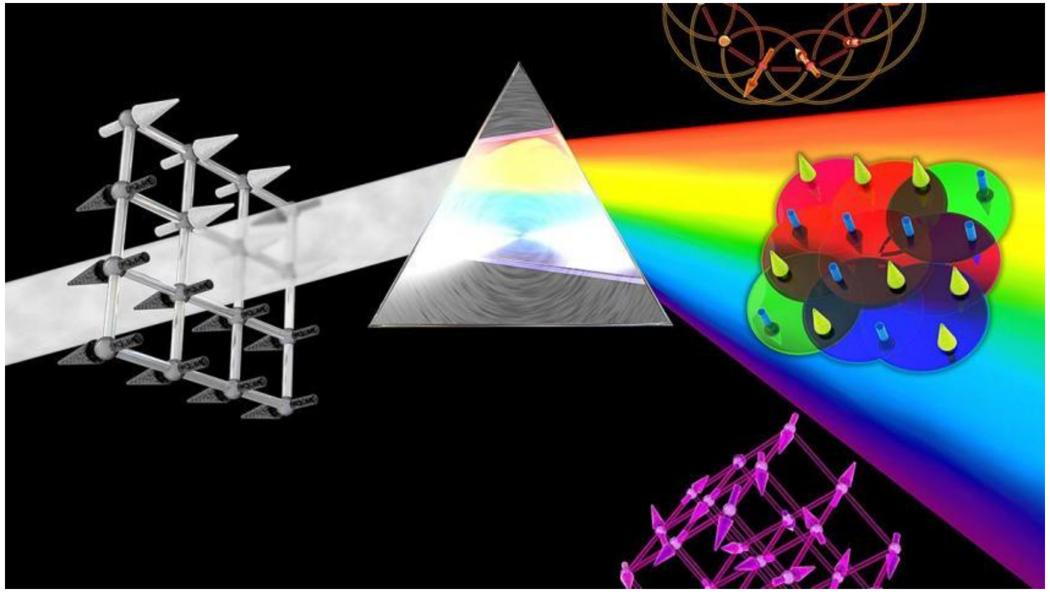
Física da Matéria Condensada

Natanael de Carvalho Costa

IF - UFRJ



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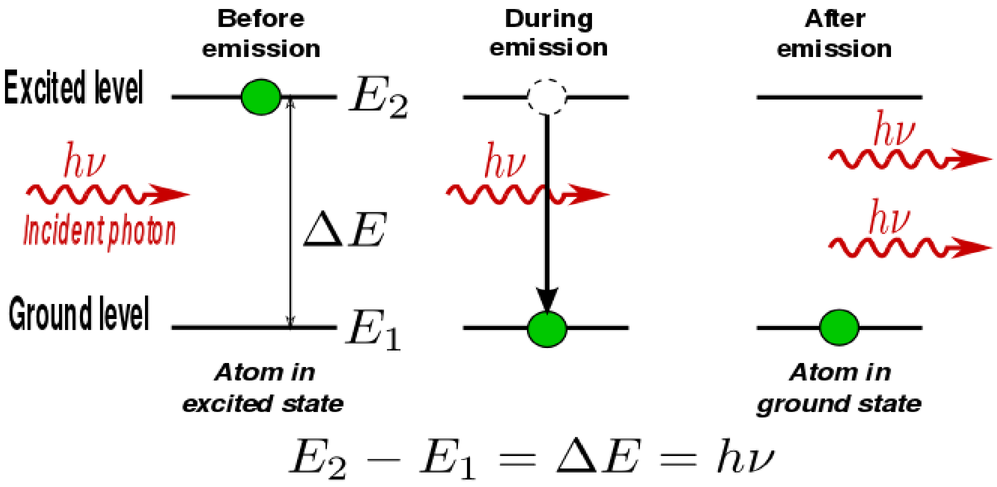
Agosto/2023

Sobre a importância de se estudar Ciência Básica (materiais)

Sobre a importância de se estudar Ciência Básica (materiais)

Laser

light amplification by stimulated emission of radiation



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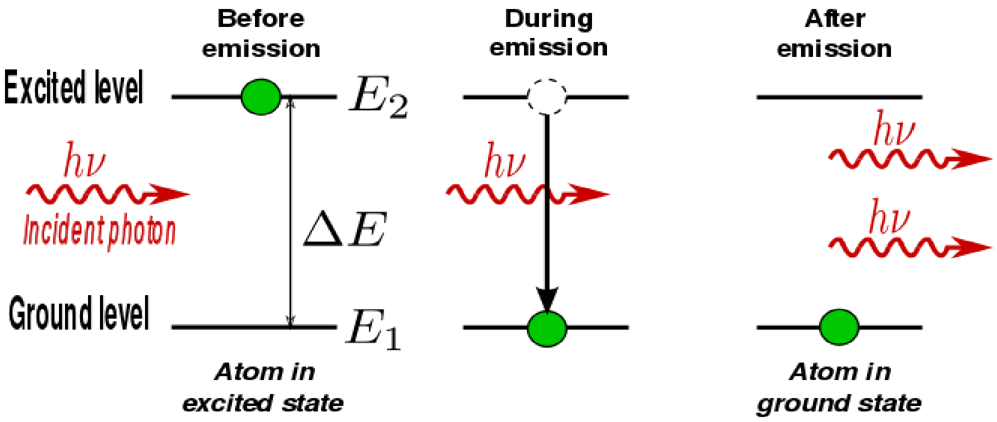


$$E_2 - E_1 = \Delta E = h\nu$$

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.

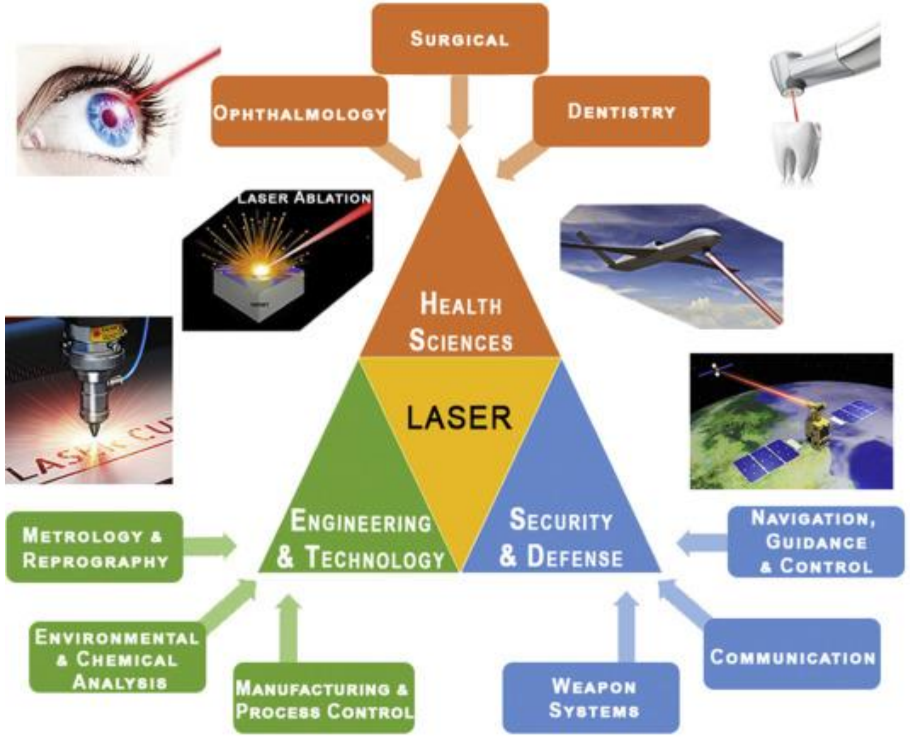
Nicolay Gennadiyevich Basov

Prize share: 1/4

Photo from the Nobel Foundation archive.

Aleksandr Mikhailovich Prokhorov

Prize share: 1/4



Surgical

Ophthalmology

Dentistry

Laser Ablation

Health Sciences

LASER

Engineering & Technology

Security & Defense

Metrology & Reprography

Navigation, Guidance & Control

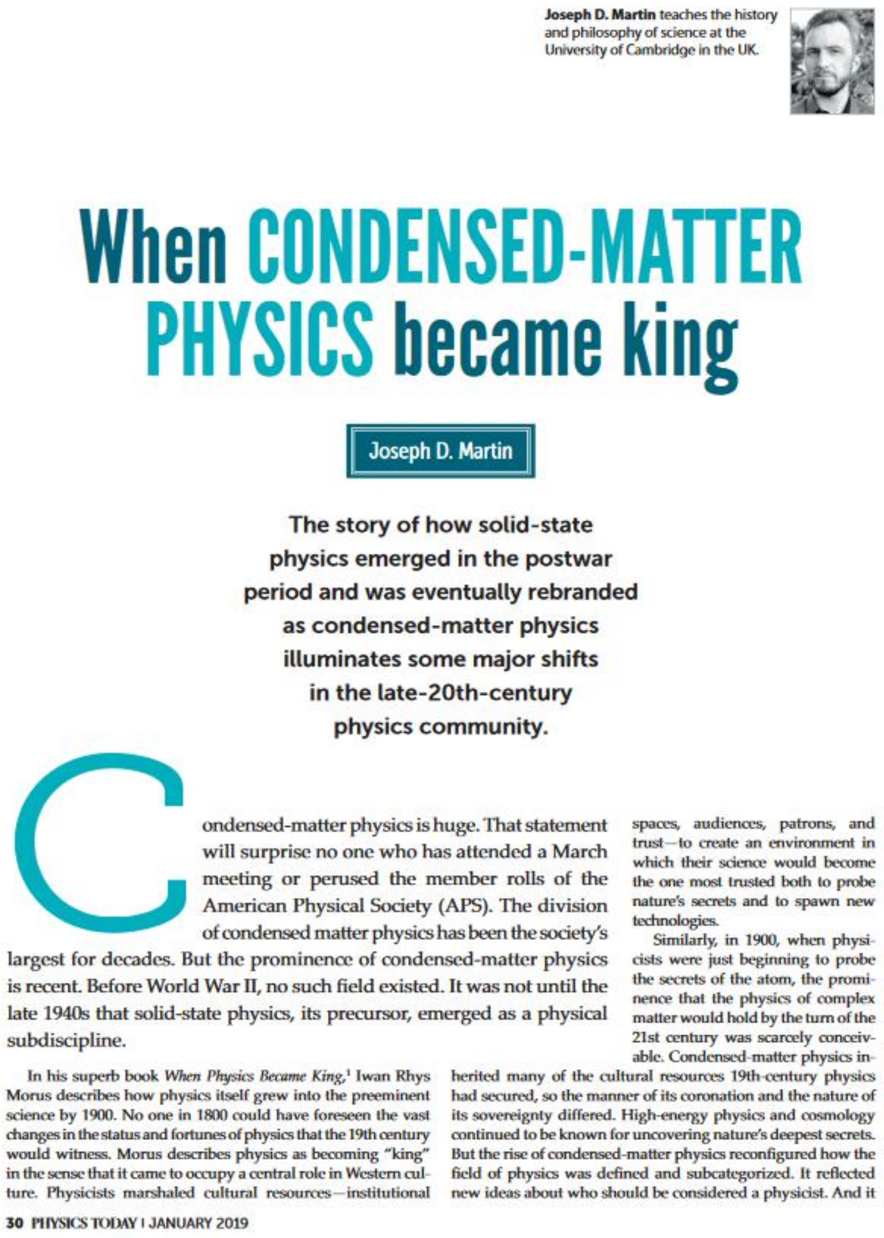
Environmental & Chemical Analysis

Manufacturing & Process Control

Weapon Systems

Communication

Sobre a importância de se estudar Ciência Básica (materiais)



Joseph D. Martin teaches the history and philosophy of science at the University of Cambridge in the UK.

When CONDENSED-MATTER PHYSICS became king

Joseph D. Martin

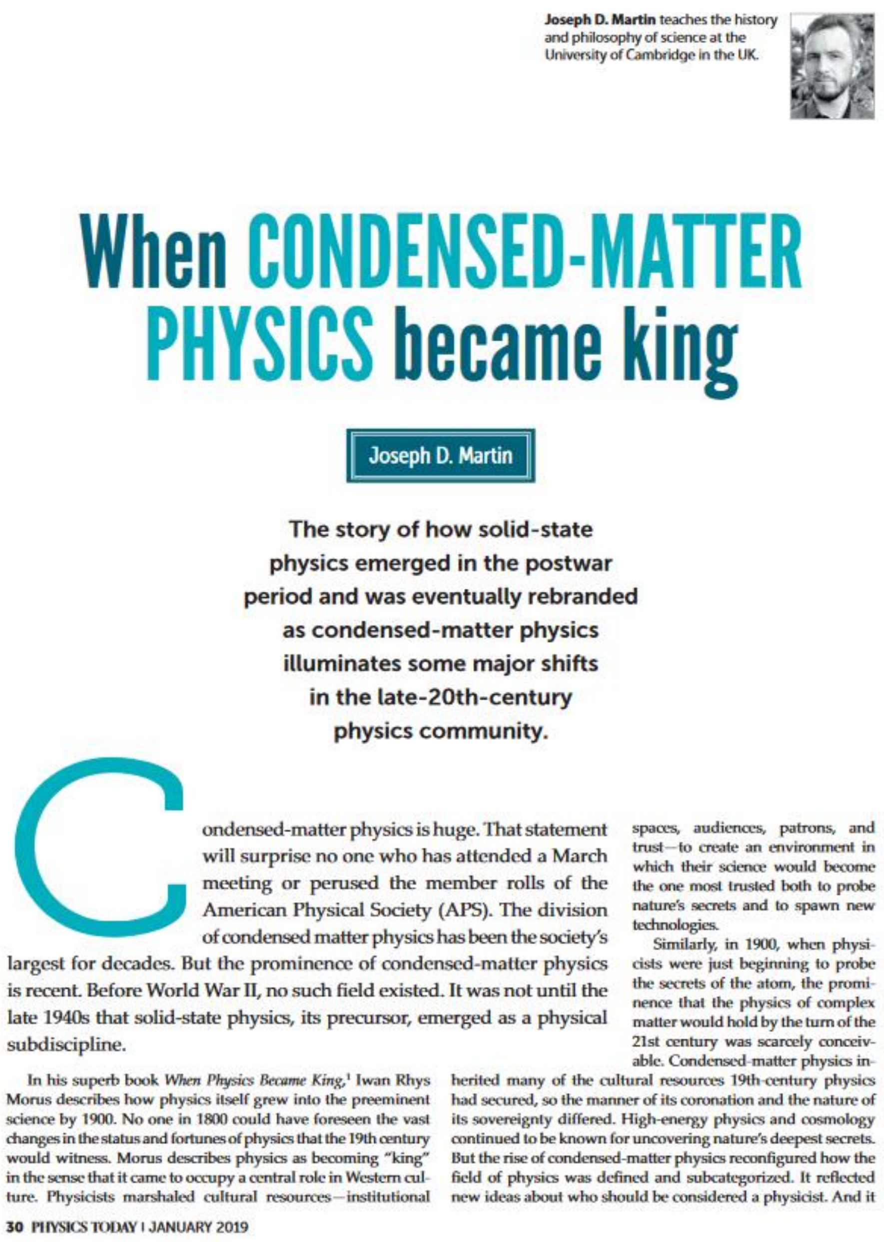
The story of how solid-state physics emerged in the postwar period and was eventually rebranded as condensed-matter physics illuminates some major shifts in the late-20th-century physics community.

Condensed-matter physics is huge. That statement will surprise no one who has attended a March meeting or perused the member rolls of the American Physical Society (APS). The division of condensed matter physics has been the society's largest for decades. But the prominence of condensed-matter physics is recent. Before World War II, no such field existed. It was not until the late 1940s that solid-state physics, its precursor, emerged as a physical subdiscipline.

In his superb book *When Physics Became King*,[1] Iwan Rhys Morus describes how physics itself grew into the preeminent science by 1900. No one in 1800 could have foreseen the vast changes in the status and fortunes of physics that the 19th century would witness. Morus describes physics as becoming "king" in the sense that it came to occupy a central role in Western culture. Physicists marshaled cultural resources—institutional spaces, audiences, patrons, and trust—to create an environment in which their science would become the one most trusted both to probe nature's secrets and to spawn new technologies.

Similarly, in 1900, when physicists were just beginning to probe the secrets of the atom, the prominence that the physics of complex matter would hold by the turn of the 21st century was scarcely conceivable. Condensed-matter physics inherited many of the cultural resources 19th-century physics had secured, so the manner of its coronation and the nature of its sovereignty differed. High-energy physics and cosmology continued to be known for uncovering nature's deepest secrets. But the rise of condensed-matter physics reconfigured how the field of physics was defined and subcategorized. It reflected new ideas about who should be considered a physicist. And it

Sobre a importância de se estudar Ciência Básica (materiais)



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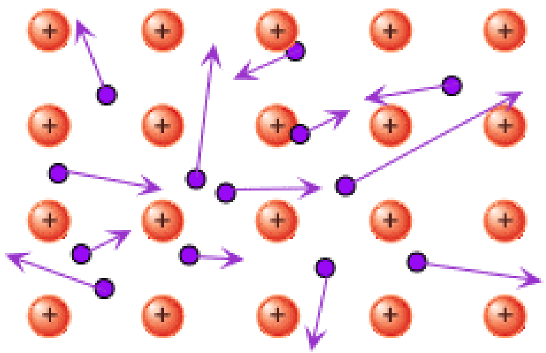
30 PHYSICS TODAY | JANUARY 2019

Compreensão sobre a natureza microscópica da matéria



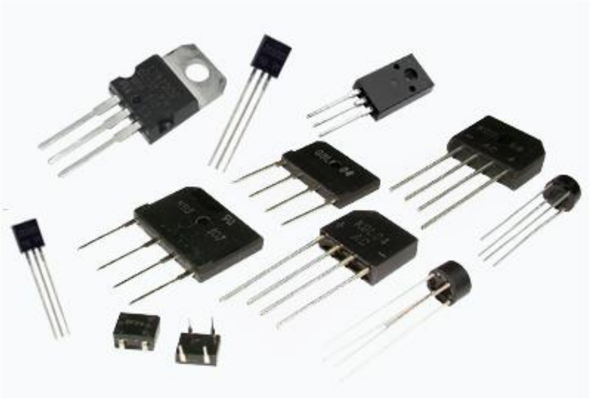
Condutividade eletrônica

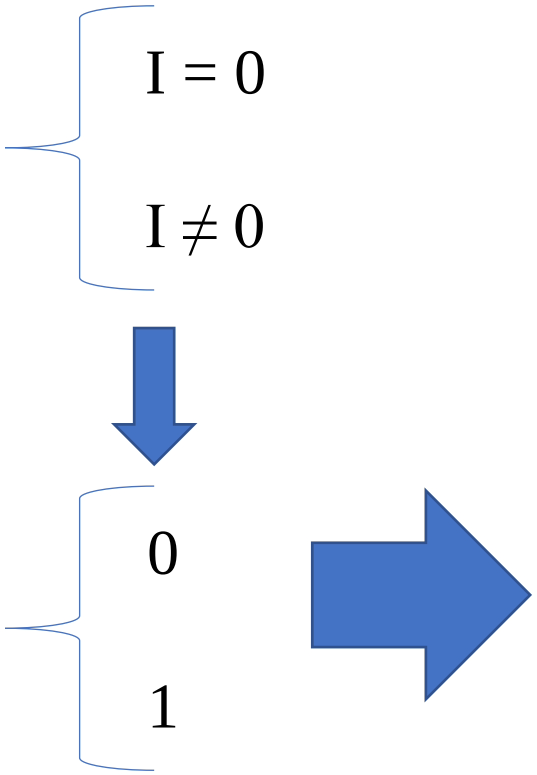
Com o advento da Mecânica Quântica foi possível compreender:

- Metais ✓
- Isolantes (de banda) ✓
- Semicondutores ✓

Sobre a importância de se estudar Ciência Básica (materiais)

- Semicondutores



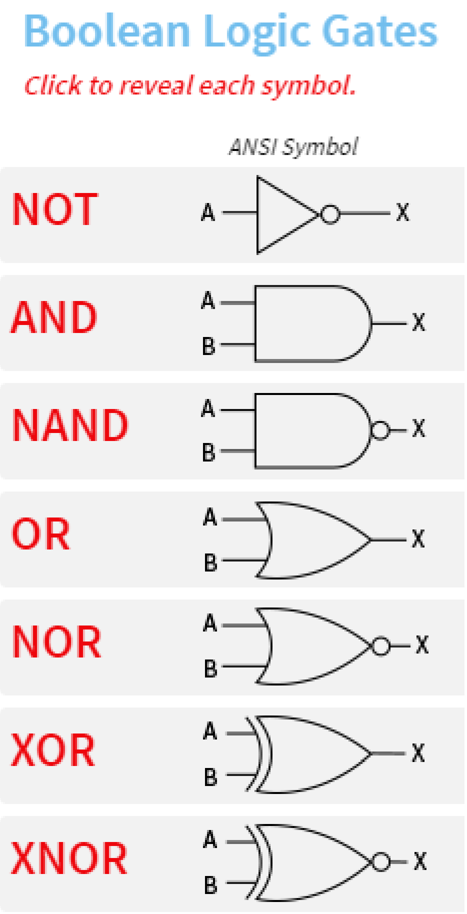


$I = 0$

$I \neq 0$

0

1



Boolean Logic Gates

Click to reveal each symbol.

