Superconductivity: The magic of the quantum world in front of your eyes.

André-Marie Tremblay
Galileo Galilei

1564-1642
Richard Feynman

1918-1988
The race for absolute zero temperature
An important step towards zero temperature

• Heike Kamerlingh Onnes
  (Leiden) (1853/1926)
The beginnings of team work in research

J.G. Flim, cryogeny
G. Dorsma: thermometry
G. Holst: electronics
Glass blower
And so what?

- What happens to electrical resistance?

8 April 1911
Solvay Congress, 1911
And the winner is

- Heike Kamerlingh Onnes
  (Leiden) (1853/1926)

http://www.nobel.se

1913: Nobel in Physics

To Professor H. Kamerlingh Onnes from Leiden, for his experiments on the properties of matter at low temperature that have led, concomitantly, to the production of liquid Helium.
Power transmission
Transmission cables

BiSrCaCuO
7 Octobre 2010, American Superconductors

3,000 km of superconducting cables for South Korea
Power generation vs need
Power generation vs need
Going around in circles while doing something useful
André-Marie Ampère

1775 - 1836
The first superconducting magnet

Martin Wood, 1962
Supercurrents
The Superconductivity Magazine

Sir Martin Wood
Founder, Oxford Instruments
Transportation
Maglev, Shanghai airport

350 km/h (220 mph) in 2 minutes,
Maximum speed 431 km/h (268 mph).
Record 12 November 2006, 501 km/h (311 mph).
Test, magnetic levitation train, Japan Rail

JR-MLX01 maglev train at Yamanashi test track
In medecine
Magnetic medical imaging
And where you least expect it
Back to levitation
Michael Faraday

1791-1867
Induction
Perfect diamagnetism (Meissner-Ochsenfeld effect)

R. Ochsenfeld (1900-1992)

http://www.magnet.fsu.edu/education/tutorials/pioneers/meissner.html

http://kvphysics.blogspot.com/
Two important properties

1. Zero resistance (if $B=0$)

2. Diamagnetism
How do we explain superconductivity?
Bloch’s theorem: 1930

• All theories of superconductivity can be proven false.
• Feynman: no one is bright enough to find the solution.
Some unsuccessful attempts

Feynman

Heisenberg

Bohr

Einstein

Failed: F

Failed: F

Failed: F

Some unsuccessful attempts
An analogy

- Broken symmetry
- Rigidity
A simple example from statistical physics

\[ E = - \sum_{i,j} J_{i,j} S_i S_j \]

\[ S_i = \pm 1 \]

\[ E = - \sum_{i,j} J_{i,j} (S_i \langle S_j \rangle + \langle S_i \rangle S_j) \]

\[ = - \sum_i h_{\text{eff}} S_i \]
Quantum behavior at the macroscopic scale

Leon Cooper

John Bardeen*

Robert Schrieffer

• John Bardeen:
  • Only one to have received 2 Nobel Prizes in Physics !!!

Nobel Prize: 1972
Invention: TRANSISTOR!

W. Shockley, J. Bardeen, W.H. Brattain

Marie Curie:
1903 Physics with H.A. Becquerel
1911 Chemistry (alone)
What was known

• Resistance vanishes
• Meissner effect
• Transparent to low frequency microwaves
• Isotopic effect

http://users-phys.au.dk/philip/pictures/physicsfigures/physicsfigures.html
Attraction mechanism in the metallic state
#1 Cooper pair,  #2 Phase coherence

\[
E_P = \sum_{p,p'} U_{p-p'} \psi_{p\uparrow,-p\downarrow} \psi^{\ast}_{p'\uparrow,-p'\downarrow}
\]

\[
E_P = \sum_{p,p'} U_{p-p'} \left( \langle \psi_{p\uparrow,-p\downarrow} \rangle \psi^{\ast}_{p'\uparrow,-p'\downarrow} + \psi_{p\uparrow,-p\downarrow} \langle \psi^{\ast}_{p'\uparrow,-p'\downarrow} \rangle \right)
\]

\[
|\text{BCS}(\theta)\rangle = \ldots + e^{iN\theta} |N\rangle + e^{i(N+2)\theta} |N+2\rangle + \ldots
\]
Waves

WAVES

IN PHASE

ANTIPHASE

WAVE INTERFERENCE
Interference
Applications of the Josephson effect

Nobel 1973
SQUID "Superconducting Quantum Interference Device"
The quantum computer

L'ordinateur quantique se matérialise

We're right at the bleeding edge of actually having a quantum processor

Erik Lucero
University of California, Santa Barbara

L'une des percées les plus concrètes dans la perspective de la création d'ordinateurs quantiques performants a été présentée lors de la rencontre annuelle de l'American Physical Society qui se tient à Dallas, aux États-Unis.

