$
Baryon number	$\frac{1}{3}$

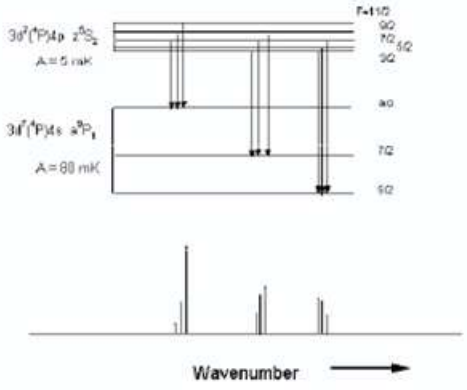
Nuclide	Spin	Natural abundance	Gyromagnetic ratio γ [10^7 rad T^{-1} s^{-1}]	NMR Frequency (at 18.8 Tesla)	Relative receptivity
Proton (^{1}H)	½	99.985	26.7522	799.734 (1)	1.00
Carbon-12 (^{12}C)	0	98.9	-	-	-
Carbon-13 (^{13}C)	½	1.108	6.7283	201.133 (1/3.976)	6.73×10^{-7}
Nitrogen-14 (^{14}N)	1	99.63	1.9338	57.820 (1/13.831)	1.00×10^{-3}
Nitrogen-15 (^{15}N)	½	0.37	-2.7126	81.093 (1/9.861)	3.85×10^{-6}

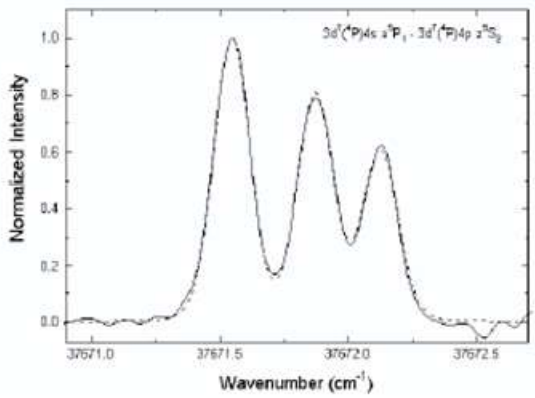
Table 1. Some nuclei properties important for NMR detection.

Dr. Pauli: electron's magnetic moment and Exclusion Principle!

1924 Wolfgang Pauli: Hyperfine structure is result of interaction of the nuclear magnetic moment with the electron's magnetic moment. He postulated the existence of a nuclear spin.

Hyperfine structure permitted fairly accurate determination of the magnetic moment for many atoms.