ANSI Symbol

NOT

AND

NAND

OR

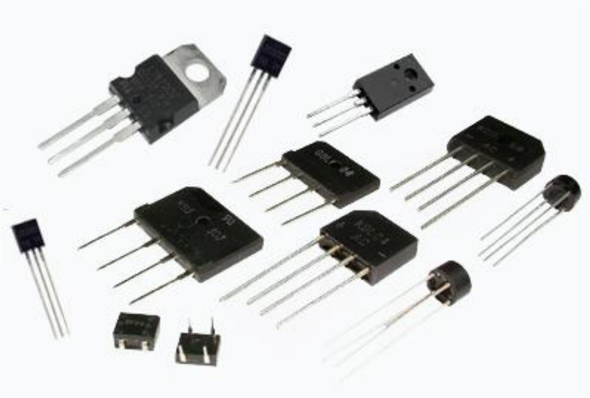
NOR

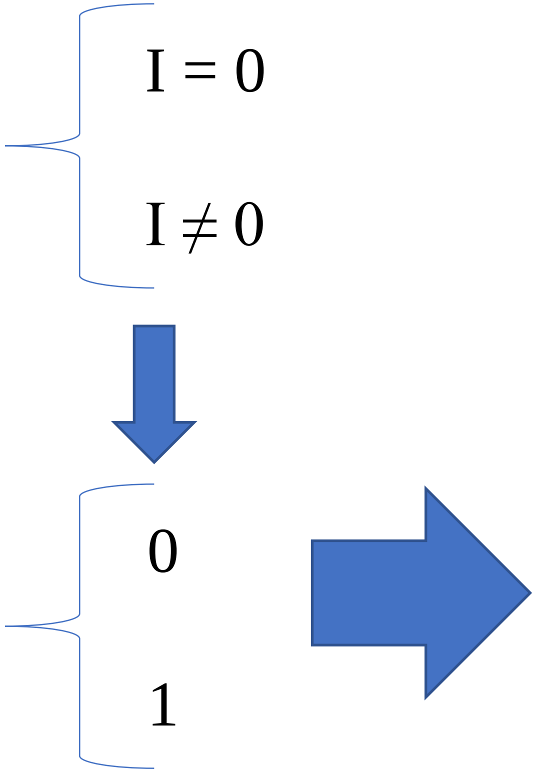
XOR

XNOR

Sobre a importância de se estudar Ciência Básica (materiais)

- Semicondutores





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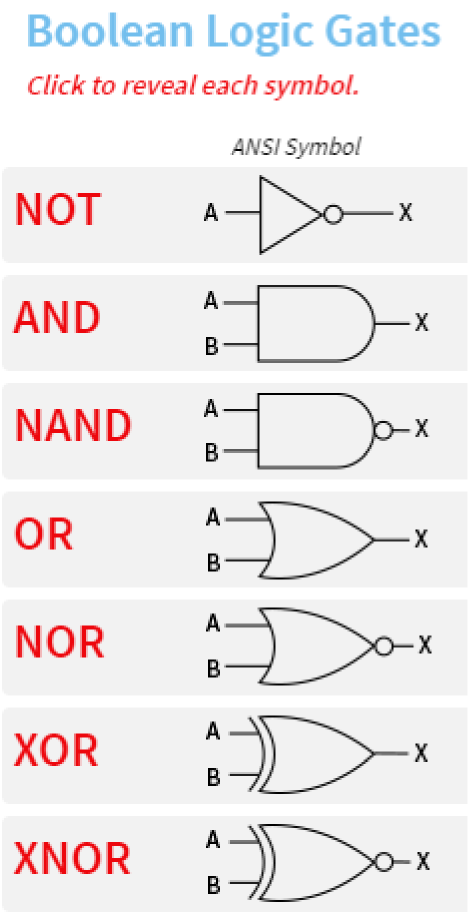

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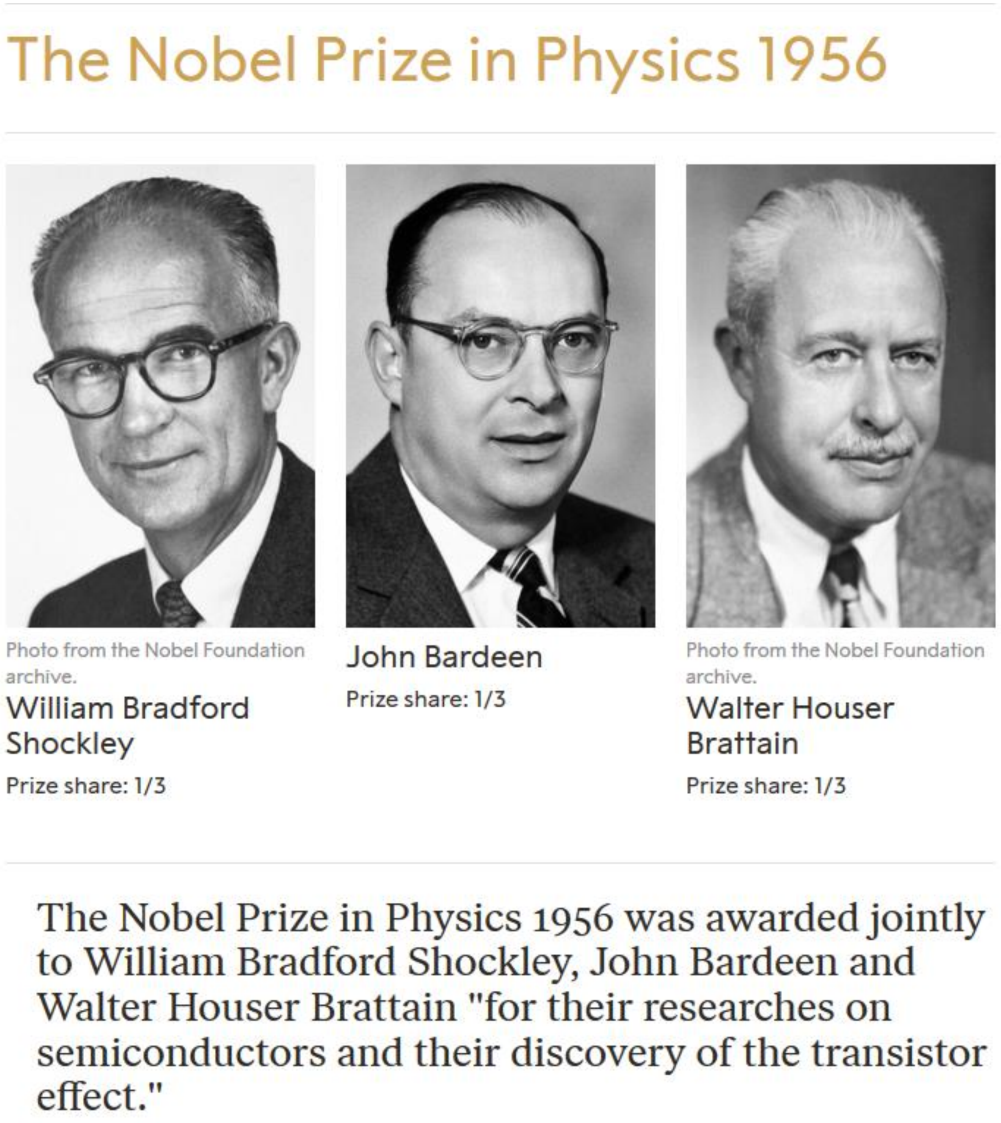


The Nobel Prize in Physics 1956

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

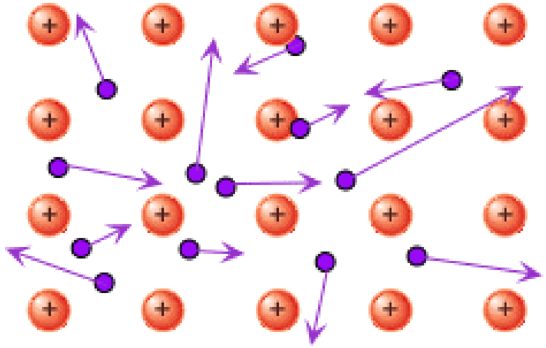
Prize share: 1/3

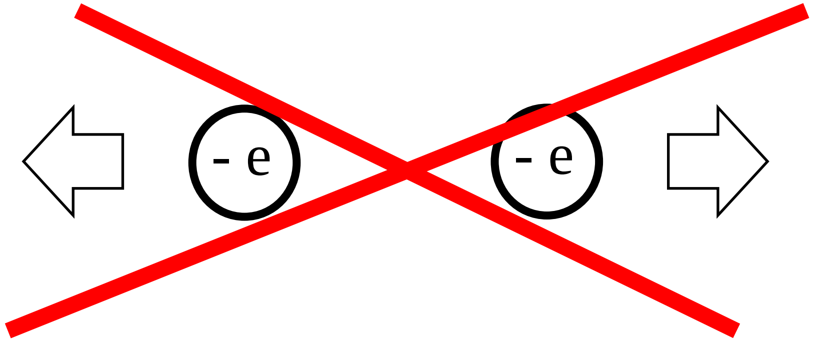
The Nobel Prize in Physics 1956 was awarded jointly to William Bradford Shockley, John Bardeen and Walter Houser Brattain "for their researches on semiconductors and their discovery of the transistor effect."

Sobre a importância de se estudar Ciência Básica (materiais)

- Elétrons independentes

Despreza-se o custo energético da repulsão eletrônica





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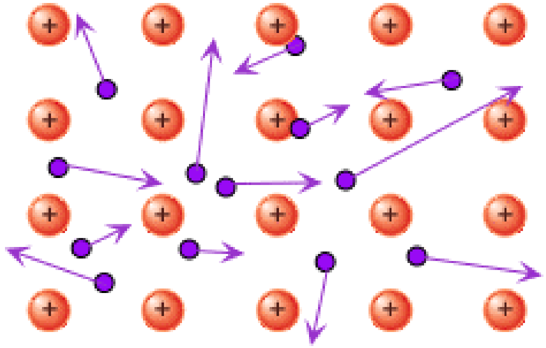
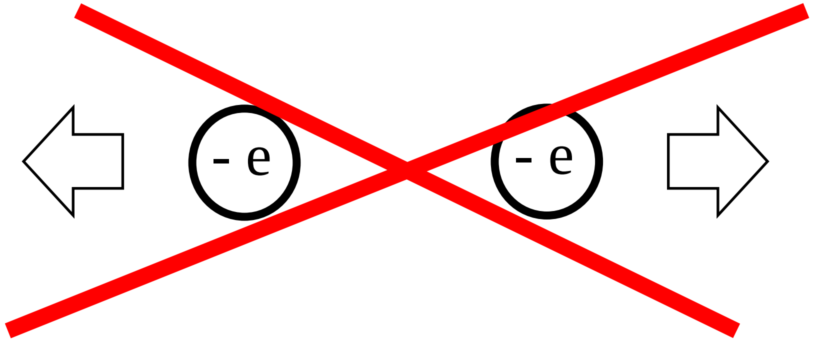




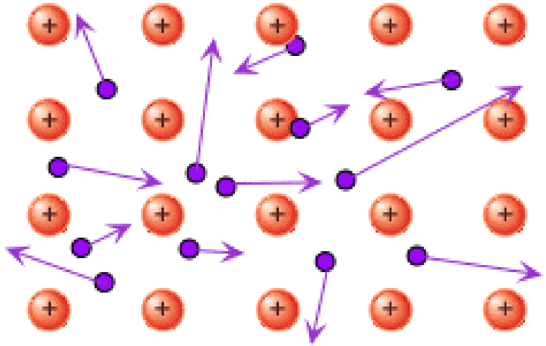
- Metais ✓
- Isolantes (de banda) ✓
- Semicondutores ✓
- ~~Magnetismo~~ ✗
- ~~Supercondutividade~~ ✗
- ~~Ordenamento de carga~~ ✗

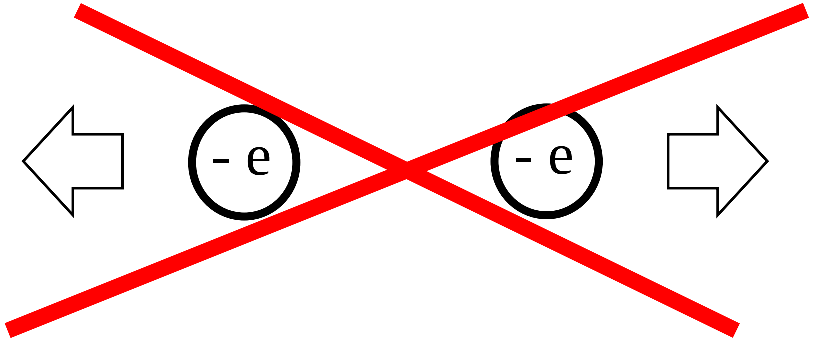
→ Sistemas fortemente correlacionados!!

Sobre a importância de se estudar Ciência Básica (materiais)

- Elétrons independentes

Despreza-se o custo energético da repulsão eletrônica





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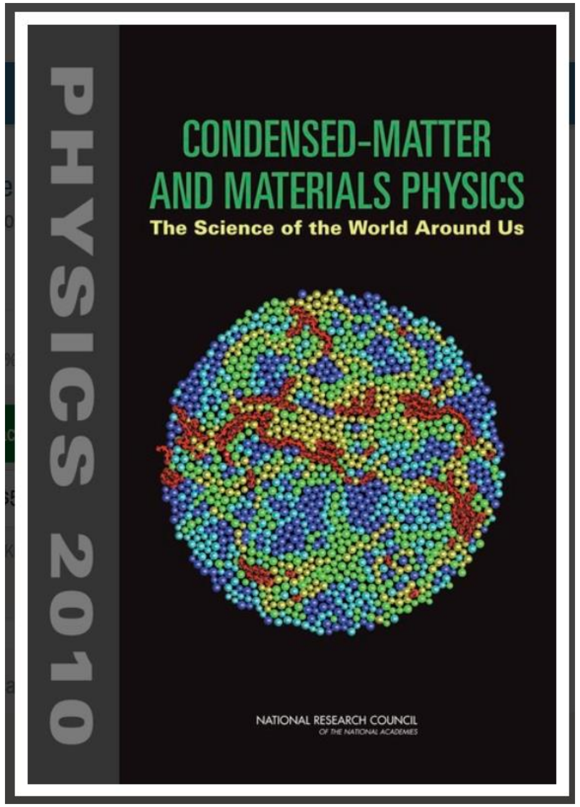
Sistemas fortemente correlacionados!!

O que são sistemas fortemente correlacionados?

Sistemas que exibem propriedades cuja natureza é intrisicamente relacionada à interação entre elétrons.

O que são sistemas fortemente correlacionados?

NATIONAL ACADEMY
OF SCIENCES



PHYSICS 2010

CONDENSED-MATTER AND MATERIALS PHYSICS

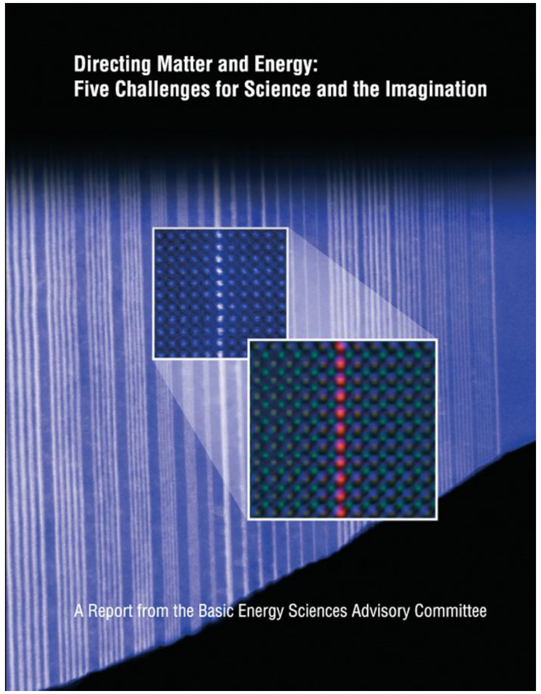
The Science of the World Around Us

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

Um dos desafios da próxima década:

“How do complex phenomena emerge from simple ingredients?”

U.S. DEPARTMENT OF ENERGY | Office of Science



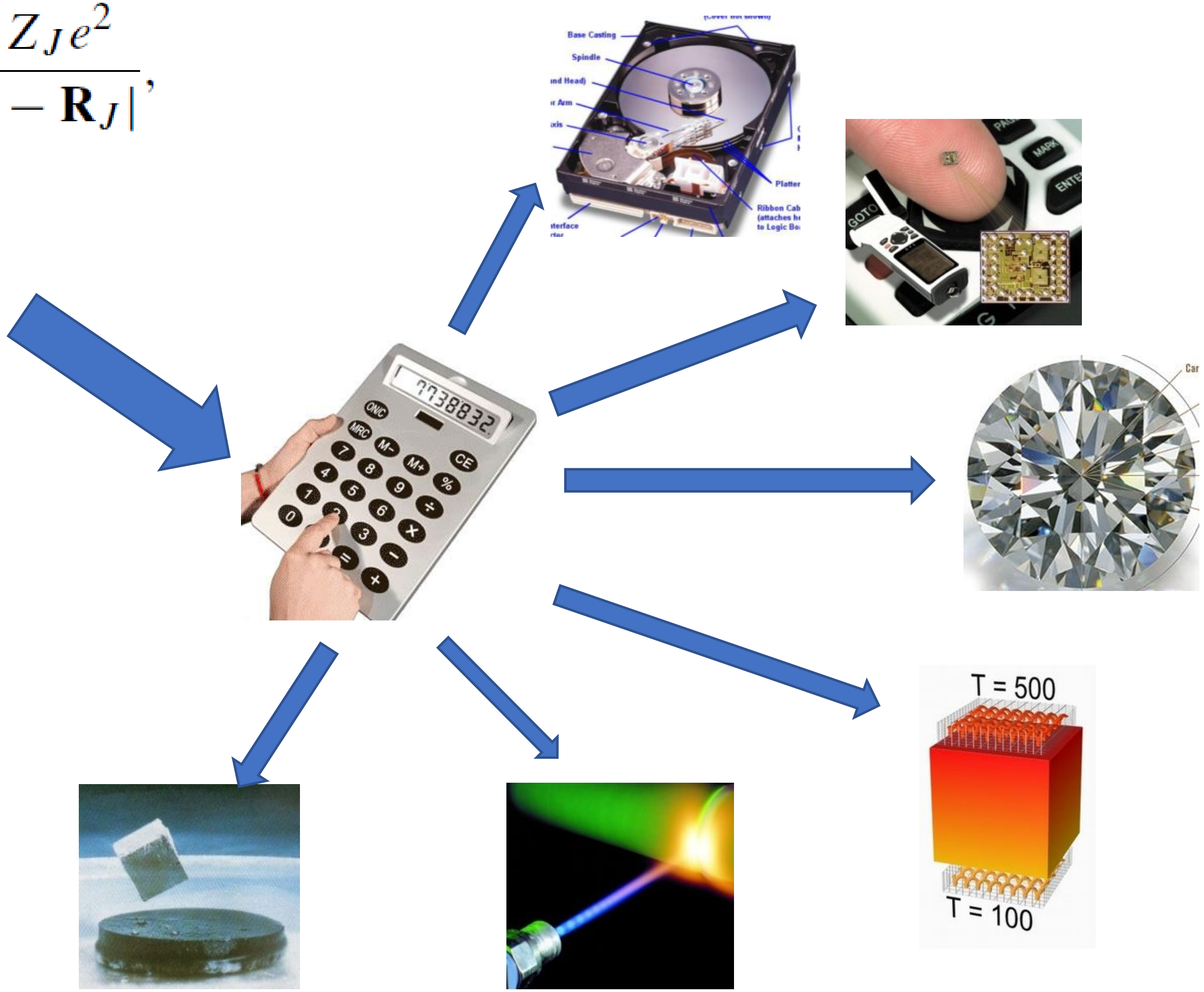
Directing Matter and Energy:
Five Challenges for Science and the Imagination