Le chercheur Erik Lucero et ses collègues de l'Université de la Californie ont créé des puces de 6 cm par 6 cm contenant des circuits quantiques de 4 Qubits chacun. Le Qubit est l'unité de base du calcul quantique et, contrairement au bit classique, il peut changer de nature. Ainsi, il peut être 1,0 ou même les deux à la fois, ce qui augmente de beaucoup les capacités de calcul d'un ordinateur.

M. Lucero pense qu'il sera possible d'inclure sur une puce jusqu'à 10 Qubit d'ici la fin de
Superconductivity everywhere...
Superfluid $^3$He
Possible Analogy between the Excitation Spectra of Nuclei and Those of the Superconducting Metallic State

A. BOHR, B. R. MOTTELSON, AND D. PINES

Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark, and Nordisk Institut for Teoretisk Atomfysik, Copenhagen, Denmark

(Received January 7, 1958)

The evidence for an energy gap in the intrinsic excitation spectrum of nuclei is reviewed. A possible analogy between this effect and the energy gap observed in the electronic excitation of a superconducting metal is suggested.
Neutron stars

The Crab Nebula (4 July 1054) in Blue and White
Credit & Copyright: Jay Gallagher (U. Wisc.), WIYN, AURA, NOAO, NSF
Evidence for superfluidity of ultracold fermions in an optical lattice

Standard model of elementary particles (unifying electro-weak interactions)

\[ SU(2) \otimes U(1) \rightarrow U(1) \]

\[
\begin{pmatrix}
\phi_1 \\
\phi_2
\end{pmatrix} \rightarrow
\begin{pmatrix}
0 \\
v
\end{pmatrix}
\]
Return to history
Fortunately not everything was known

- Zero resistance (except if magnet nearby)
- Meissner effect (not perfect)
- Sometimes not transparent to microwaves
- Isotope effect (sometimes wrong way)
The best understood theory

• In 1969, R.D. Parks two volumes « Superconductivity »

• From one of the authors : « It is the last nail in the coffin of superconductivity »
The search for new materials

The goal: liquid nitrogen temperature!
It was generally believed that

- Cu, Au, Fe not a good idea
- Cubic is good
- Stay away from
  - O
  - Magnets
  - Insulators
January 1986

1986 : Bednorz and Muëller, IBM Zurich
La-Ba-Cu-O $T_c \approx 30$-40K

Group of P. Chu (Houston)
Under high pressure : 50K!!!
It goes quickly…

• Boston, "Materials Research Society"
  December 1986
  – Koitchi Kitazawa and Shoji Tanaka
  Tokyo convince everyone.

• 16 Feb. 1987, Houston:
  – Press conference by Paul Chu
  to announce discovery of $Y$-$Ba$-$Cu$-$O$
  – $T_c = 93$ $K$
- Title of the New York Times the following day: "The Woodstock of Physics"

- 3000 people until three in the morning

"They began lining up outside the New York Hilton Sutton Ballroom at 5:30PM for an evening session that would last until 3:00 AM"
The “Woodstock of physics.” On March 18, 1987, thousands of physicists crammed a ballroom at the New York Hilton to celebrate the coming of the age of superconductivity.

AMERICAN INSTITUTE OF PHYSICS

(right) Alex Müller, Paul Chu, and Shoji Tanaka, answering questions at the “Woodstock” meeting. Tanaka and Koichi Kitazawa were the first to confirm Bednorz and Müller’s discovery, launching a worldwide race to find still better superconductors.

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What is special about these superconductors?
Atomic structure
What is special

- Cu, Au, Fe not good
- Cubic
- Stay away from
  - O
  - Magnets
  - Insulators

- Cu
- Layered
- Stay close to
  - O
  - Magnets
  - Insulators
Layered organic conductors (κ–BEDT-X family)
Pnictides (2008)

http://www.stanford.edu/~tpd/research_hightc.html
Strong correlations
How to make a metal

Courtesy, S. Julian
Experimental phase diagram BEDT-X

Phase diagram \((X=\text{Cu[N(CN)₂]Cl})\)
S. Lefebvre et al. PRL 85, 5420 (2000), P. Limelette, et
A quantum traffic jam (A.P.): Mott insulator
Spectral weight transfer

Meinders et al. PRB 48, 3916 (1993)
Cuprates as doped Mott insulators
Experiment: X-Ray absorption

Chen et al. PRL 66, 104 (1991)

Peets et al. PRL 103, (2009), Phillips, Jarrell arXiv

Number of low energy states above $\omega = 0$ scales as $2x$ +
Not as $1+x$ as in Fermi liquid

Meinders et al. PRB 48, 3916 (1993)
Phase diagram

Insulator even if $n=1$

Armitage, Fournier, Greene, RMP (2009)
Theoretical method
Hubbard model

1931-1980

\[ H = - \sum_{<ij>_{\sigma}} t_{i,j} \left( c_{i\sigma}^{\dagger} c_{j\sigma} + c_{j\sigma}^{\dagger} c_{i\sigma} \right) + U \sum_i n_{i\uparrow} n_{i\downarrow} \]

Effective model, Heisenberg: \( J = 4t^2 / U \)
Mott transition and Dynamical Mean-Field Theory. The beginnings in $d = \infty$ 

- Compute scattering rate (self-energy) of impurity problem.
- Use that self-energy ($\omega$ dependent) for lattice.
- Project lattice on single-site and adjust bath so that single-site DOS obtained both ways be equal.