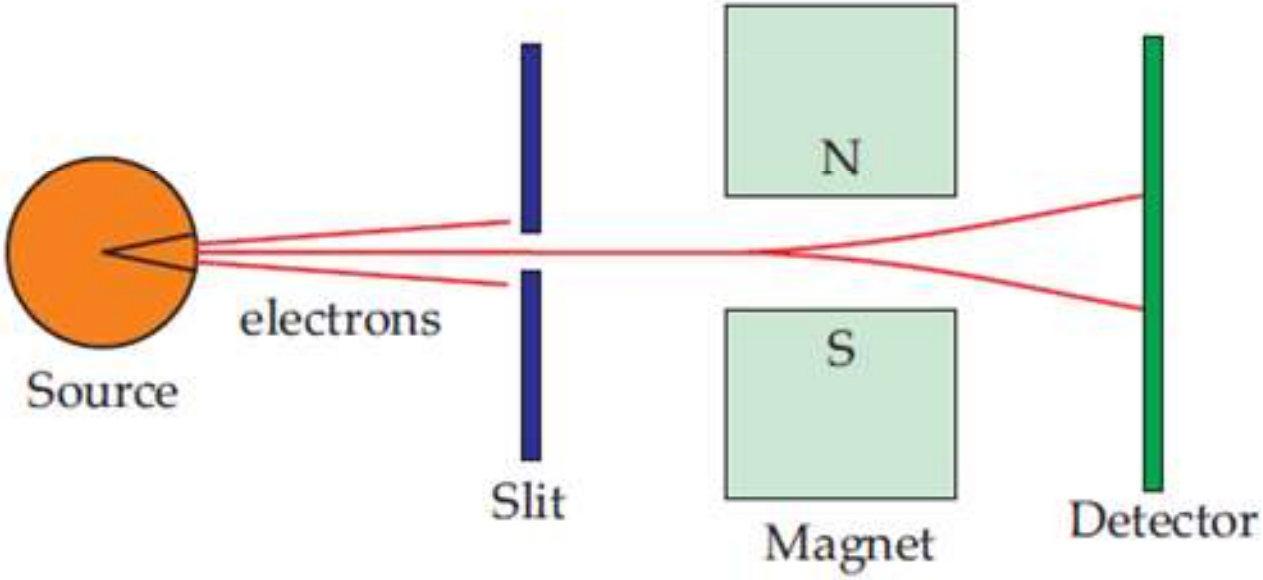


1945 Pauli wins the *Nobel Prize* in Physics (for the Exclusion Principle).

The Pauli exclusion principle is the quantum mechanical principle that states that two identical fermions (particles with half-integer spin) cannot occupy the same quantum state simultaneously.

Drs. Stern & Gerlach: electron's magnetic moment in inhomogeneous magnet!

1921 Otto Stern & Walther Gerlach: Beam of electrons split into two paths when passed through an inhomogeneous magnet due to the *electron's magnetic moment.*



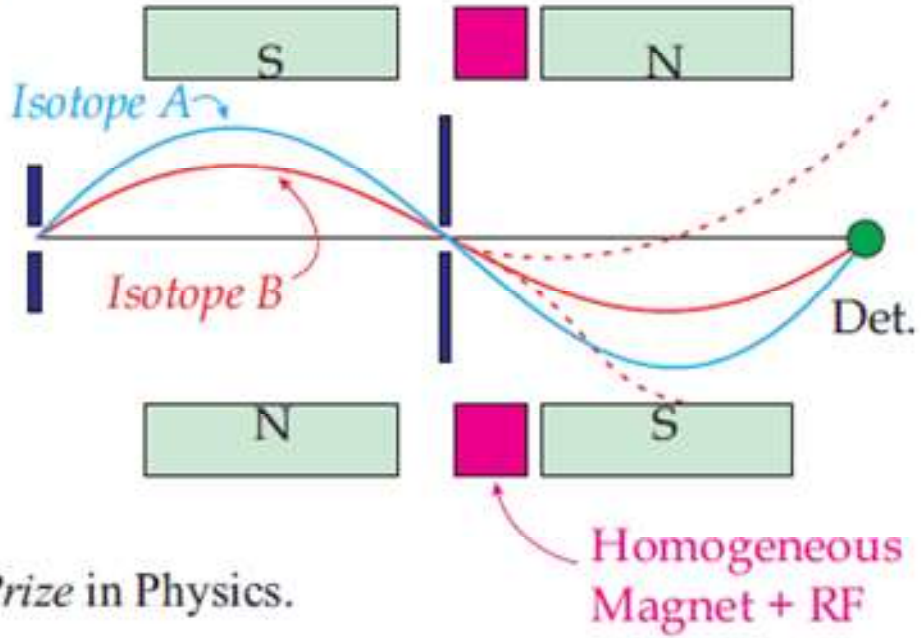
1943 Stern wins the *Nobel Prize* in Physics

Dr. Rabi: electron's magnetic moment in homogeneous magnet!

1938 I.I. Rabi (Columbia) refines the Stern & Gerlach technique to observe the effect from the nuclear magnetic moment. Using a homogeneous magnet (with field strength B) and applying a specific radio frequency he observed that a beam of atoms split into separate paths. This showed that there were quantized energy levels separated by:

$$\Delta E = \gamma \hbar B_0$$

Highly accurate magnetic moments were obtained with this method.