A Report from the Basic Energy Sciences Advisory Committee

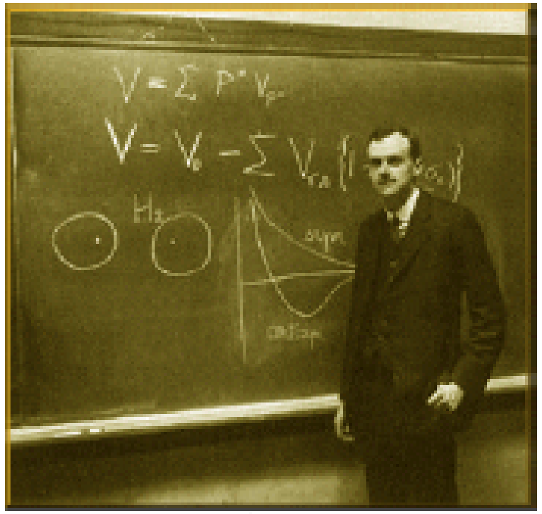
“**Grand Challenge #3:** How do remarkable properties of matter emerge from complex correlations of the atomic or electronic constituents and how can we control these properties?

$$\hat{H} = -\frac{\hbar^2}{2m_e}\sum_i \nabla_i^2 - \sum_{i,I}\frac{Z_I e^2}{|\mathbf{r}_i - \mathbf{R}_I|} + \frac{1}{2}\sum_{i\neq j}\frac{e^2}{|\mathbf{r}_i - \mathbf{r}_j|}$$

$$- \sum_I \frac{\hbar^2}{2M_I}\nabla_I^2 + \frac{1}{2}\sum_{I\neq J}\frac{Z_I Z_J e^2}{|\mathbf{R}_I - \mathbf{R}_J|},$$

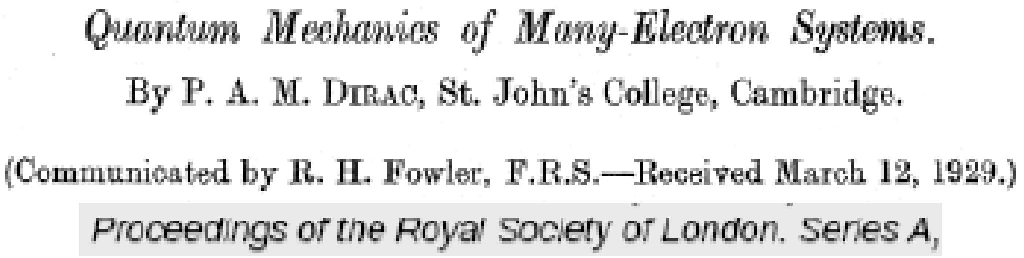


O sonho de Dirac



Dirac

Premio Nobel 1933

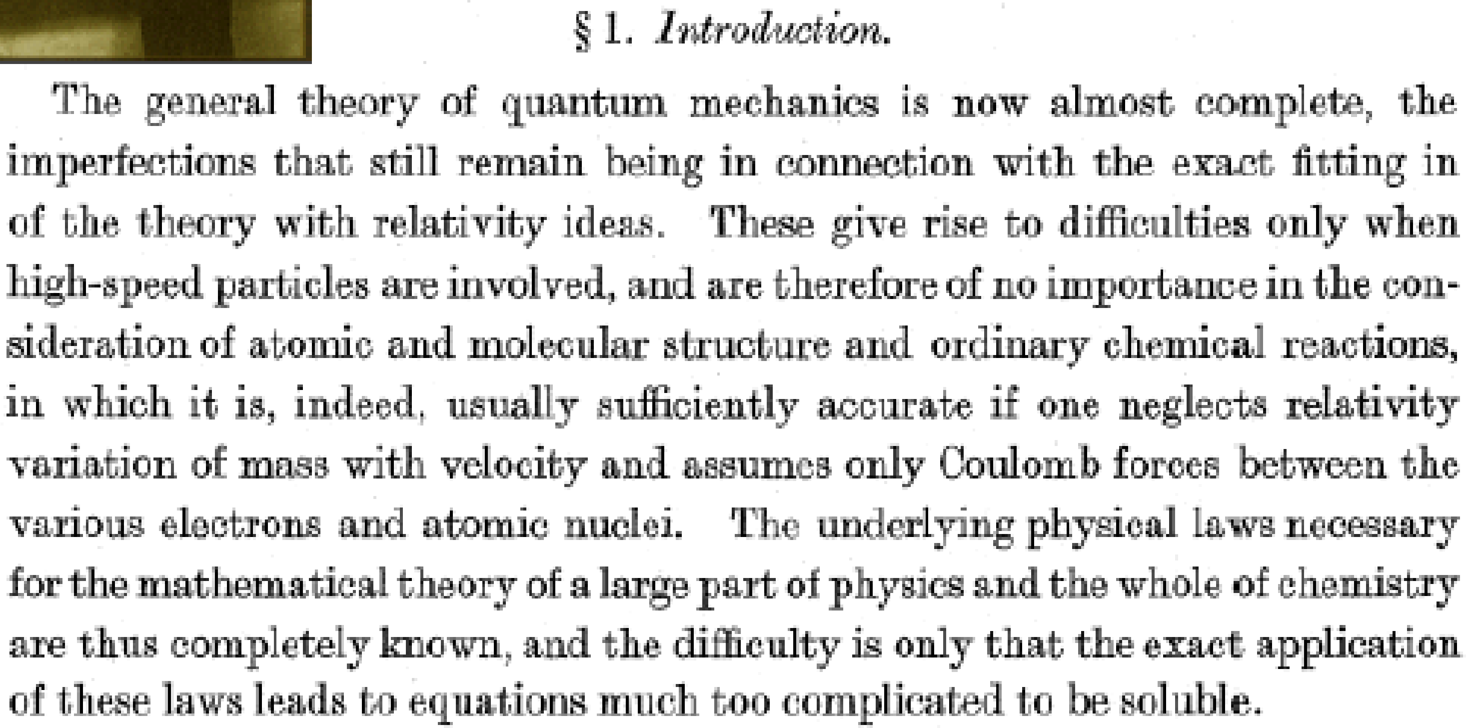


Quantum Mechanics of Many-Electron Systems.

By P. A. M. Dirac, St. John's College, Cambridge.

(Communicated by R. H. Fowler, F.R.S.—Received March 12, 1929.)

Proceedings of the Royal Society of London. Series A,



§ 1. *Introduction.*

The general theory of quantum mechanics is now almost complete, the imperfections that still remain being in connection with the exact fitting in of the theory with relativity ideas. These give rise to difficulties only when high-speed particles are involved, and are therefore of no importance in the consideration of atomic and molecular structure and ordinary chemical reactions, in which it is, indeed, usually sufficiently accurate if one neglects relativity variation of mass with velocity and assumes only Coulomb forces between the various electrons and atomic nuclei. The underlying physical laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known, and the difficulty is only that the exact application of these laws leads to equations much too complicated to be soluble.

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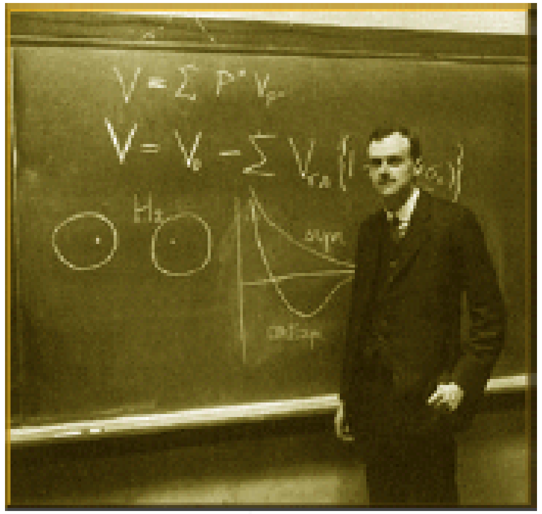

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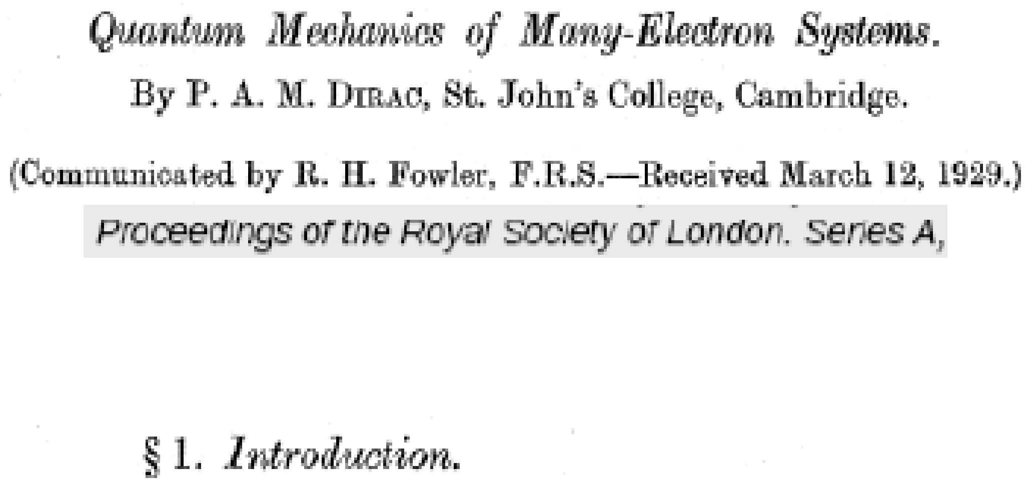

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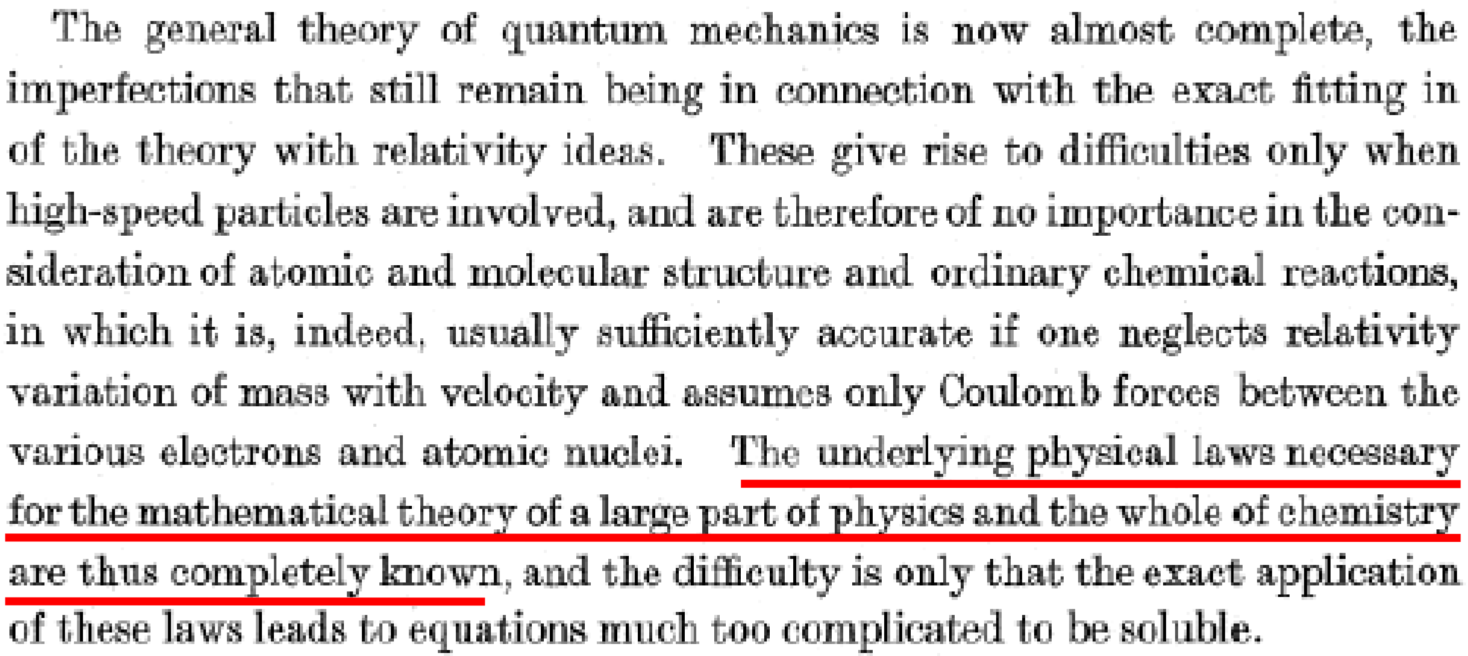

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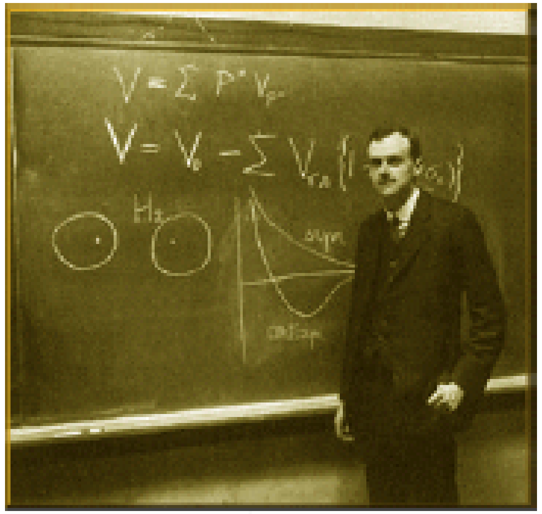
Pesadelo



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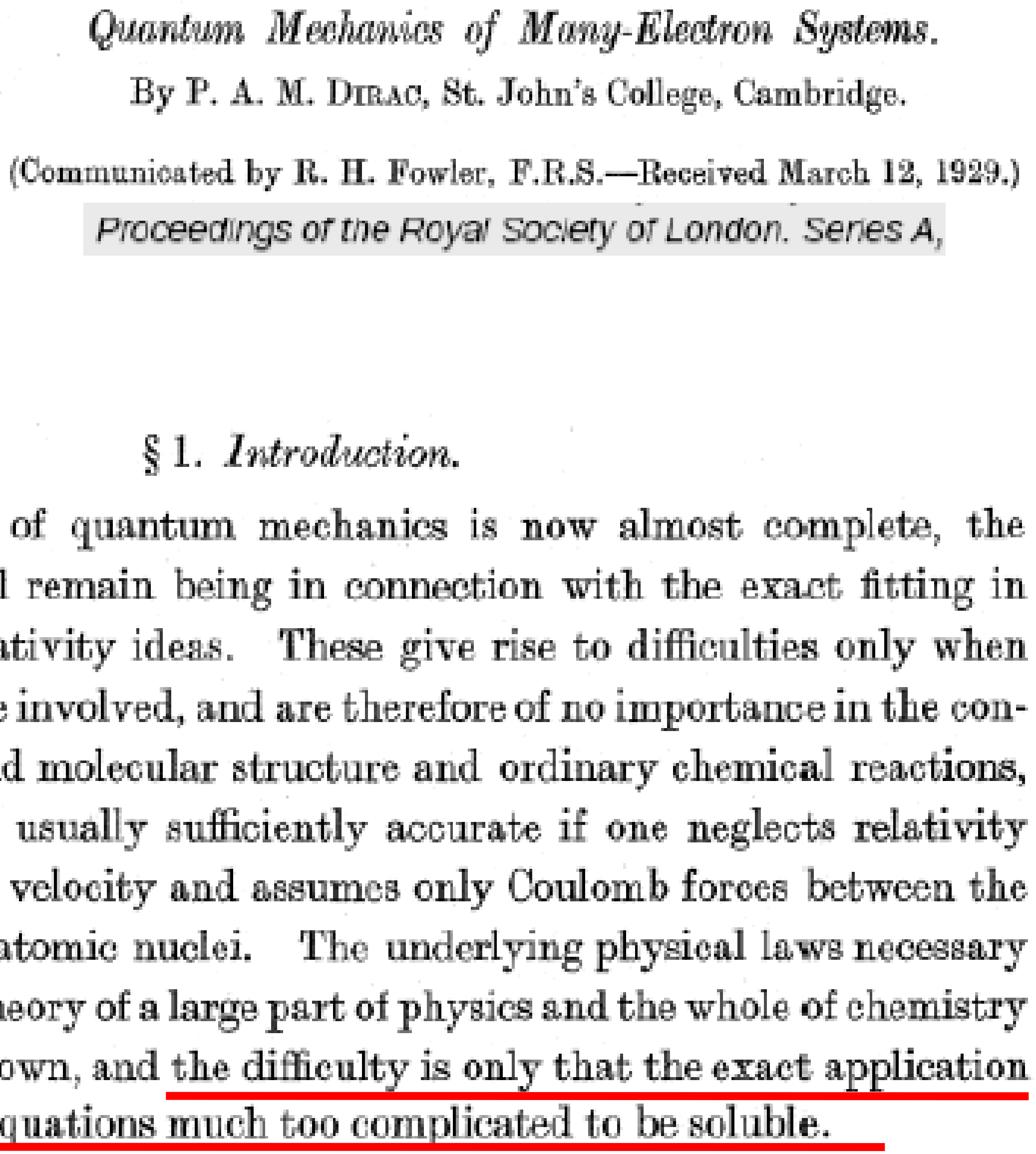

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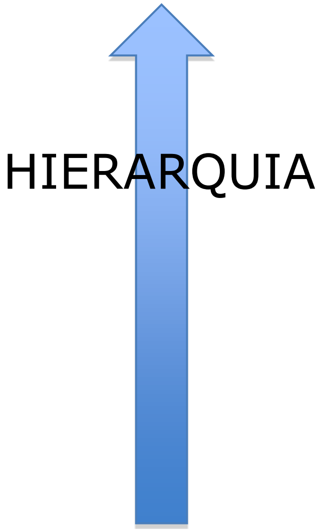
Visão reducionista da Física