W. Metzner and D. Vollhardt, PRL (1989)  
A. Georges and G. Kotliar, PRB (1992)  
M. Jarrell PRB (1992) 

DMFT, ($d = 3$)
2d Hubbard: Quantum cluster method

Hettler …Jarrell…Krishnamurty PRB 58 (1998)
Kotliar et al. PRL 87 (2001)
Maier, Jarrell et al., Rev. Mod. Phys. 77, 1027 (2005)
Solving cluster in a bath problem

- Continuous-time Quantum Monte Carlo calculations to sum all diagrams generated from expansion in powers of hybridization.
  
  
Strongly Correlated Superconductivity

Phase diagram
Exact diagonalization as impurity solver ($T=0$).
Dome vs Mott (CDMFT)

Kancharla, Kyung, Civelli, Sénéchal, Kotliar AMST
CDMFT global phase diagram

Kancharla, Kyung, Civelli, Sénéchal, Kotliar AMST

Armitage, Fournier, Greene, RMP (2009)
The glue
Im $\Sigma_{an}$ and electron-phonon in Pb

Maier, Poilblanc, Scalapino, PRL (2008)
The glue


Wakimoto … Birgeneau
PRL (2004)
The glue and neutrons

FIG. 3 (color online). Q-integrated dynamic structure factor $S(\omega)$ which is derived from the wide-$H$ integrated profiles for LBCO 1/8 (squares), LSCO $x = 0.25$ (diamonds; filled for $E_i = 140$ meV, open for $E_i = 80$ meV), and $x = 0.30$ (filled circles) plotted over $S(\omega)$ for LBCO 1/8 (open circles) from [2]. The solid lines following data of LSCO $x = 0.25$ and 0.30 are guides to the eyes.

\[ H(t) = - \sum_{ij \sigma} t_{ij} c_{i\sigma} \bar{c}_{j\sigma} e^{-i \int_{i}^{j} d r_{ij} \cdot A(r,t)} + U \sum_{i} n_{i\uparrow} n_{i\downarrow} \]

\[ \Delta_p = \frac{1}{V} \sum_{p'} U (p - p’) \langle e_{-p’\downarrow} c_{p’\uparrow} \rangle \]

\[ |BCS(\theta)\rangle = \cdots + e^{iN\theta} |N\rangle + e^{i(N+2)\theta} |N + 2\rangle + \cdots \]
A Hundred Years of Superconductivity

Cent ans de supraconductivité
\[ H(t) = - \sum_{i,j,\sigma} t_{ij} c_{i\sigma}^\dagger c_{j\sigma} e^{-i \int_{t_1}^{t} ds_j A(r,s)} + U \sum_i n_{i\uparrow} n_{i\downarrow} \]

\[ \Delta_p = \frac{1}{V} \sum_{p'} U(p - p') \langle c_{-p'\downarrow} c_{p'\uparrow} \rangle \]

\[ |BCS(\theta)\rangle = \cdots + e^{iN\theta} |N\rangle + e^{i(N+2)\theta} |N+2\rangle + \cdots \]
Conclusion
The dream

http://www.physique.usherbrooke.ca/taillefer/Vulgarisation.html
Science and technology, hand in hand
Steam engine and thermodynamics

Watts 1765

Carnot 1824
Induction and electric motor

Induction, Faraday (1831)

Electric motor, Tesla (1880)
Induction
Electron and television

Thomson, 1897

Television, 1940
Quantum mechanics and the transistor

Schrödinger  Heisenberg  Transistor 1947

Quantum mechanics 1926
Quantum mechanics and the transistor
Laser and CD-ROM

Stimulated emission 1925
Laser 1960
Eye surgery
CD-ROM (1980-90)
Edward Bellamy (USA) 1887

- Novel: « Looking backward » 2000-1887
- If we could have devised an arrangement for providing everybody with music in their homes, perfect in quality, unlimited in quantity, suited to every mood, and beginning and ceasing at will, we should have considered the limit of human felicity already attained, and ceased to strive for further improvements.

Merci

http://sweetladiesbakery.com/gallery/female-cakes/