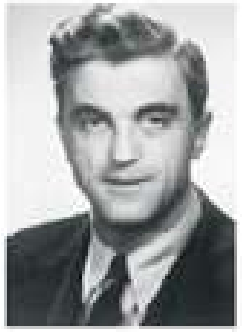
1944 Rabi wins the *Nobel Prize* in Physics.

Limitation: Only applicable to molecular beams under high vacuum.

Drs. Purcell & Bloch: NMR has begun!

1936 C.J. Gorter tries to measure resonance as a temperature change with the absorption of RF. He failed but reported his result and his work encouraged Rabi's work.

1945-6 Edward Purcell with Henry C. Torrey and Robert V. Pound (MIT) observe NMR signal from paraffin wax (December 15, 1945).



1945-6 Felix Bloch, with W.W. Hansen and Martin Packard (Stanford) use a different method they call *nuclear induction* to observe proton signal from H_2O in early January 1946.

Both groups agreed that they were observing the same phenomena and called it NMR. (Bloch's method is closer to techniques used today).

1952 Bloch and Purcell win the *Nobel Prize* in Physics.

Drs. Purcell & Bloch: NMR has begun – the 1st NMR spectra!

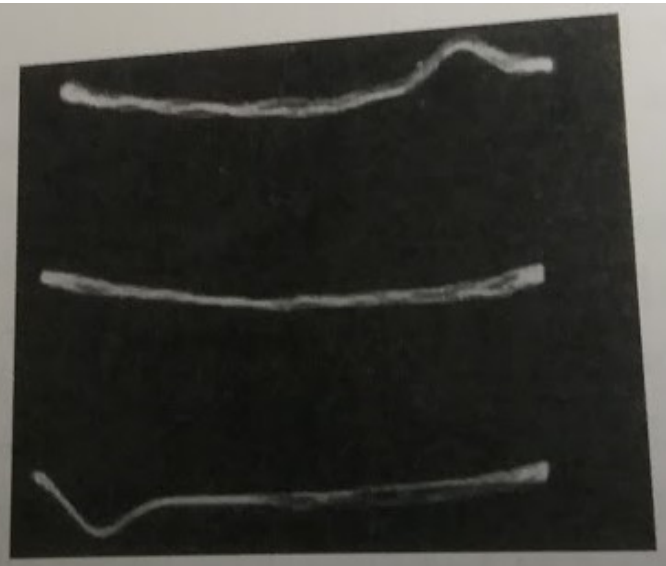


Figure 1.2 The first proton NMR signal from a water sample as seen on the screen of an oscilloscope by Bloch, Hansen, and Packard at Stanford University, California, USA, in January 1946 (Reprinted with permission from [2]. Copyright 1946 by the American Physical Society).

The early NMR achievements: the discovery of chemical shift!

Early Work in NMR

Early applications of NMR were for studying the physics of the nucleus and making measurements of nuclear magnetic moments.

NMR was not even on the chemist's radar until magnet homogeneity improved and...

1950 Proctor and Yu accidentally discover that two different nitrogen atoms of NH_4NO_3 resonate at different frequencies.

1950 Other reports of similar differences in resonance frequencies of different compounds for proton (water vs. mineral oil) and fluorine (CF_3 vs. aromatic F).

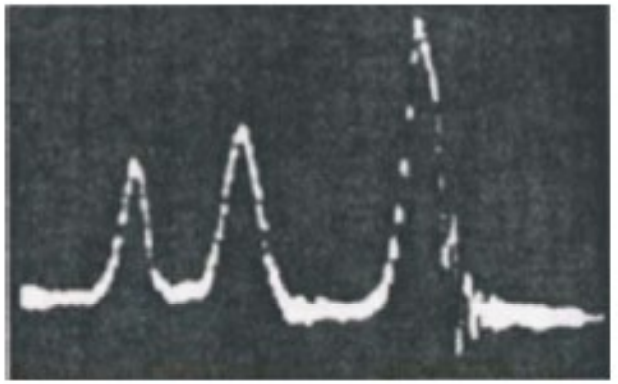
1951 Arnold, Dharmatti and Packard (Stanford) are the first to report different resonance frequency for protons in the same molecule.