- ***Teoria de campos-partículas elementares***

↓ *núcleos*

- ***Física Atômica***

↓ *moléculas*

- ***Química***

↓ *sólidos*

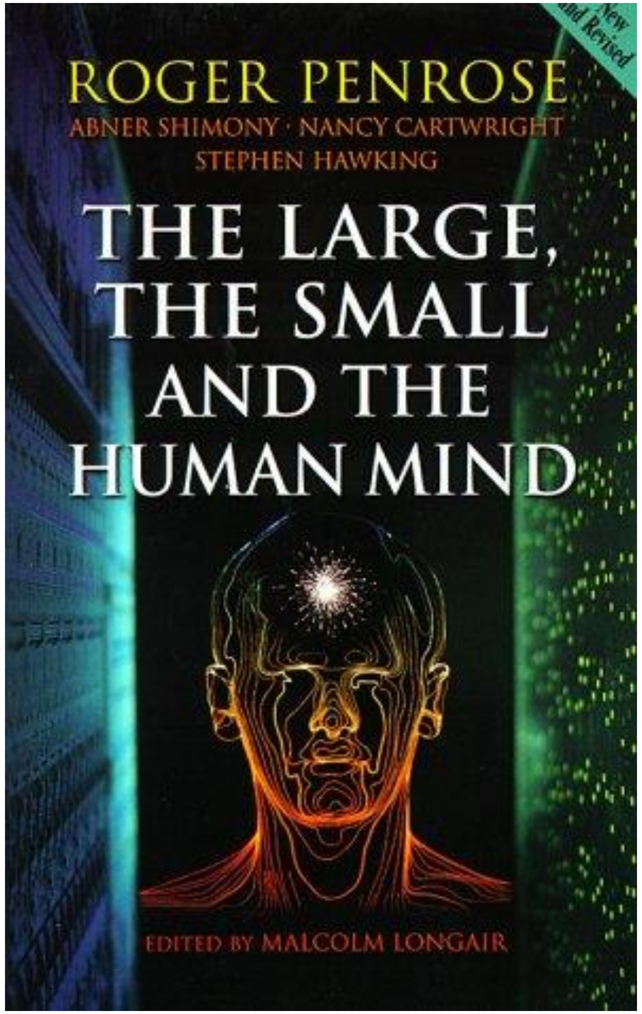
- ***Física da Matéria Condensada***

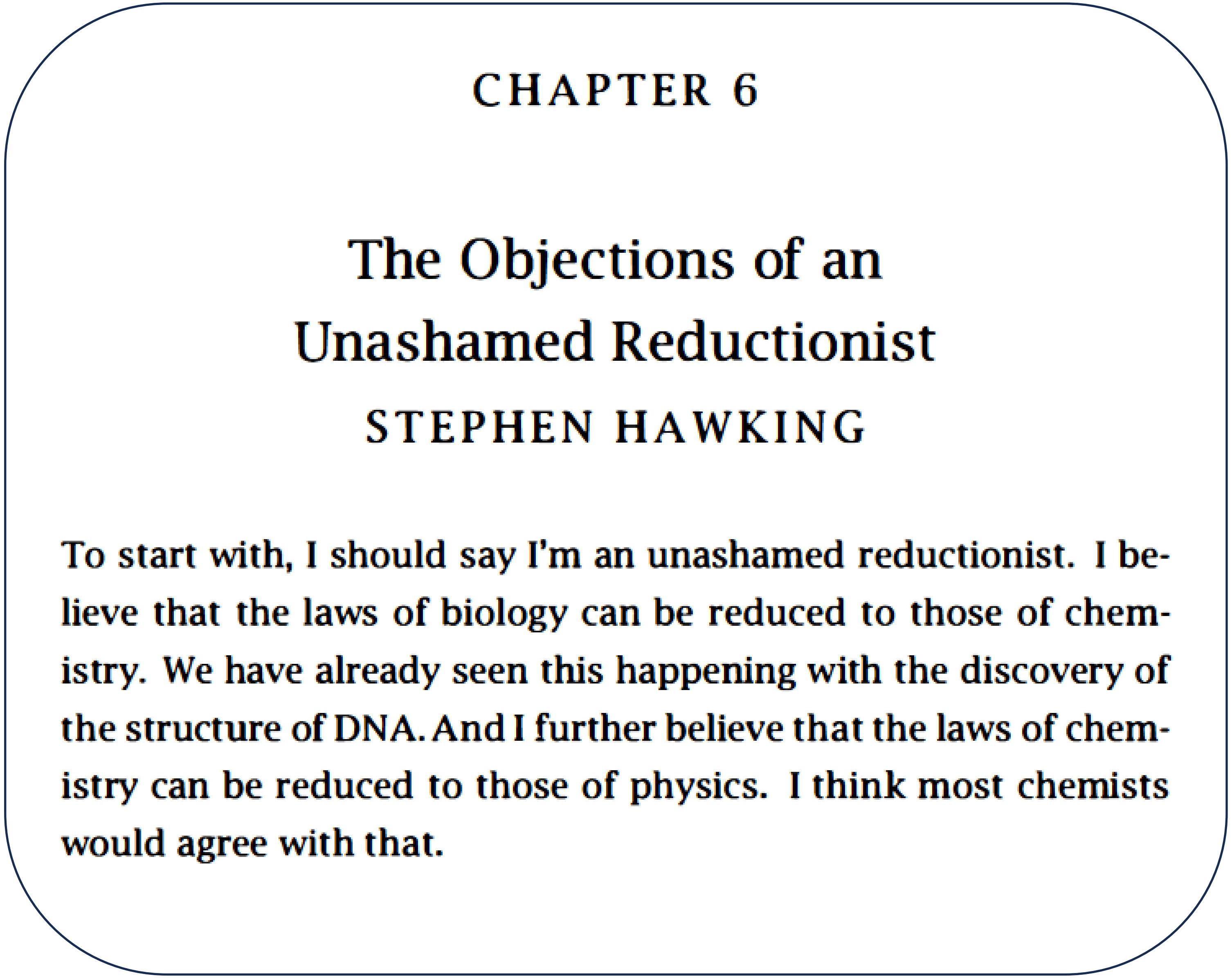
↓ *+ interação gravitacional*

- ***Astrofísica***

↓ *+ relatividade*

- ***Gravitação***





CHAPTER 6

The Objections of an Unashamed Reductionist

STEPHEN HAWKING

To start with, I should say I'm an unashamed reductionist. I believe that the laws of biology can be reduced to those of chemistry. We have already seen this happening with the discovery of the structure of DNA. And I further believe that the laws of chemistry can be reduced to those of physics. I think most chemists would agree with that.

VISÃO REDUCIONISTA DA FÍSICA

- ***Teoria de campos-partículas elementares***

↓ *núcleos*

- ***Física Atômica***

↓ *moléculas*

- ***Química***

↓ *sólidos*

- ***Física da Matéria Condensada***

↓ *+ interação gravitacional*

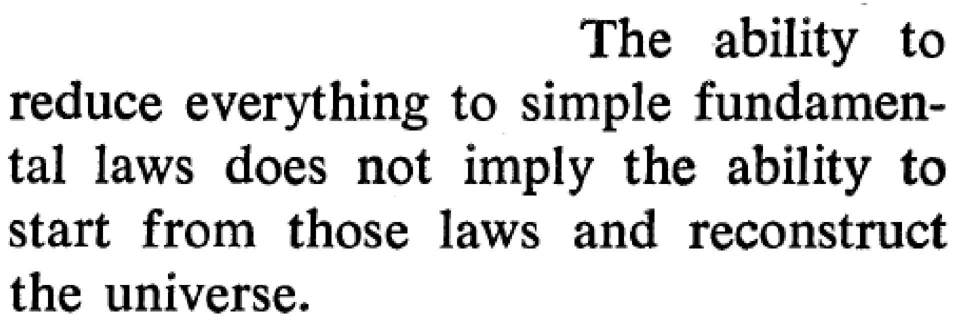
- ***Astrofísica***

↓ *+ relatividade*

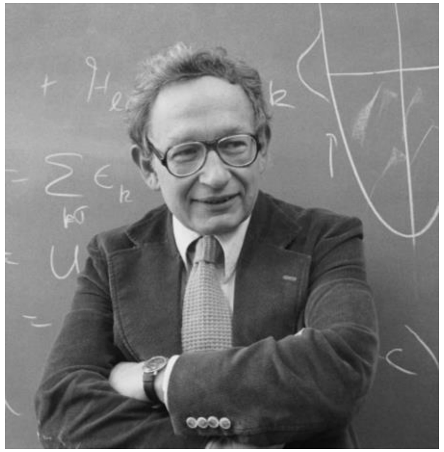
- ***Gravitação***

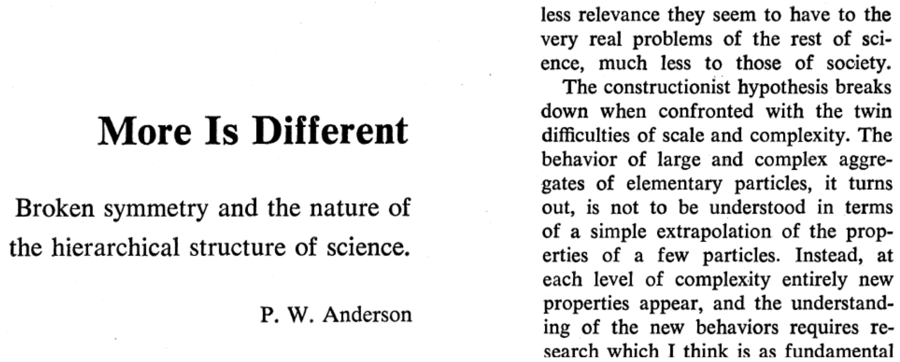
Não funciona!

4 August 1972, Volume 177, Number 4047 **SCIENCE**



The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe.





More Is Different

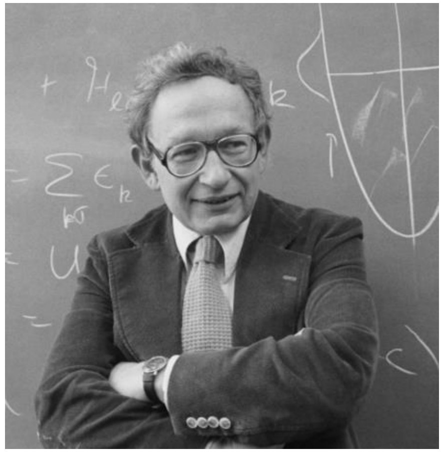
Broken symmetry and the nature of the hierarchical structure of science.

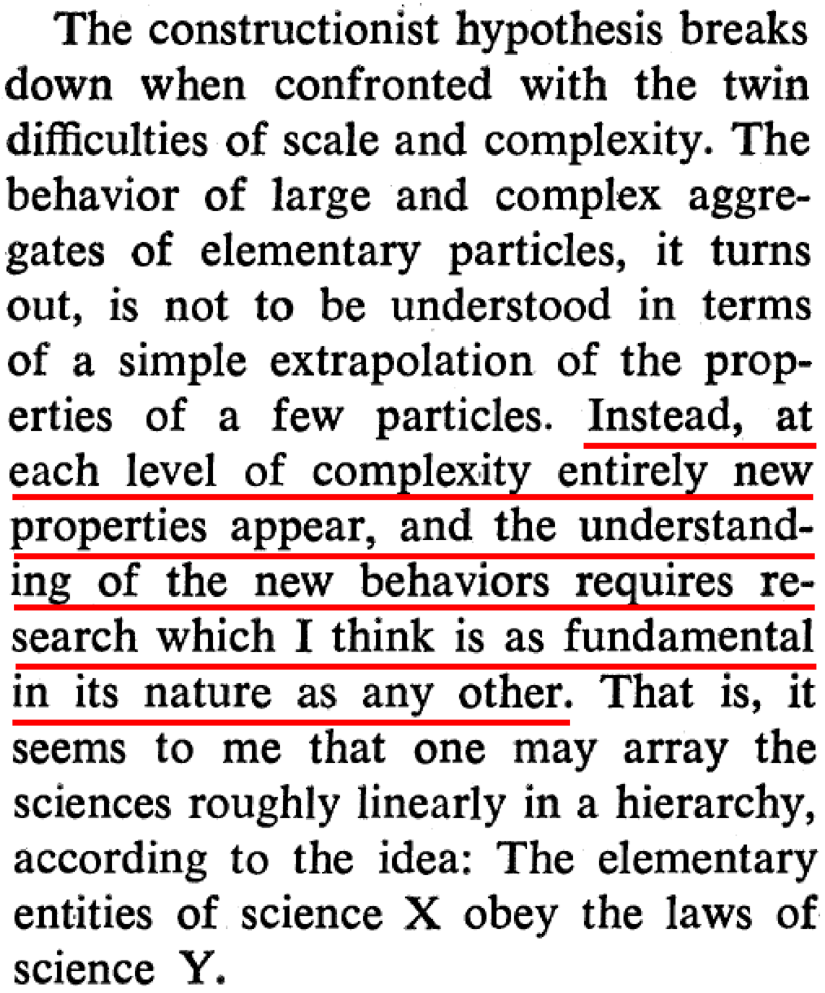
P. W. Anderson

less relevance they seem to have to the very real problems of the rest of science, much less to those of society.

The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity. The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental

“More is different”





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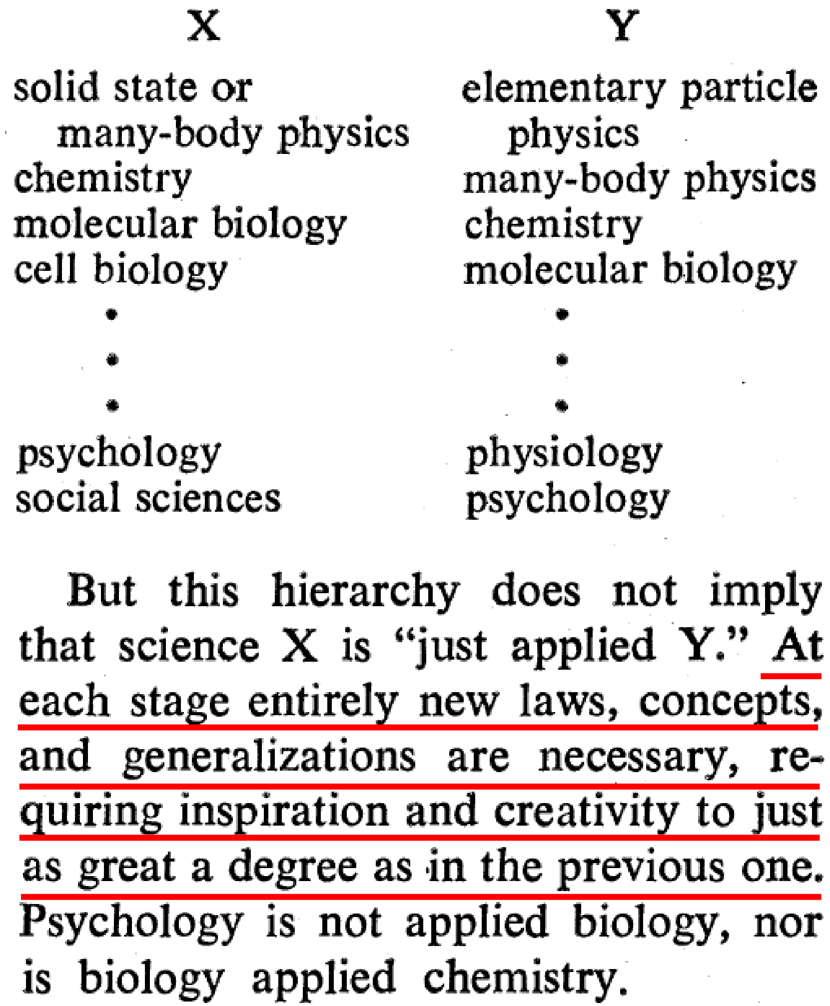
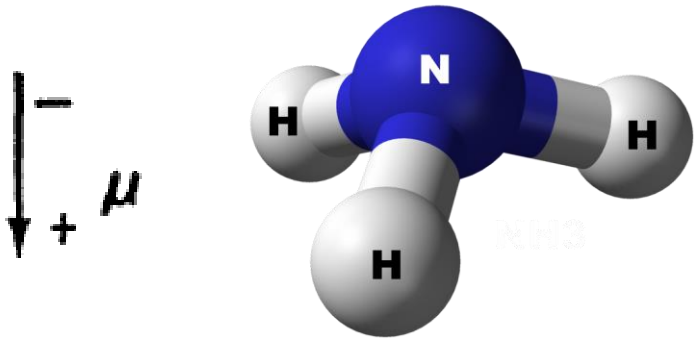


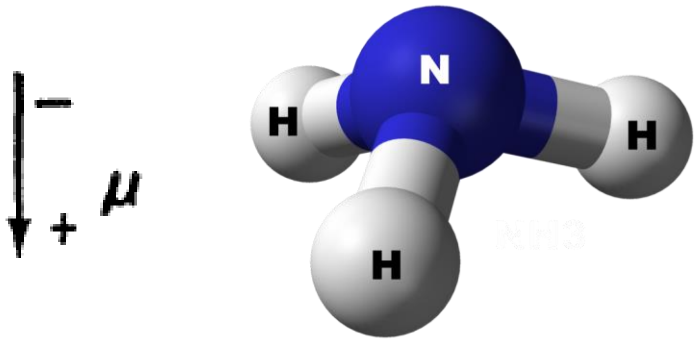
X	Y
solid state or many-body physics	elementary particle physics
chemistry	many-body physics
molecular biology	chemistry
cell biology	molecular biology
•	•
•	•
•	•
psychology	physiology
social sciences	psychology

But this hierarchy does not imply that science X is “just applied Y.” At each stage entirely new laws, concepts, and generalizations are necessary, requiring inspiration and creativity to just as great a degree as in the previous one. Psychology is not applied biology, nor is biology applied chemistry.

“More is different”

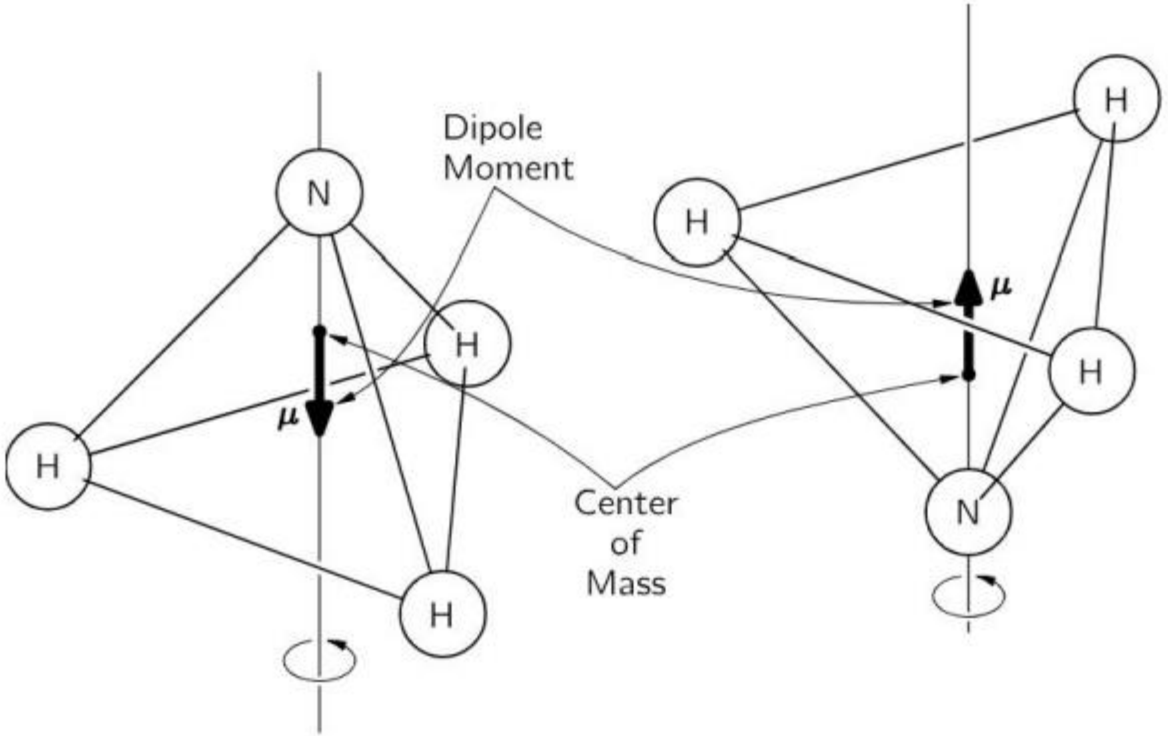


“More is different”



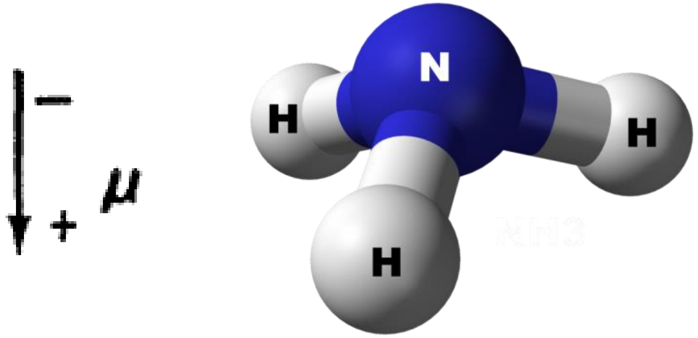
$$H = H_0 + W$$

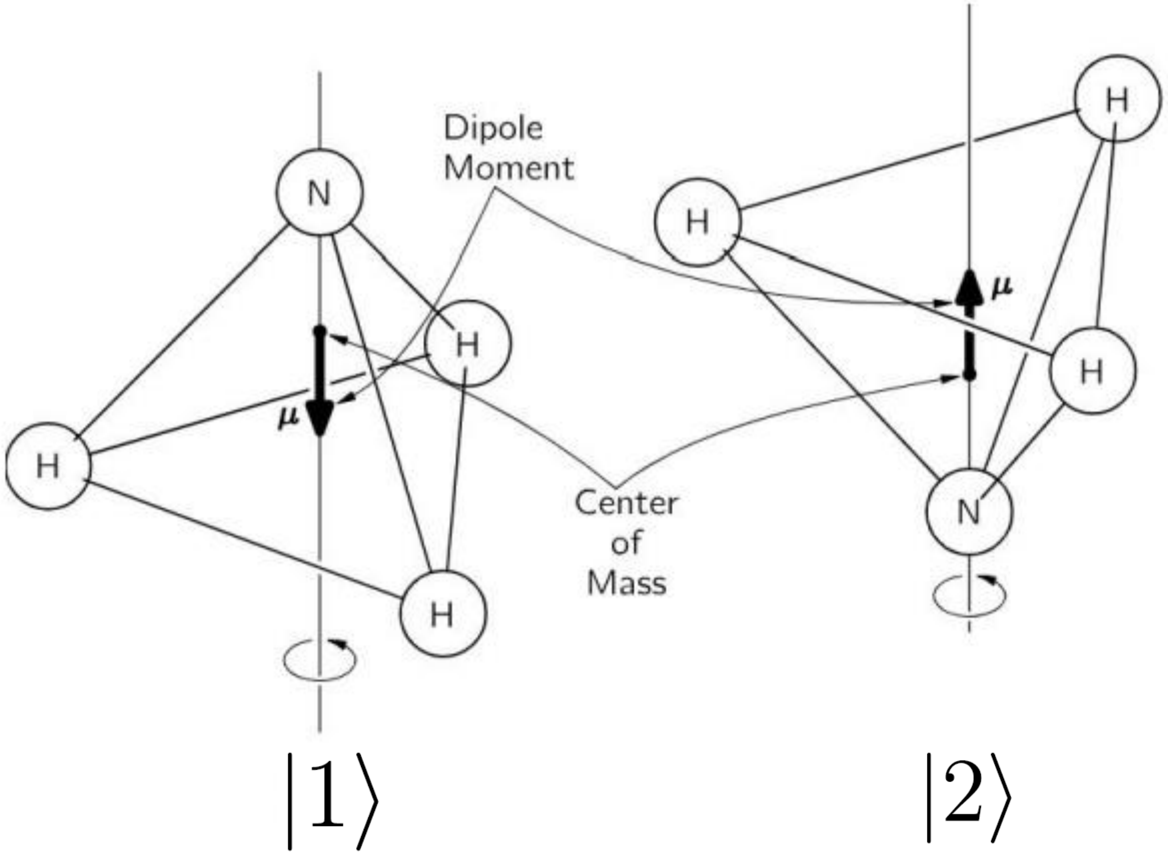
$$H_0 = E_0 I \qquad W = -A\sigma_x$$



$|1\rangle$ $|2\rangle$

“More is different”





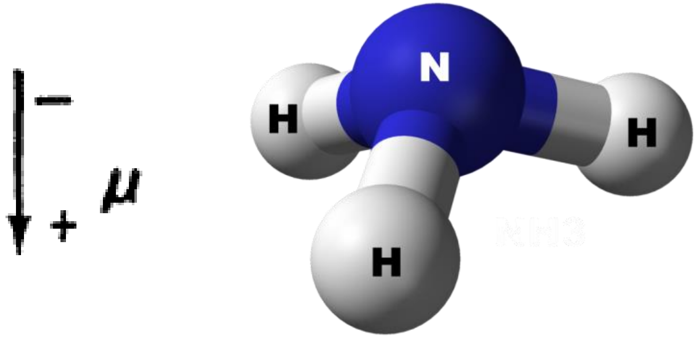
$$H = H_0 + W$$

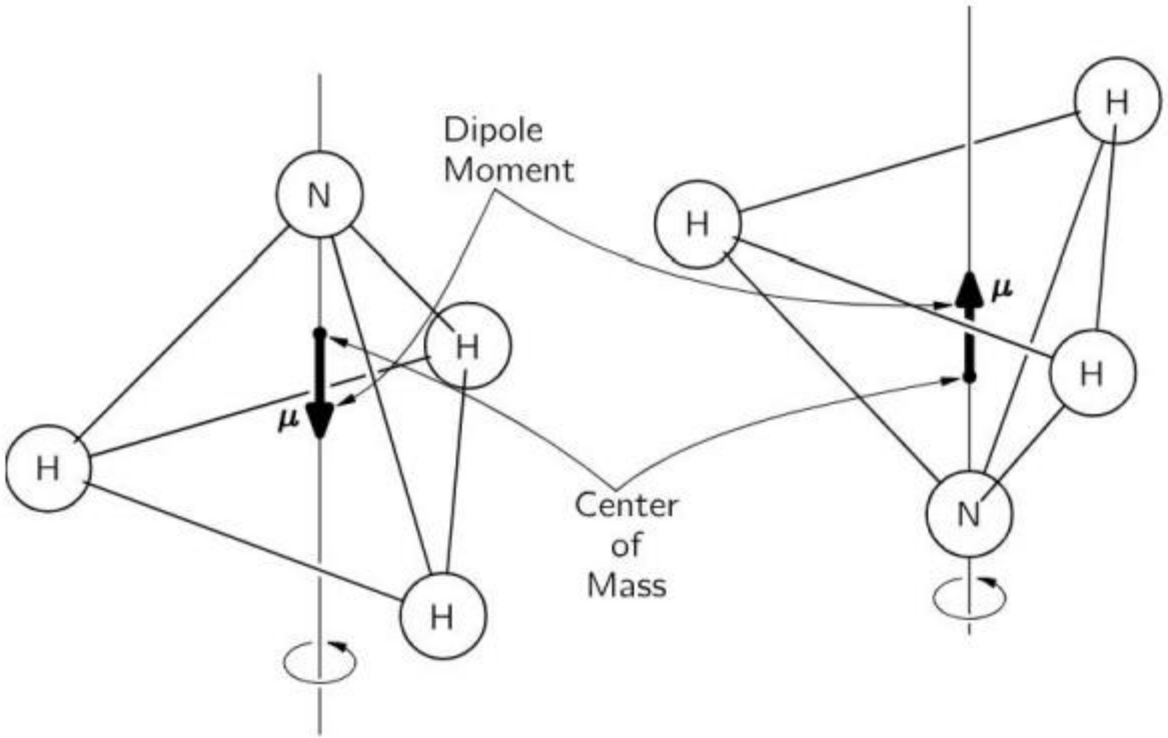
$$H_0 = E_0 I \qquad W = -A\sigma_x$$

$$[H] = \begin{array}{cc} \langle 1| & \langle 2| & \\ \end{array}$$

$$[H] = \begin{array}{ccc} \langle 1| & \langle 2| & \\ E_0 & -A & |1\rangle \\ -A & E_0 & |2\rangle \end{array}$$

“More is different”





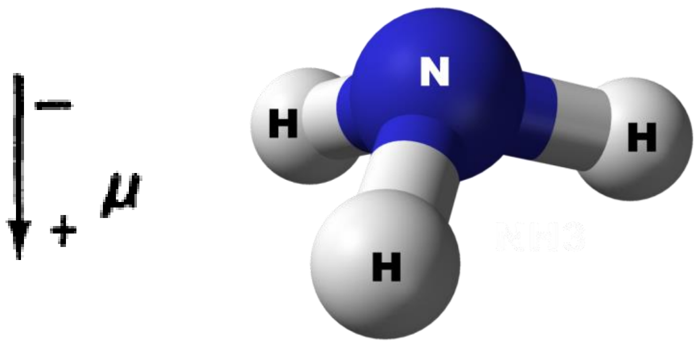
$$|1\rangle \qquad |2\rangle$$

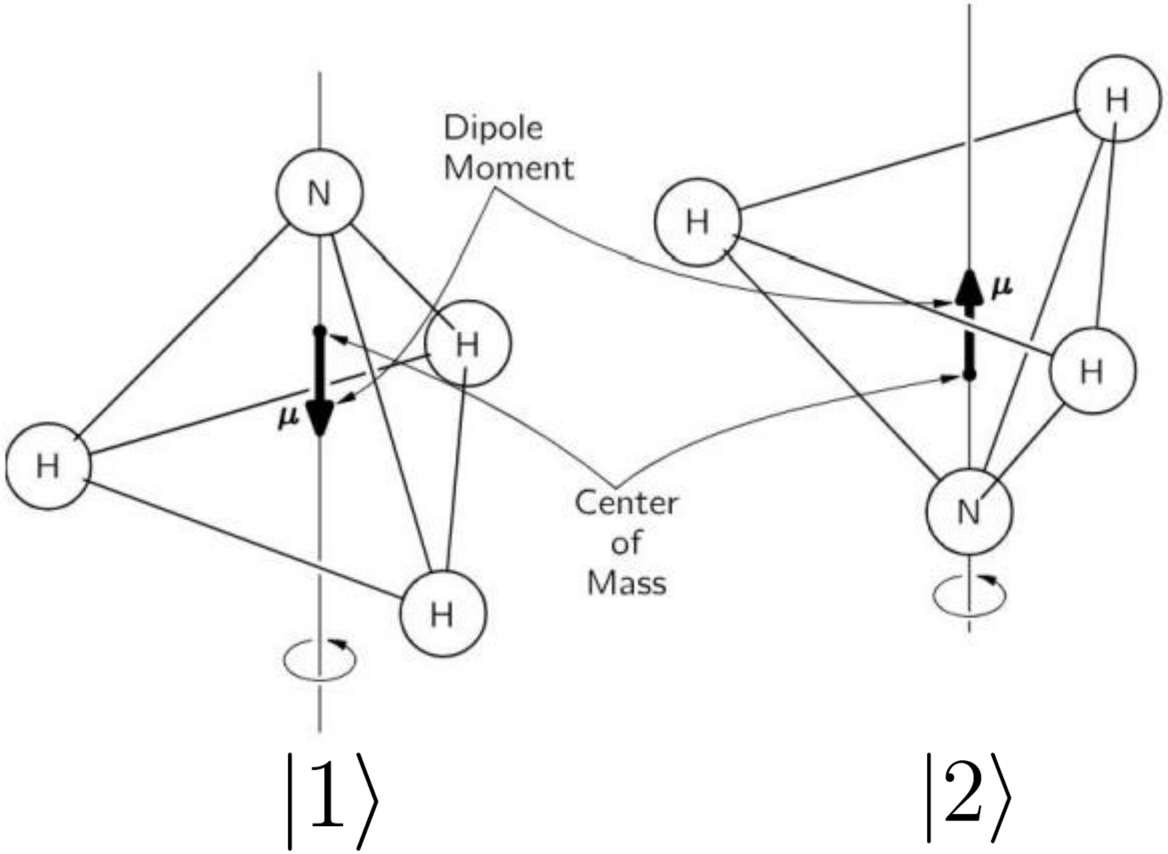
$$H = H_0 + W$$

$$H_0 = E_0 I \qquad W = -A\sigma_x$$

$$\left\{\begin{aligned} E_\pm &= E_0 \mp A \\ |+\rangle &= \frac{1}{\sqrt{2}}[|1\rangle + |2\rangle] \\ |-\rangle &= \frac{1}{\sqrt{2}}[|1\rangle - |2\rangle] \end{aligned}\right.$$

“More is different”





$$H = H_0 + W$$

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$$E_\pm = E_0 \mp A$$

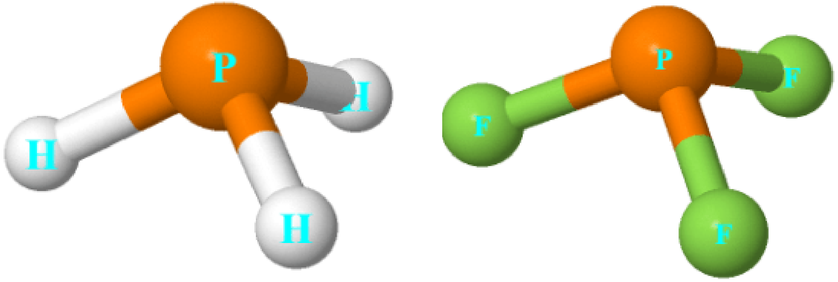
$$|+\rangle = \frac{1}{\sqrt{2}}[|1\rangle + |2\rangle]$$

$$|-\rangle = \frac{1}{\sqrt{2}}[|1\rangle - |2\rangle]$$

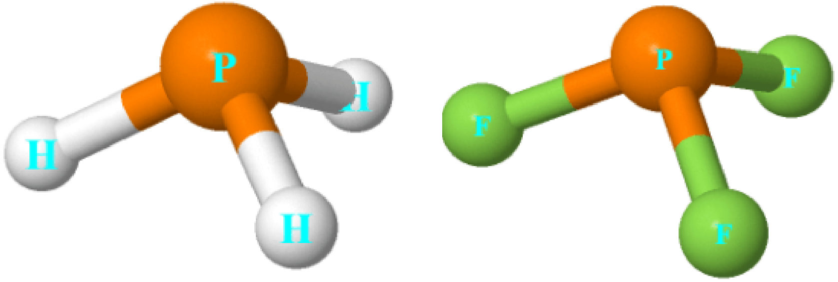
Suponha que $|\psi(0)\rangle = |1\rangle = \frac{1}{\sqrt{2}}[|+\rangle + |-\rangle]$

$$|\psi(t)\rangle = \frac{1}{\sqrt{2}} e^{-\frac{iE_0 t}{\hbar}}\left[e^{i\frac{At}{\hbar}}\,|+\rangle + e^{-i\frac{At}{\hbar}}\,|-\rangle\right]$$

“More is different”

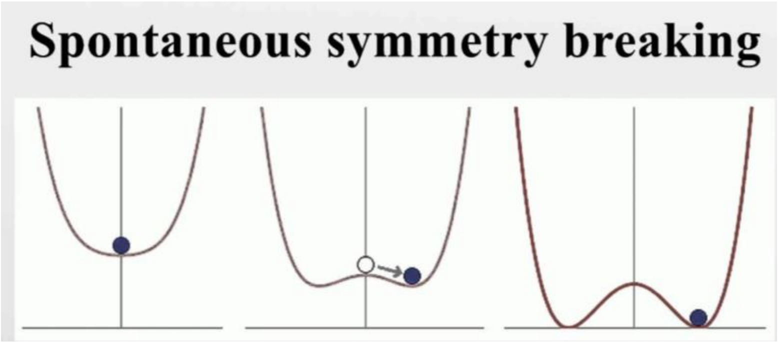


“More is different”

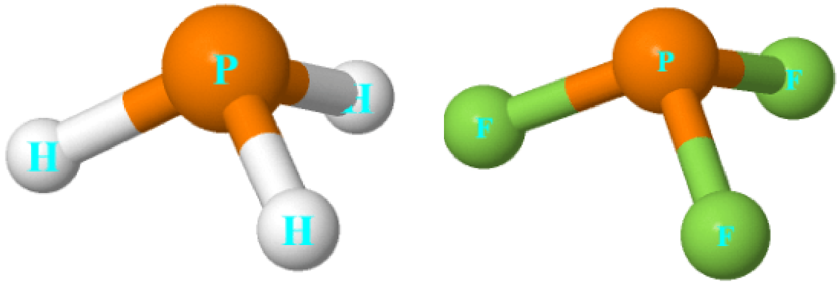


Em larga escala, temos:

- Pyroelectricity
- Ferroelectricity


Spontaneous symmetry breaking

“More is different”



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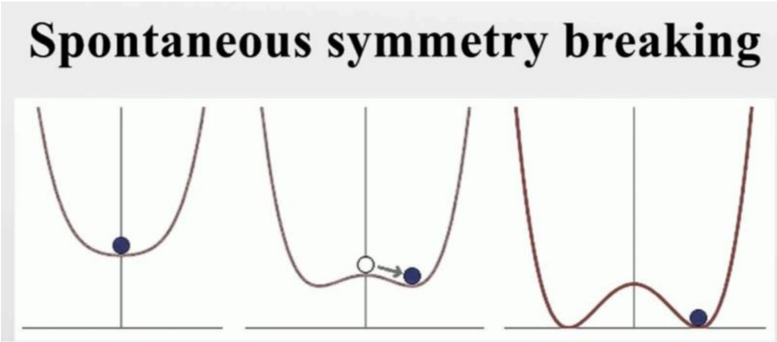
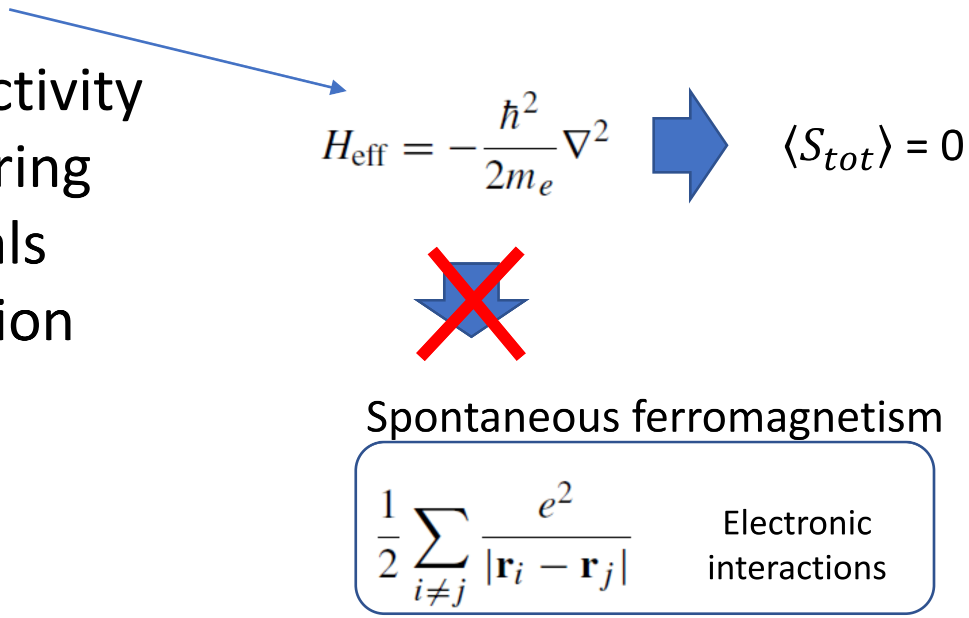

Spontaneous symmetry breaking

Outros exemplos são:

- Magnetism
- Superconductivity
- Charge ordering
- Liquid Crystals
- Mott Transition



$$H_{\text{eff}} = -\frac{\hbar^2}{2m_e}\nabla^2 \Rightarrow \langle S_{tot} \rangle = 0$$

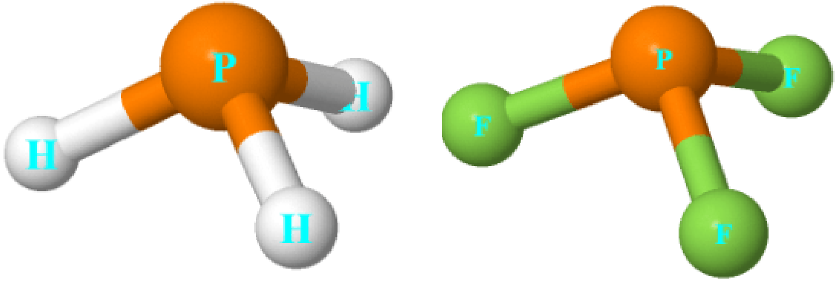
$$\cancel{\Downarrow}$$

Spontaneous ferromagnetism

$$\frac{1}{2}\sum_{i\neq j}\frac{e^2}{|\mathbf{r}_i - \mathbf{r}_j|}$$

Electronic interactions

“More is different”



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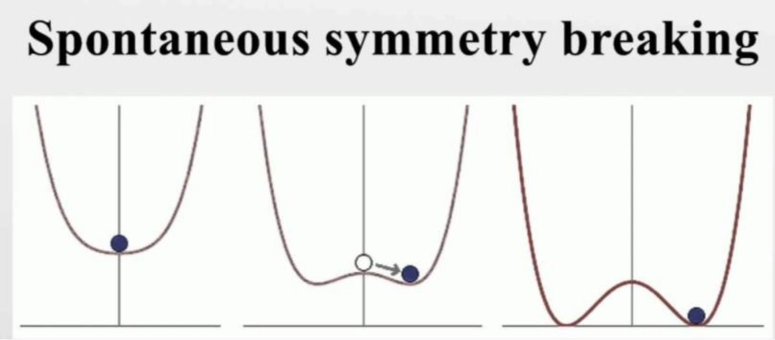

Spontaneous symmetry breaking

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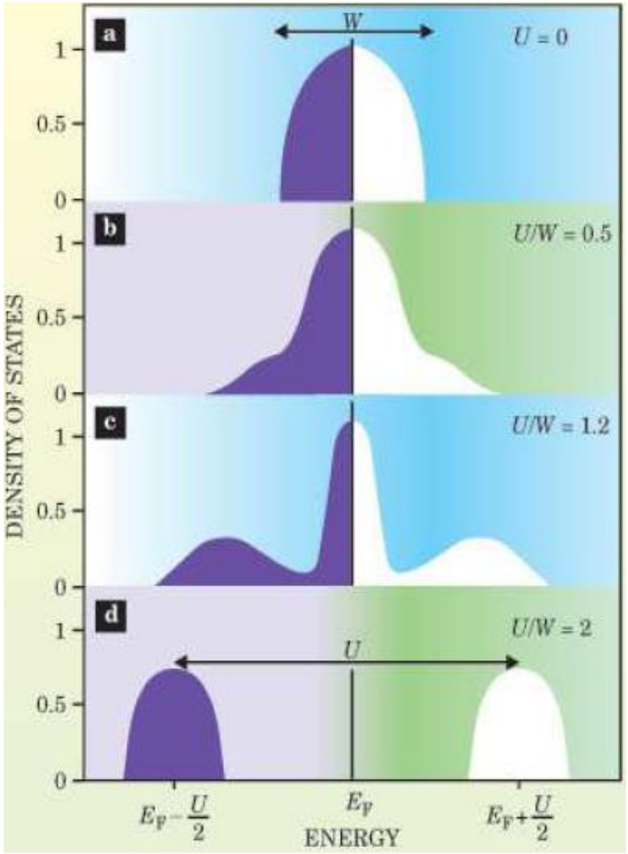
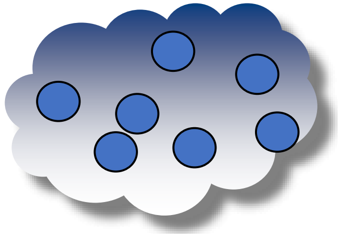
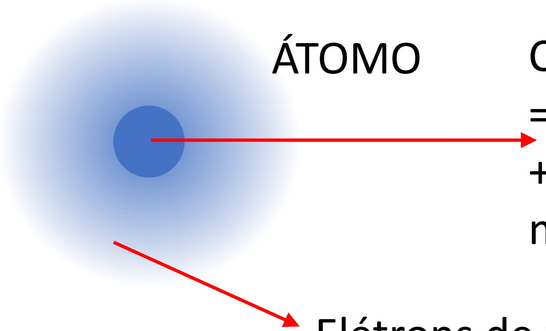


Não há quebra espontânea de simetria numa transição de Mott.