The *chemical shift* was discovered.

NMR as a instrumental device in research!

The three peaks of ethanol observed by the Packard group in 1951.

Here is a photo of the first spectrum captured off an oscilloscope display:

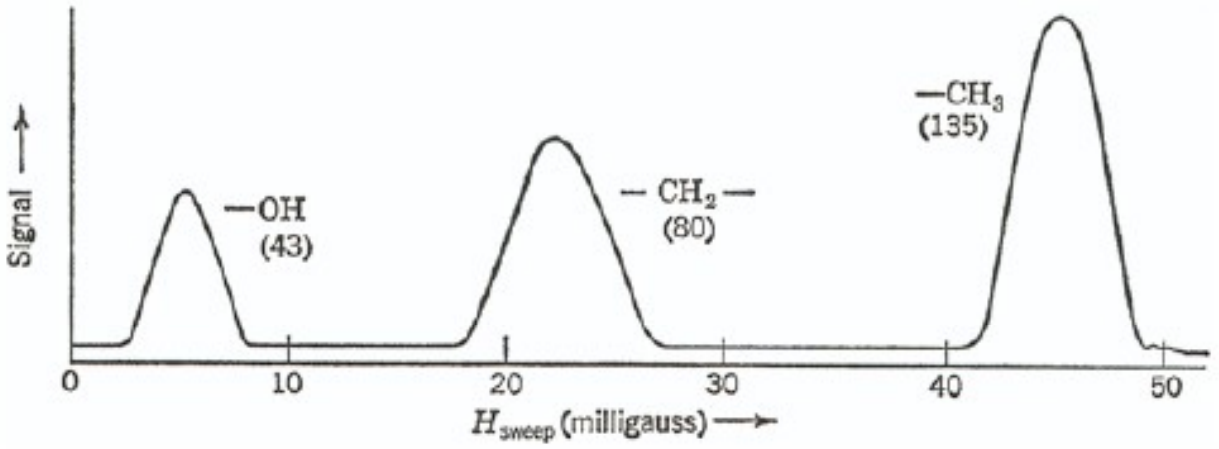


The operating field of the magnet was 7,600 gauss. That gave a proton resonance at 32.4 MHz. It would be a few generations of instruments before plotters were integrated…

An early custom-built 30 MHz instrument:

The early NMR achievements: chemical shift, chemical environment and nuclear quantity!

Here is a reproduction of the data:



This is a swept field spectrum (CW). Note scale has higher field to right. This nomenclature is still used even though we no longer collect data by sweeping the field.

⟸ Lower Field	Higher Field ⟹
Down-Field	*Up-Field*
Higher Frequency	Lower Frequency
De-shielded	*Shielded*

The early NMR time: FT-NMR, RF, computation!

1965-6 Richard Ernst and Weston Anderson (Varian) use pulse excitation and *FT* to produce first spectrum.

Early minicomputers (DEC PDP-8) took 20 min to process a data set.

Advances in computers during the late 1960's and early 1970's allowed instrument development to bring *FT*-NMR to researchers.

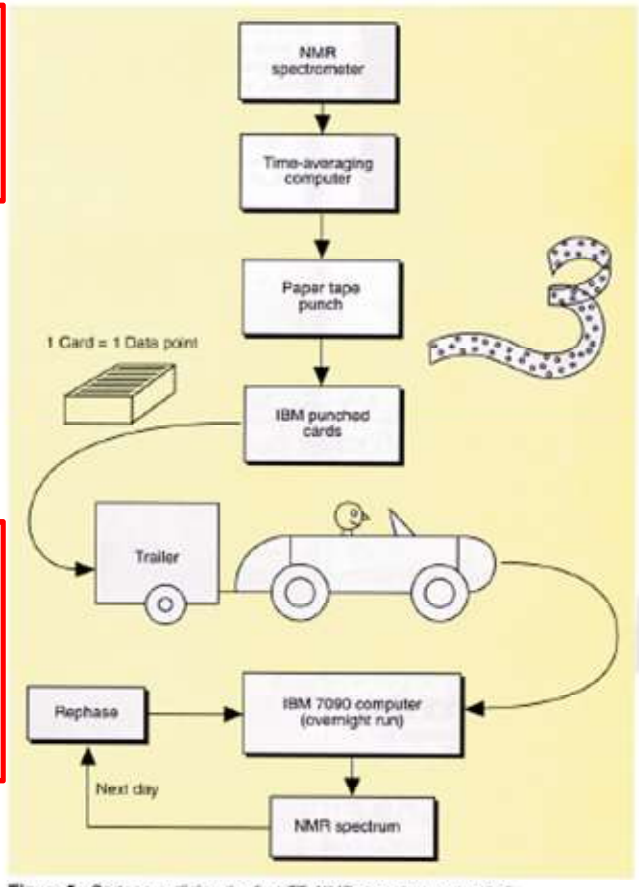


Figure 5. Cartoon outlining the first FT-NMR experiments in 1965.

1965 Cooley and Tukey publish the *Fast Fourier Transform* (*FFT*) algorithm. This reduced the processing time to seconds.

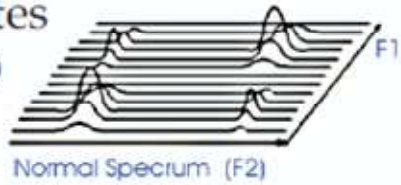
1968 First commercial *FT* accessory for existing CW instruments was introduced.

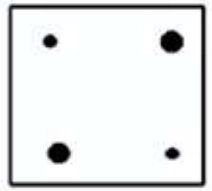
Modern NMR time: 2D and biomolecules!

Multi-Dimensional Techniques:

1971 Jean Jeneer conceives the first two dimensional experiment.

1976 Richard Ernst executes and publishes the first 2D experiment (COSY).





1976- Explosions of new techniques and applications.

1985 Kurt Wűthrich publishes first solution-phase protein structure determined by NMR measurements.

1991 Ernst wins the *Nobel Prize* in Chemistry

2002 Wűthrich wins the *Nobel Prize* in Chemistry

NMR in Medical Diagnosis: MRI!

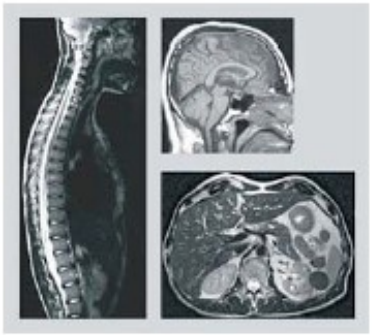
NMR Imaging (MRI)

1973 Paul Lauterbur (SUNY, Stony Brook) uses magnetic field gradients in three dimensions and computer axial tomography (CAT)-scan (back-projection) to produce the first NMR images.

1975 Kumar, Welti and Ernst develop a switched time domain gradient method for the basic reconstruction method (which is used in MR imaging today).

1975 Peter Mansfield et. al., develops a phase encoding technique for image collection and publishes first human body part image (finger cross-section).