“More is different”

Quase-partículas





ÁTOMO

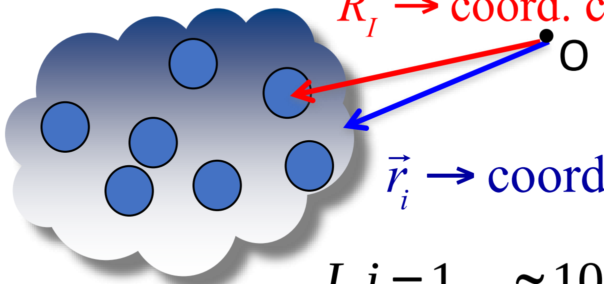
Caroço
= núcleo
+ elétrons
mais ligados

Elétrons de valência

Exemplo:
Na – 11 elétrons

1s(2) 2s(2) 2p(6) → caroço (Ne) inerte
3s(1) → valência

$\vec{R}_I \rightarrow$ coord. caroço

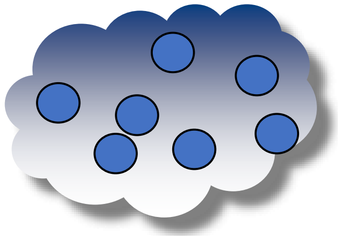


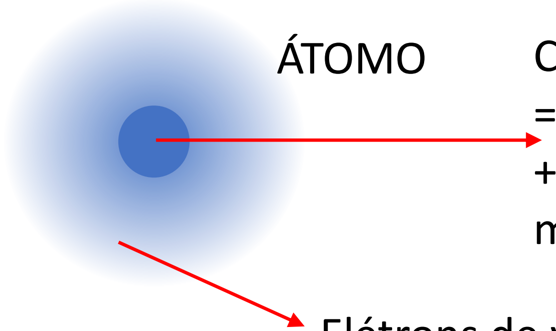
$\vec{r}_i \rightarrow$ coord. eletrônica

$$I, i = 1, \ldots \approx 10^{23}$$

“More is different”

Quase-partículas





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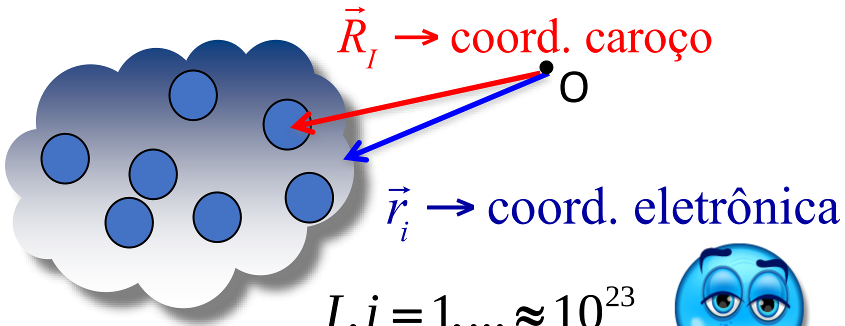


$\vec{R}_I \rightarrow$ coord. caroço

$\vec{r}_i \rightarrow$ coord. eletrônica

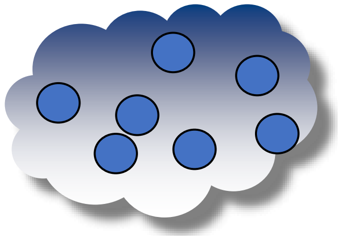
$I, i = 1, \ldots \approx 10^{23}$

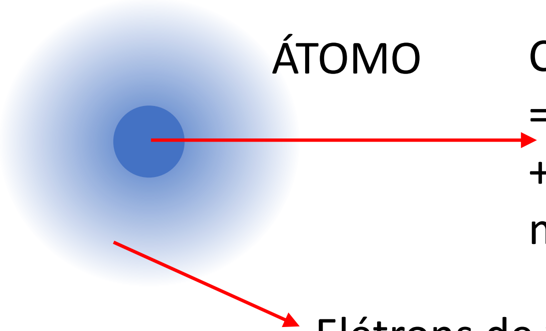
Problema de muitas partículas interagentes

ATENÇÃO: so conhecemos a solução exata do átomo de “hidrogênio” que é um problema de 2 corpos (núcleo + elétron). A solução do átomo de “hélio” exige técnicas perturbativas. Apenas alguns pouquíssimos exemplos exatos de problemas de muitos corpos são conhecidos na literatura.

"More is different"

Quase-partículas





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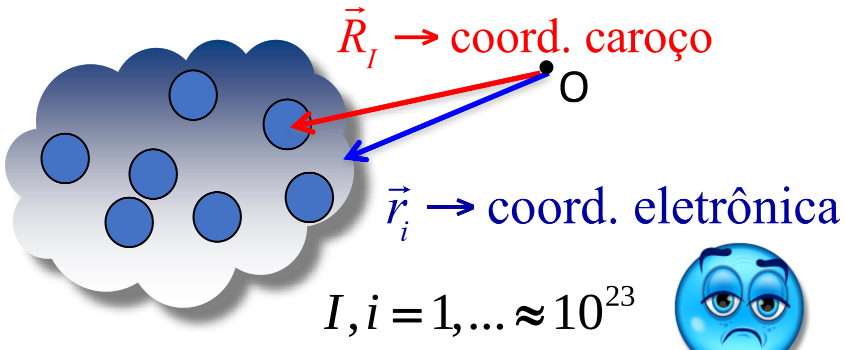

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Estratégia

mapear

Problema de partículas não-interagentes
+ correções (***quase-partículas***)

Aplicações neste curso

- Excitações elementares
  - Fônons: vibrações cristalinas
  - Magnons: excitações de spin
  - Excitons: excitações de carga
  - ...

Site do curso:

Matéria Condensada IF/UFRJ

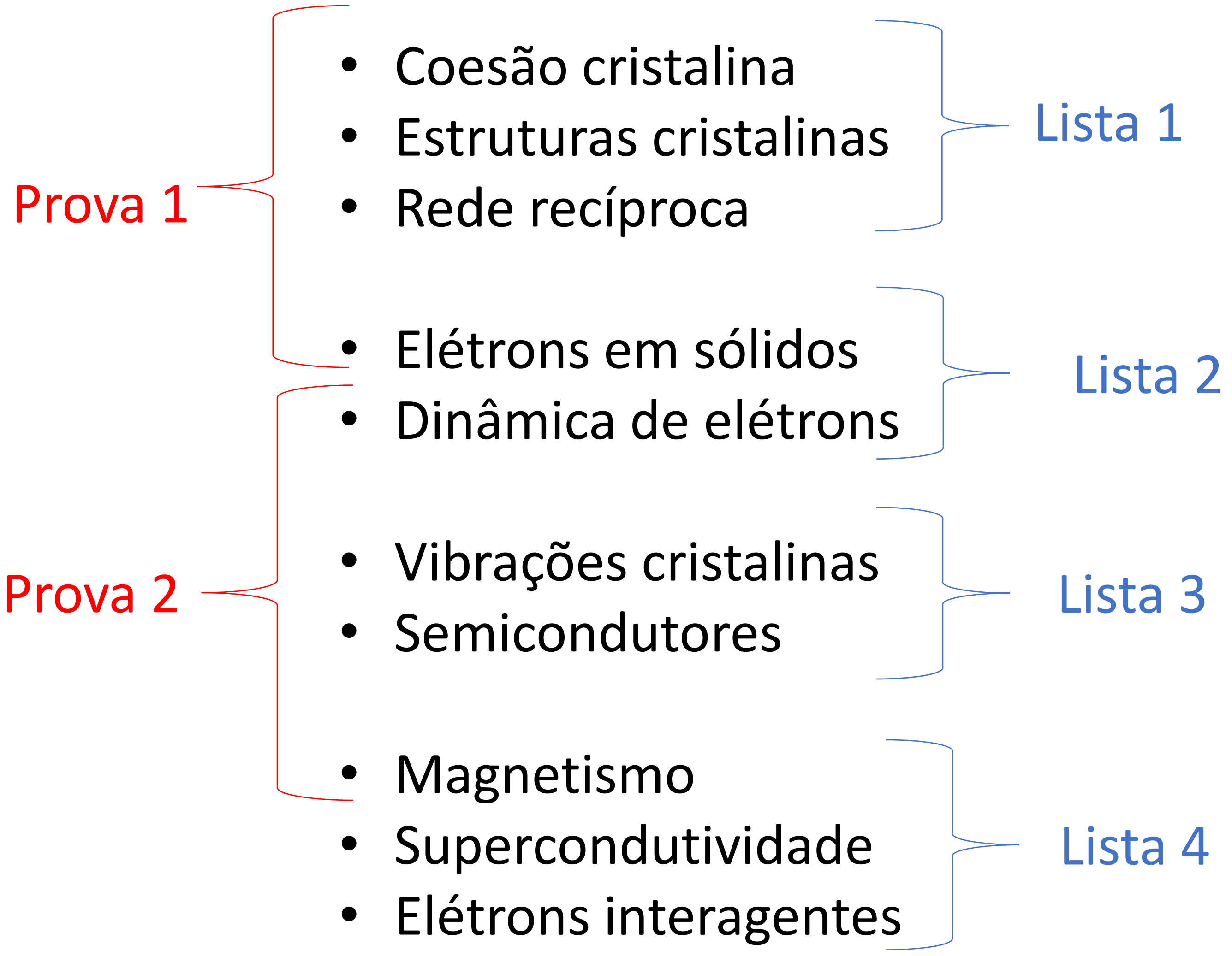
Física da Matéria Condensada (2023-2) Bibliografia e Vídeos Cronograma Listas

Critérios de avaliação

Física da Matéria Condensada (2023-2)

Professor: Natanael C. Costa

Estrutura do curso:



Prova 1

- Coesão cristalina
- Estruturas cristalinas
- Rede recíproca

Lista 1

- Elétrons em sólidos
- Dinâmica de elétrons

Lista 2

Prova 2

- Vibrações cristalinas
- Semicondutores

Lista 3

- Magnetismo
- Supercondutividade
- Elétrons interagentes

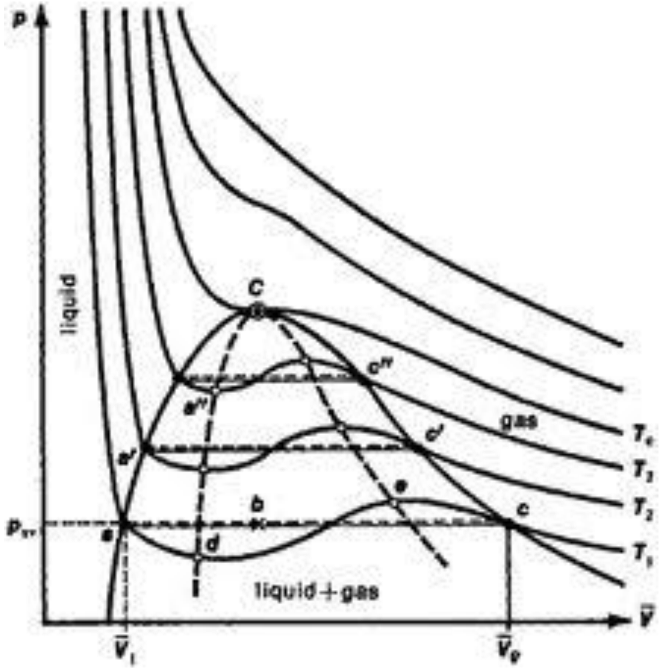
Lista 4

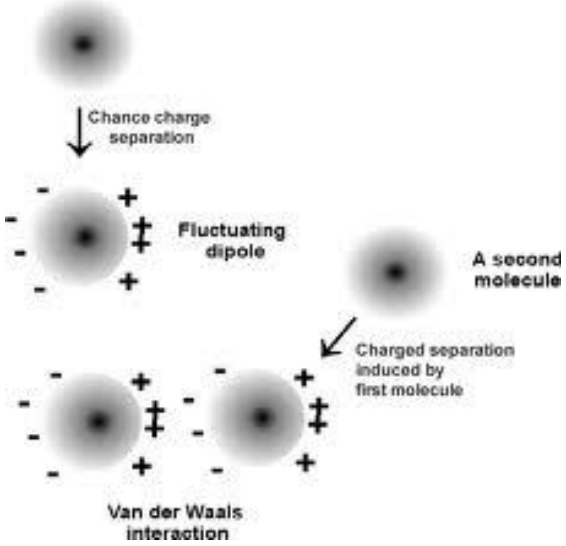
Bibliografia:

- Solid State Physics – Neil Ashcroft, David Mermin;
- Introduction to Solid State Physics – Charles Kittel;
- Solid State Basics -- Steven Simons;
- Solid State Physics – G. Grosso, G. Parravicini;
- Condensed Matter in a Nutshell – G. Mahan

Coesão Cristalina

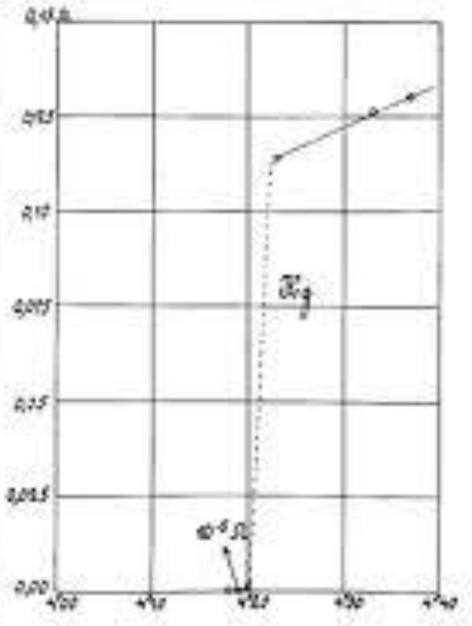
1910	J. D. Van der Waals	"for his work on the equation of state for gases and liquids".

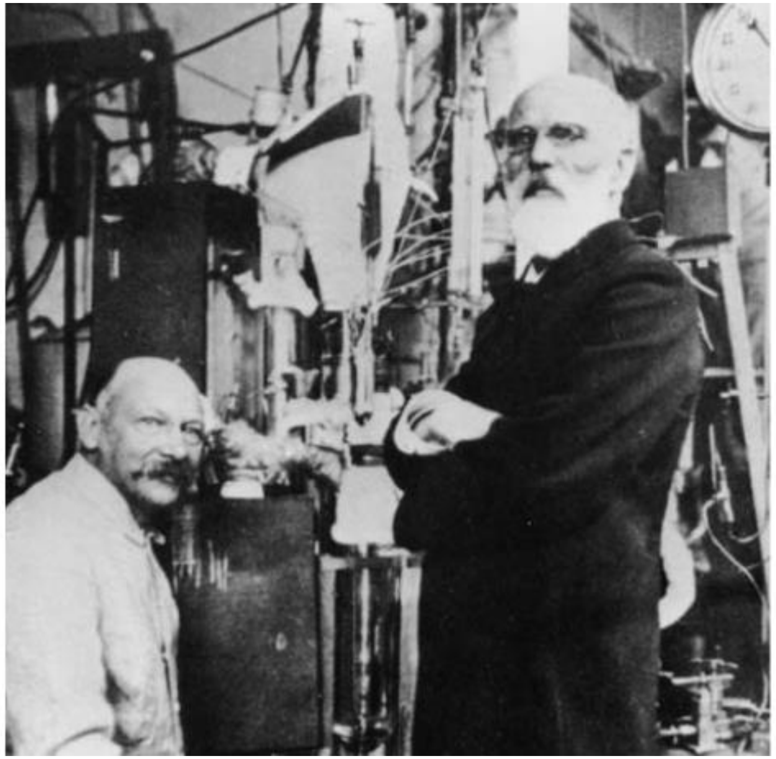




Supercondutividade

1913	H. Kamerlingh Onnes	"for his investigations on the properties of matter at low temperatures which led, inter alia to the production of liquid helium".



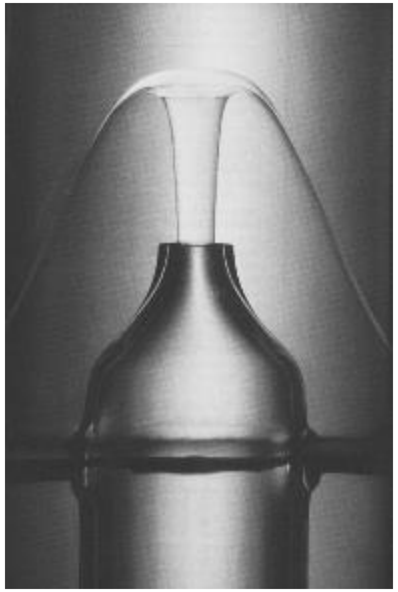


“It has become more and more clear that a change in the whole theory of electrons is necessary. Theoretical work in this direction has already been begun by a number of research workers, particularly by Planck and Einstein.”

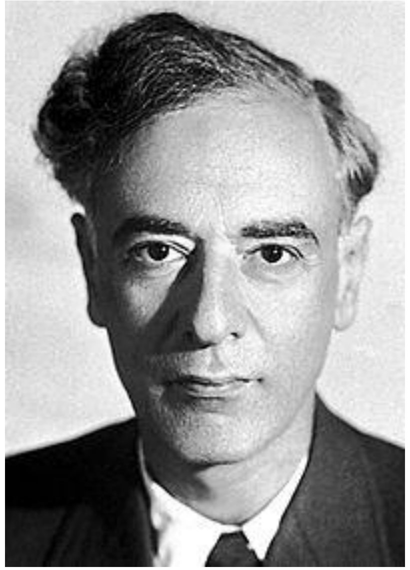
Outros Prêmios Nobel para o estudo da supercondutividade

1972	J. Bardeen, L. N. Cooper e J. R. Schrieffer	"for their jointly developed theory of superconductivity, usually called the BCS-theory".
1973	L. Esaki e I. Giaever B. D. Josephson	"for their experimental discoveries regarding tunneling phenomena in semiconductors and superconductors, respectively"; "for his theoretical predictions of the properties of a supercurrent through a tunnel barrier, in particular those phenomena which are generally known as the Josephson effects".
1987	J. G. Bednorz e K. A. Müller	"for their important breakthrough in the discovery of superconductivity in ceramic materials".
2003	A. A. Abrikosov, V. L. Ginzburg e A. J. Leggett	"for pioneering contributions to the theory of superconductors and superfluids"

Superfluidez



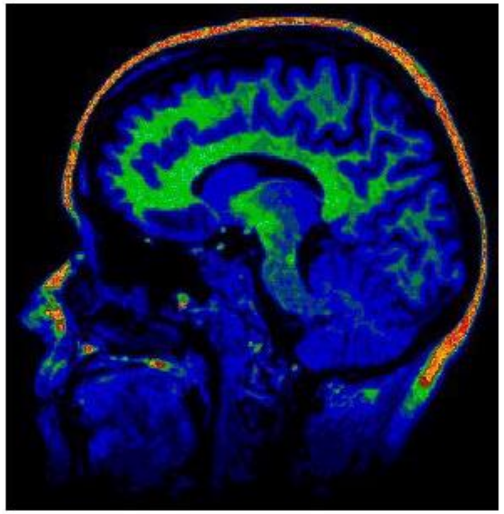
1962	L. D. Landau	"for his pioneering theories for condensed matter, especially liquid helium".
1978	P. L. Kapitza	"for his basic inventions and discoveries in the area of low-temperature physics";
1996	D. M. Lee, D. D. Osheroff e R. C. Richardson	"for their discovery of superfluidity in helium-3".