1983 First commercial imager is introduced.



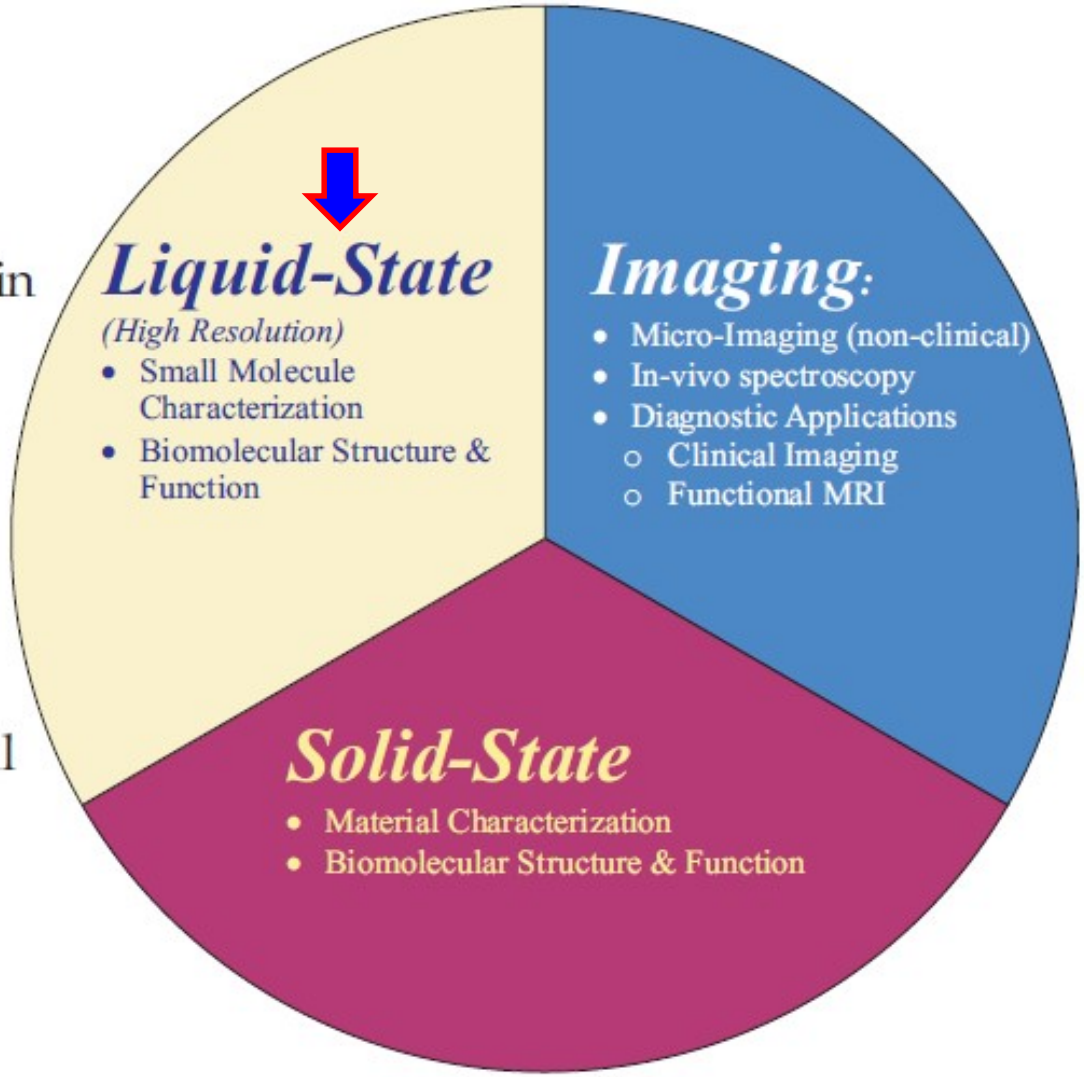
2003 Lauterbur and Mansfield win the *Nobel Prize* in "Medicine or Physiology."

NMR nowadays!

NMR Overview:

The technique has developed rapidly during its brief history. Advances in instrumentation, especially magnet technology has allowed many different applications.

The applications fall into three fairly different groups:



The evolution of NMR magnetic fields!