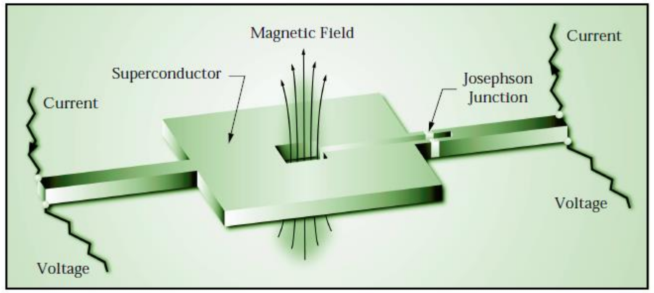
Lev Landau

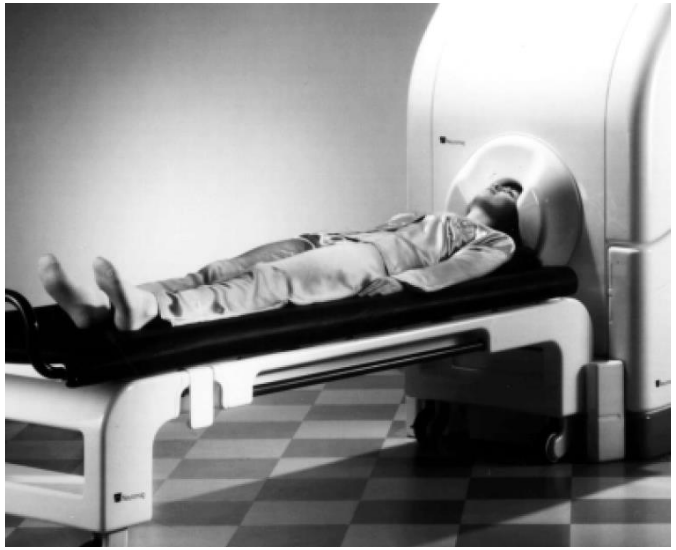
Aplicações

Imagem por Ressonância Magnética

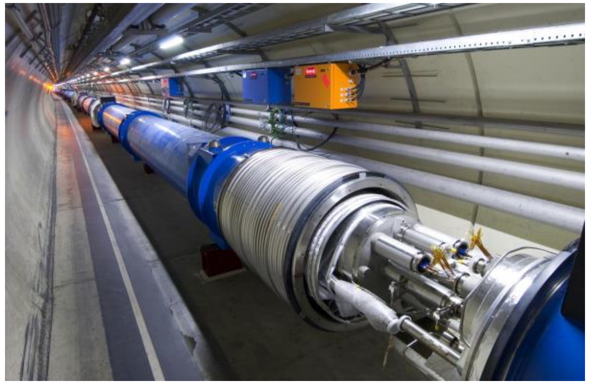


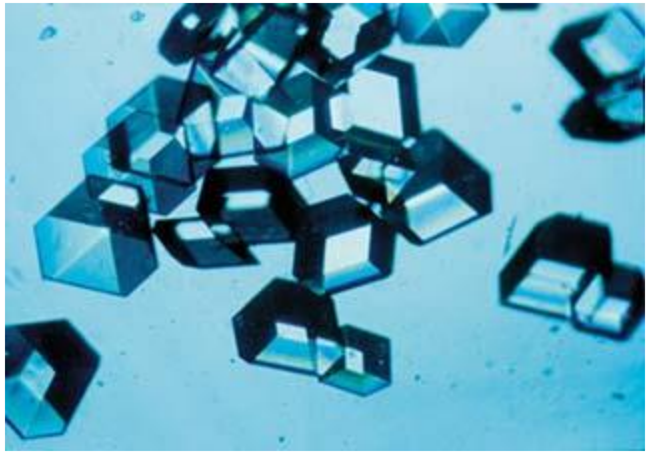
SQUID’s



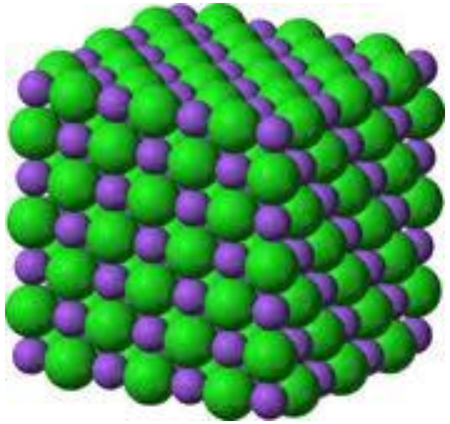


Aceleradores de partículas



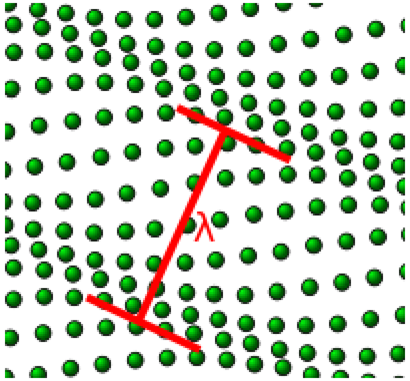


A estrutura cristalina



1914	M. T. F. von Laue	"for his discovery of the diffraction of x-rays by crystals".
1915	W. H. Bragg e W. L. Bragg	"for their services in the analysis of crystal structure by means of x-rays".
1937	C. J. Davisson e G. P. Thomson	"for their experimental discovery of the diffraction of electrons by crystals".
1994	B. N. Brockhouse C. G. Shull	"for pioneering contributions to the development of neutron scattering techniques for studies of condensed matter, specifically for the development of neutron spectroscopy"; "for pioneering contributions to the development of neutron scattering techniques for studies of condensed matter, specifically for the development of the neutron diffraction technique".

Vibrações cristalinas e fônons



1930	C. V. Raman	"for his work on the scattering of light and for the discovery of the effect named after him".

Semicondutores

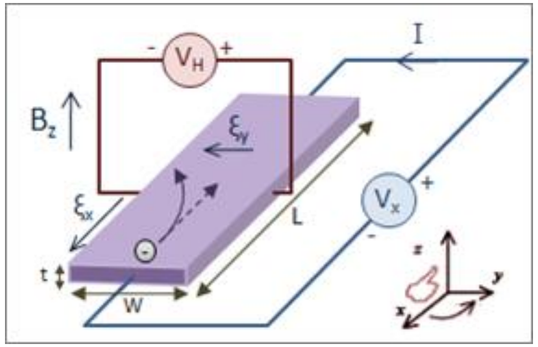
1956	W. Shockley, J. Bardeen e J. H. Brattain	"for their researches on semiconductors and their discovery of the transistor effect".

Outros Prêmios Nobel para a área de semicondutores

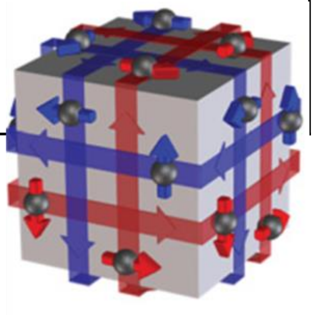
1973	L. Esaki e I. Giaever B. D. Josephson	"for their experimental discoveries regarding tunneling phenomena in semiconductors and superconductors, respectively"; "for his theoretical predictions of the properties of a supercurrent through a tunnel barrier, in particular those phenomena which are generally known as the Josephson effects".
2000	Z. I. Alferov e H. Kroemer J. S. Kilby	"for developing semiconductor heterostructures used in high-speed- and opto-electronics" "for his part in the invention of the integrated circuit"
2014	I. Akasaki, H. Amano e S. Nakamura	“for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources”

Életrons em sólidos e sua dinâmica

Efeito Hall

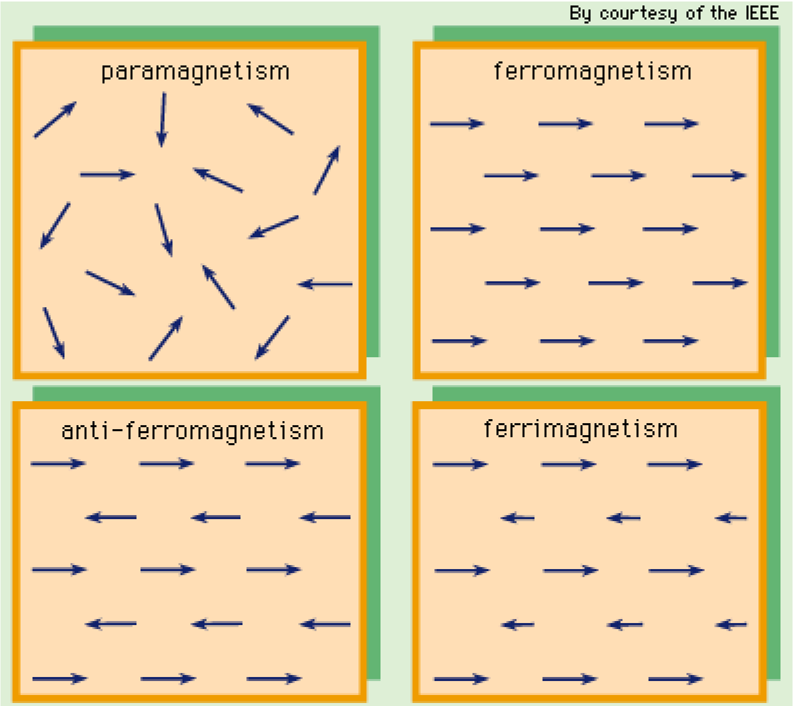


1985	K. Von Klitzing	"for the discovery of the quantized Hall effect".
1998	R. B. Laughlin, H. L. Störmer e D. C. Tsui	"for their discovery of a new form of quantum fluid with fractionally charged excitations.“
2016	David J. Thouless, F. Duncan M. Haldane e J. Michael Kosterlitz	“for theoretical discoveries of topological phase transitions and topological phases of matter”

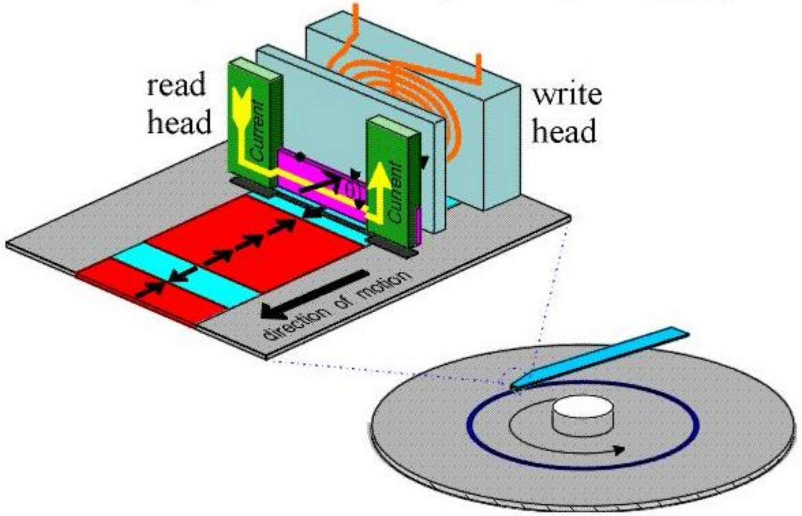


Magnetismo

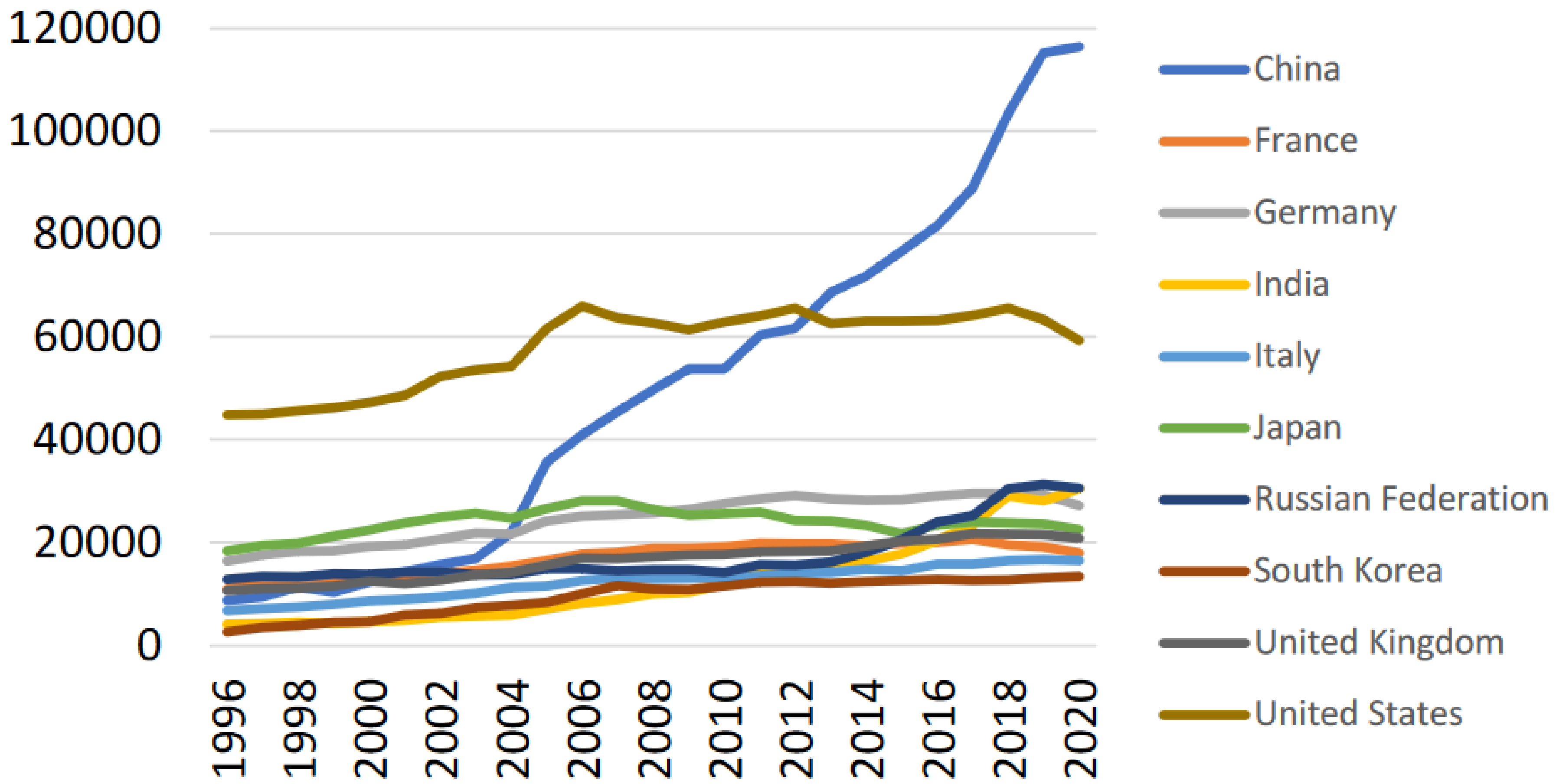
1970	L. E. F Néel	"for fundamental work and discoveries concerning antiferromagnetism and ferrimagnetism which have led to important applications in solid state physics".
1977	P. W. Anderson, N. F. Mott e J. H. Van Vleck	"for their fundamental theoretical investigations of the electronic structure of magnetic and disordered systems".
2007	A. Fert e P. Grünberg	"for the discovery of Giant Magnetoresistance"



Magnetismo e nanotecnologia

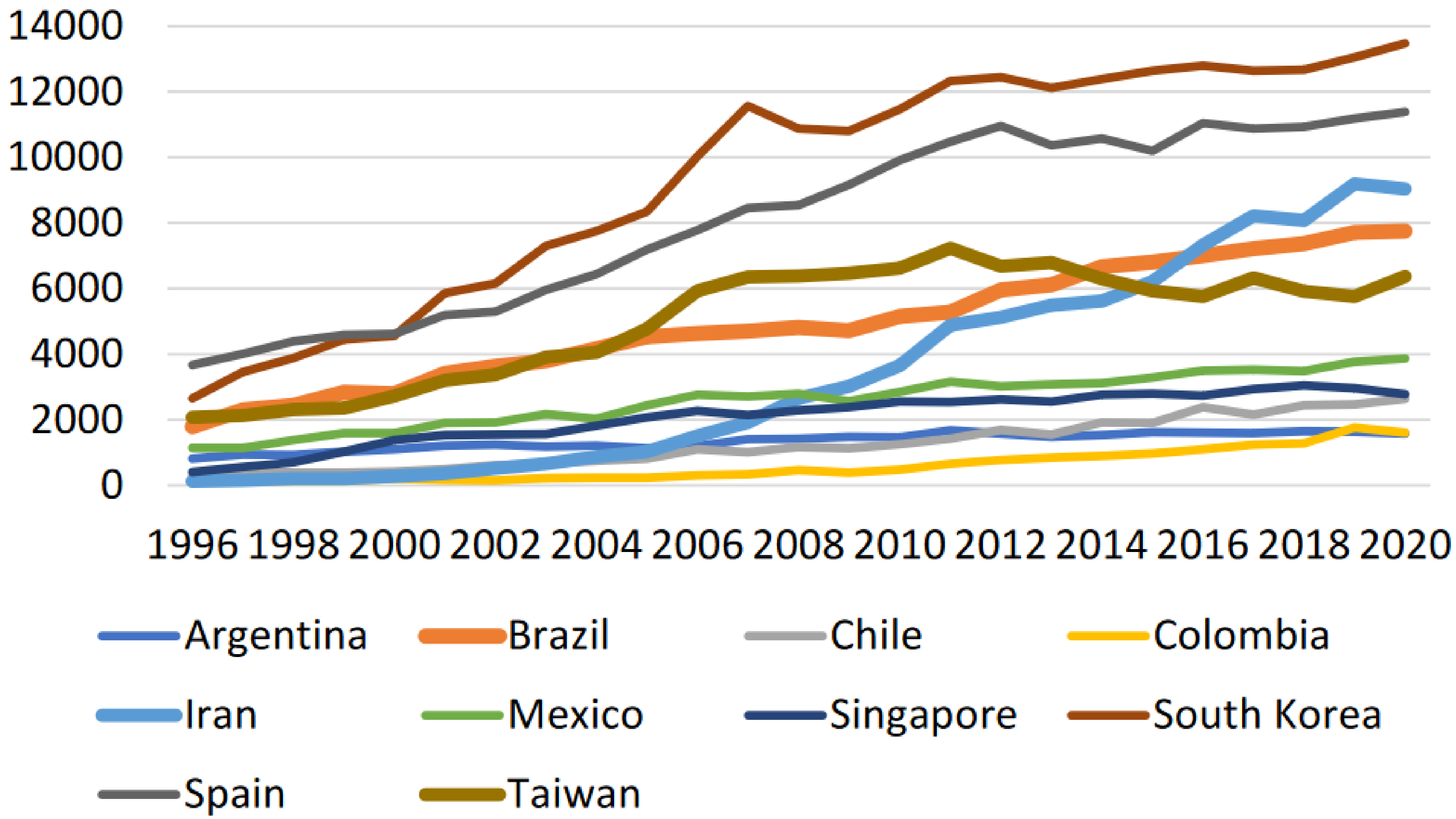


A FMC no mundo



Produção científica em física e astronomia

A FMC no mundo



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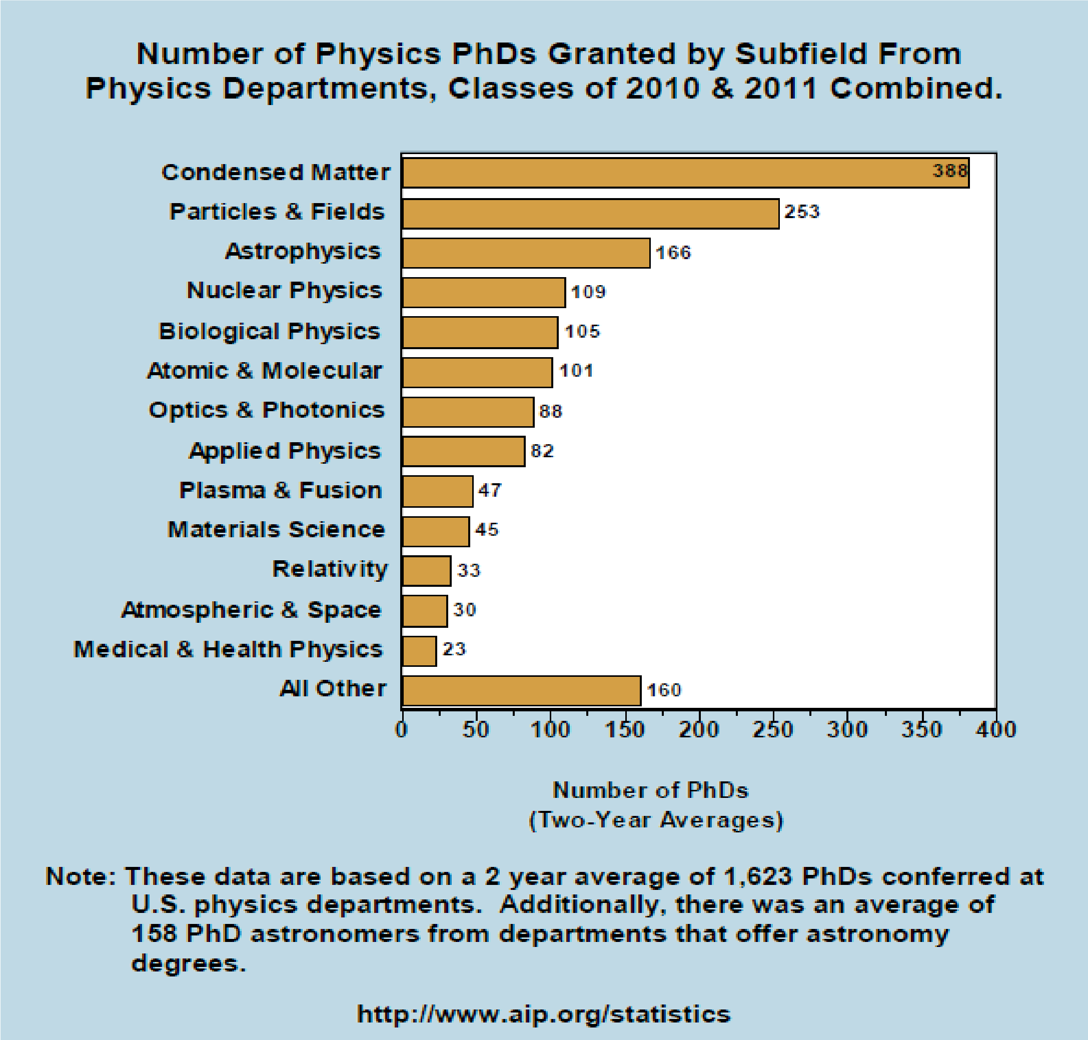
Number of Physics PhDs Granted by Subfield From Physics Departments, Classes of 2010 & 2011 Combined.

Note: These data are based on a 2 year average of 1,623 PhDs conferred at U.S. physics departments. Additionally, there was an average of 158 PhD astronomers from departments that offer astronomy degrees.

http://www.aip.org/statistics

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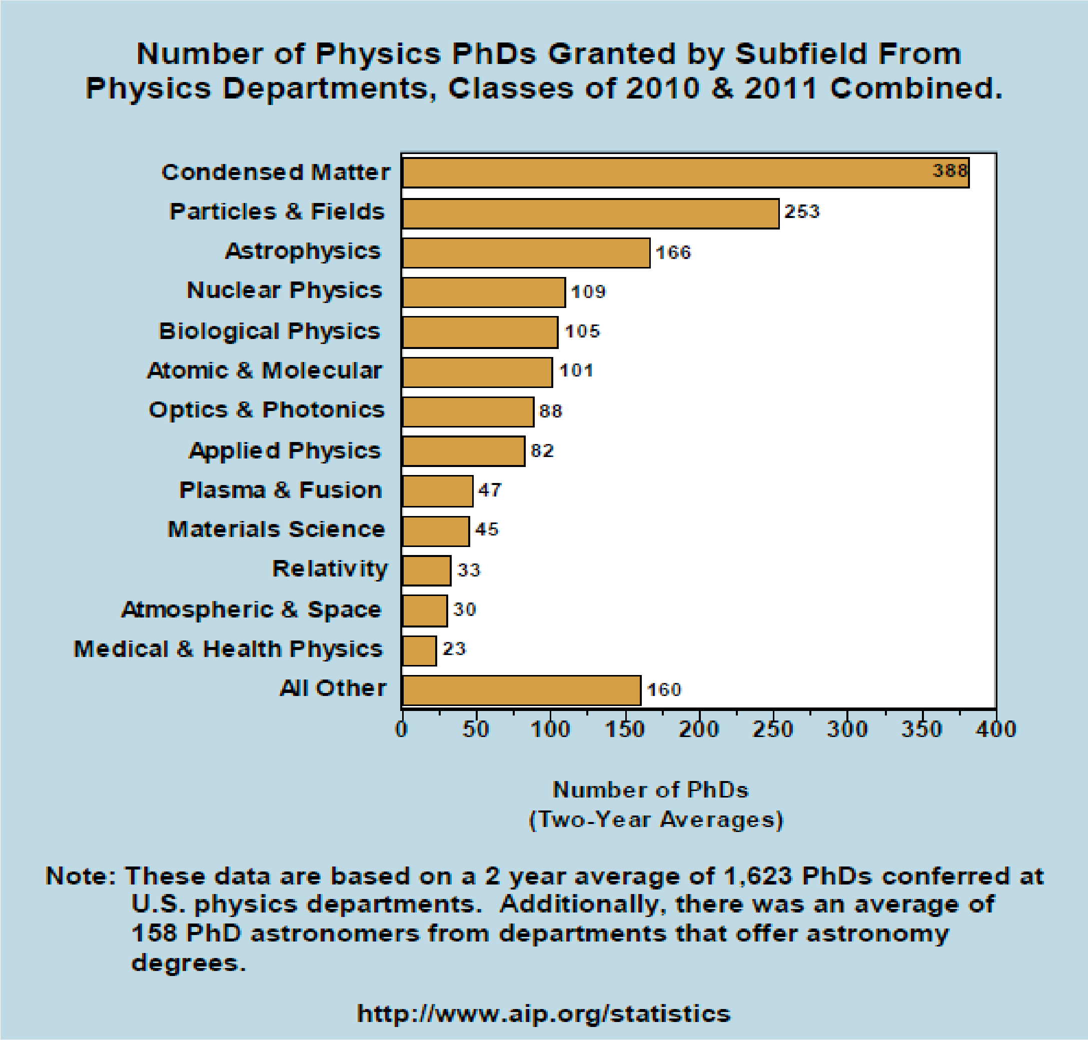

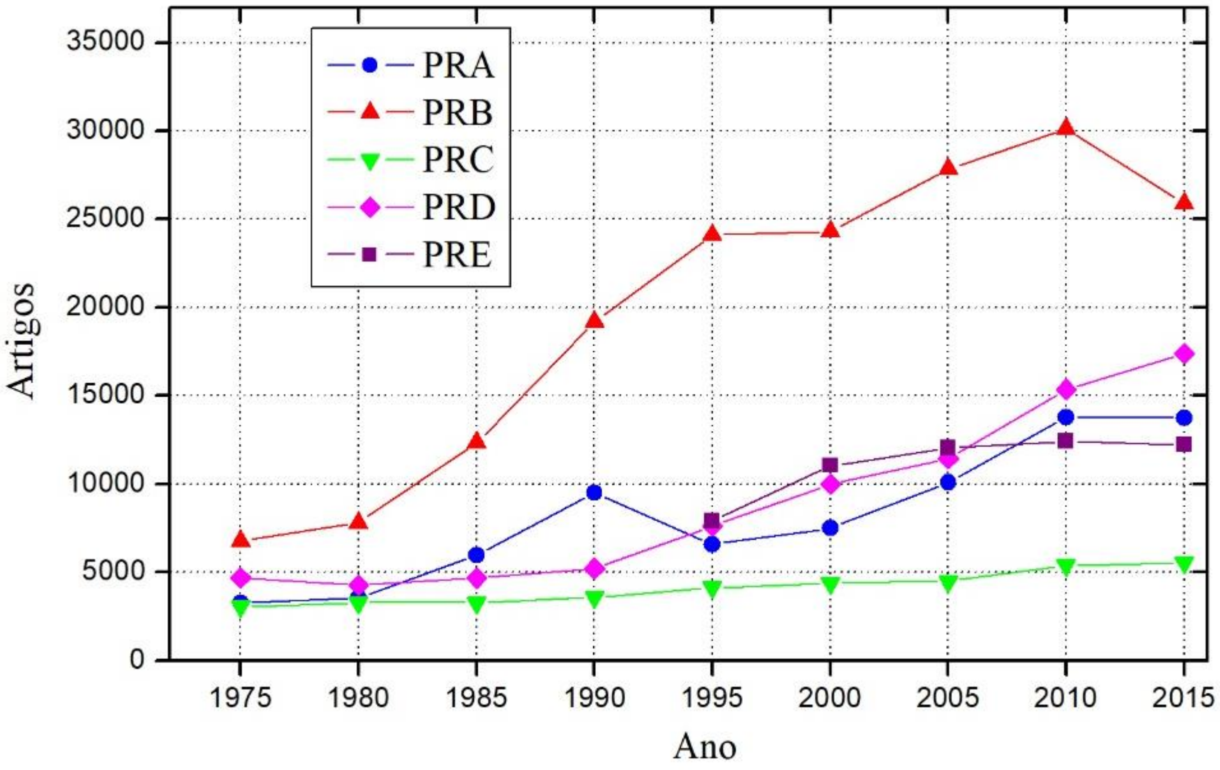

Número de artigos publicados por período de 5 anos em
PRA (*Atomic, Molecular and Optical Physics*),
PRB (*Condensed Matter and Materials Physics*),
PRC (*Nuclear Physics*),
PRD (*Particles, Fields, Gravitation and Cosmology*)
PRE (*Statistical, Nonlinear and Soft Matter Physics*).

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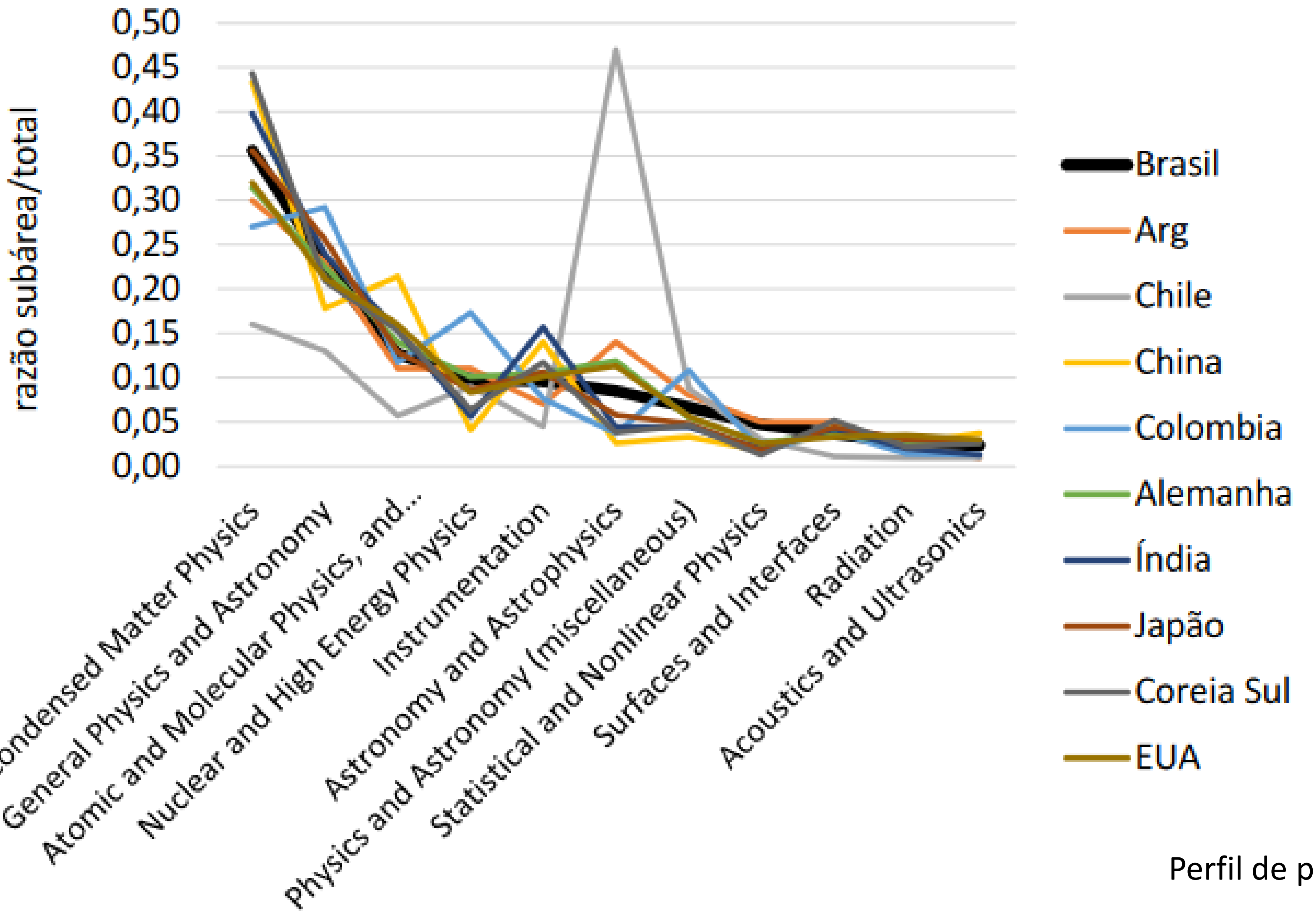

Perfil de pesquisa dos países

A FMC no Brasil

Área	Número de Associados	Porcentagem
Física Atômica e Molecular	618	7,3%
Física Biológica	489	5,8%
Física da Matéria Condensada e de Materiais	2184	25,7%
Física de Partículas e Campos	954	11,2%
Física de Plasmas	191	2,2%
Física Estatística e Computacional	978	11,5%
Física Matemática	160	1,9%
Física Médica	414	4,9%
Física na Empresa	73	0,9%
Física Nuclear e Aplicações	567	6,7%
Ótica e Fotônica	629	7,4%
Pesquisa em Ensino de Física	1240	14,6%

Associados da SBF por áreas. (2019)

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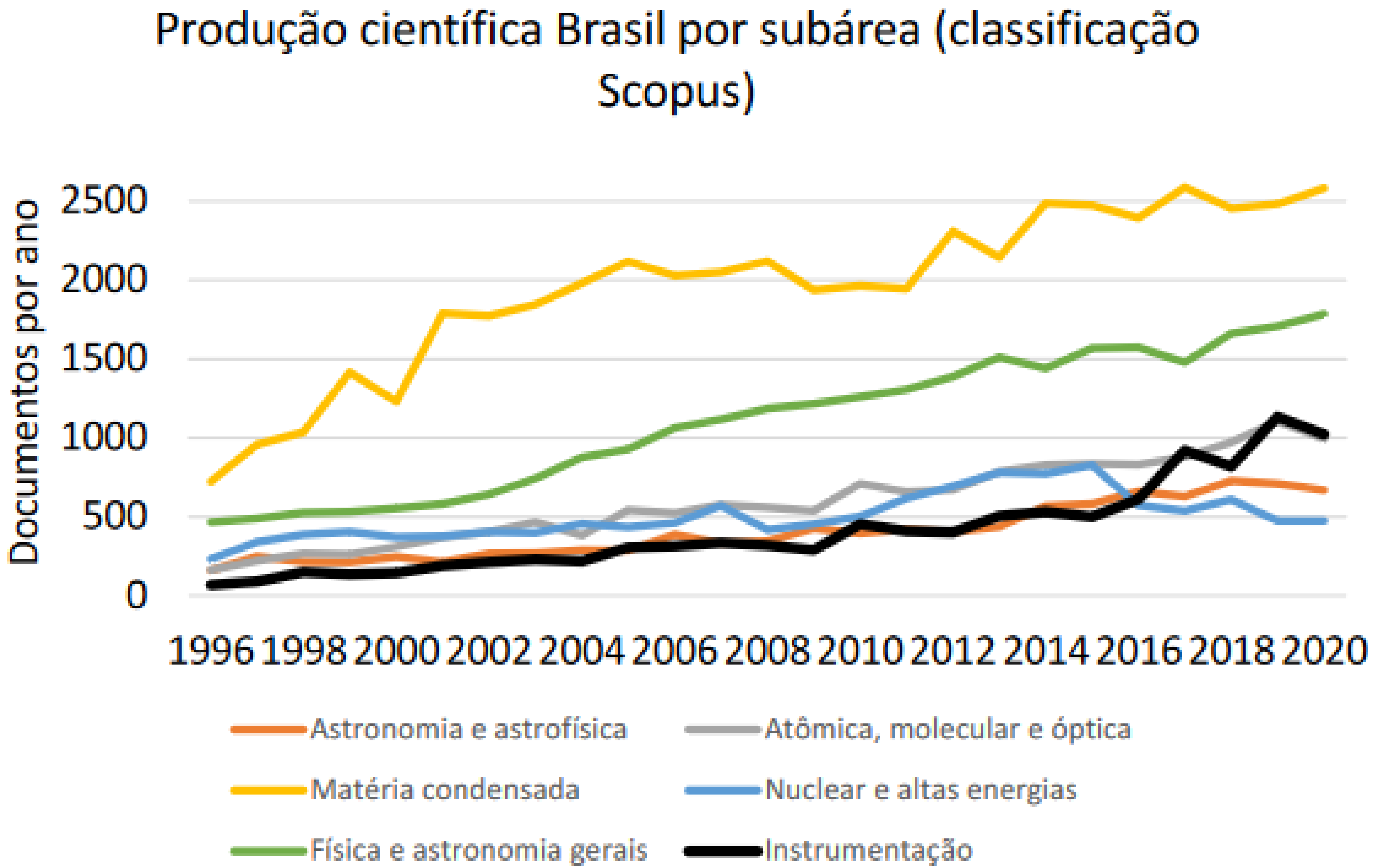

Produção científica Brasil por subárea (classificação Scopus)

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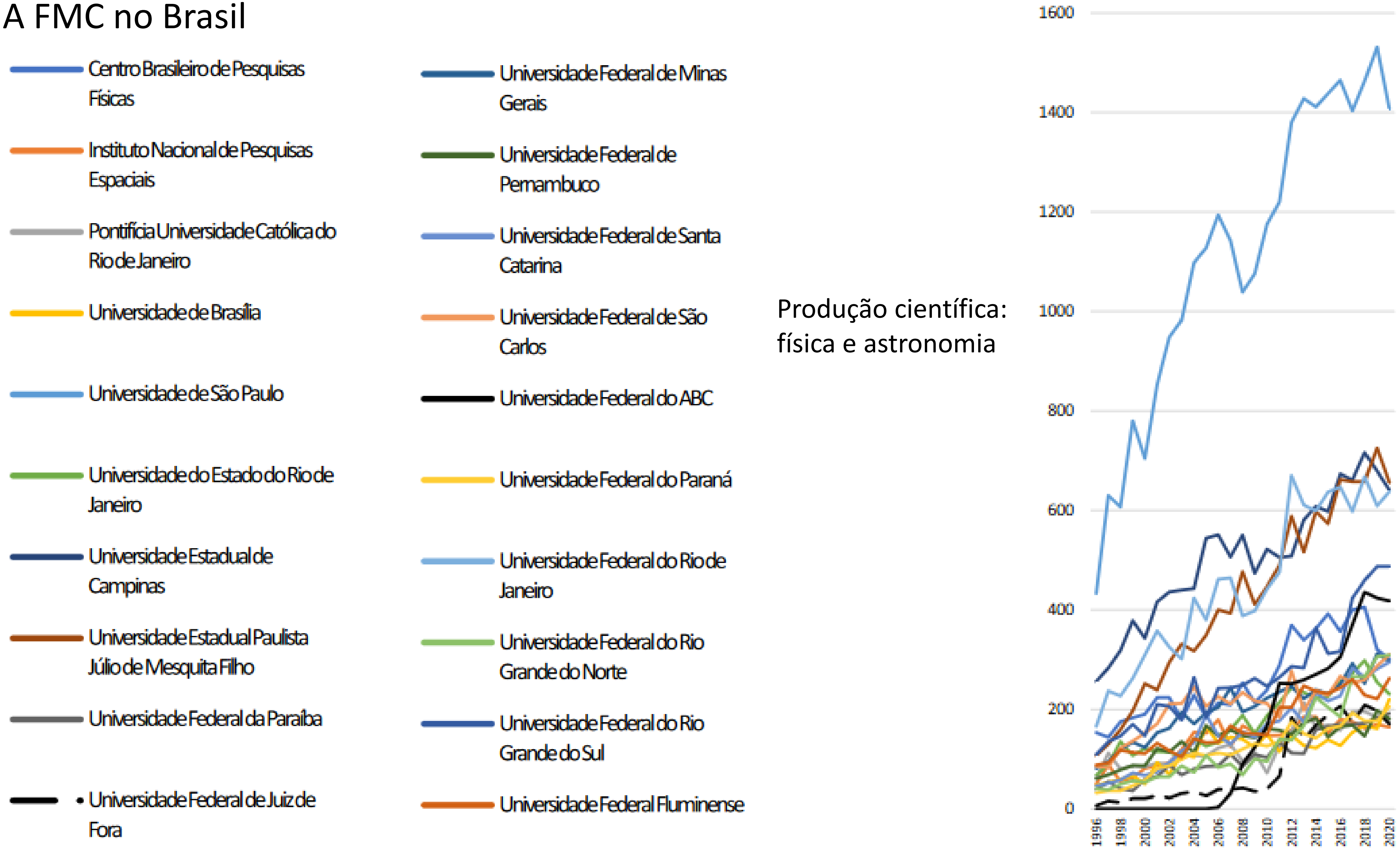

Produção científica: física e astronomia