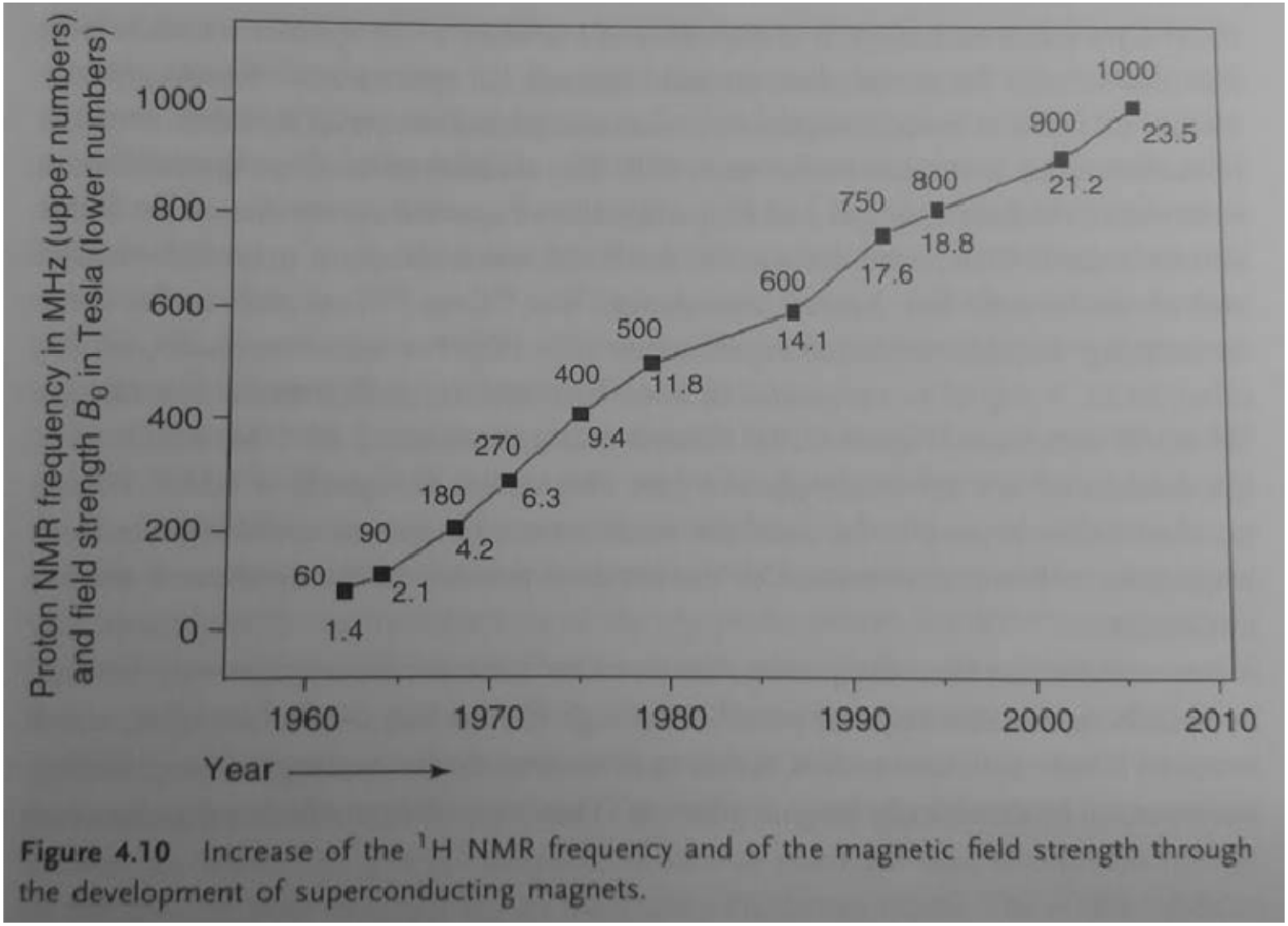


Figure 4.10 Increase of the ^{1}H NMR frequency and of the magnetic field strength through the development of superconducting magnets.