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Is fundamental physics really fundamental?

Mikhail Katsnelson

Seminar series “debating theoretical physics”

12 February 2026

erc Synergy Grant

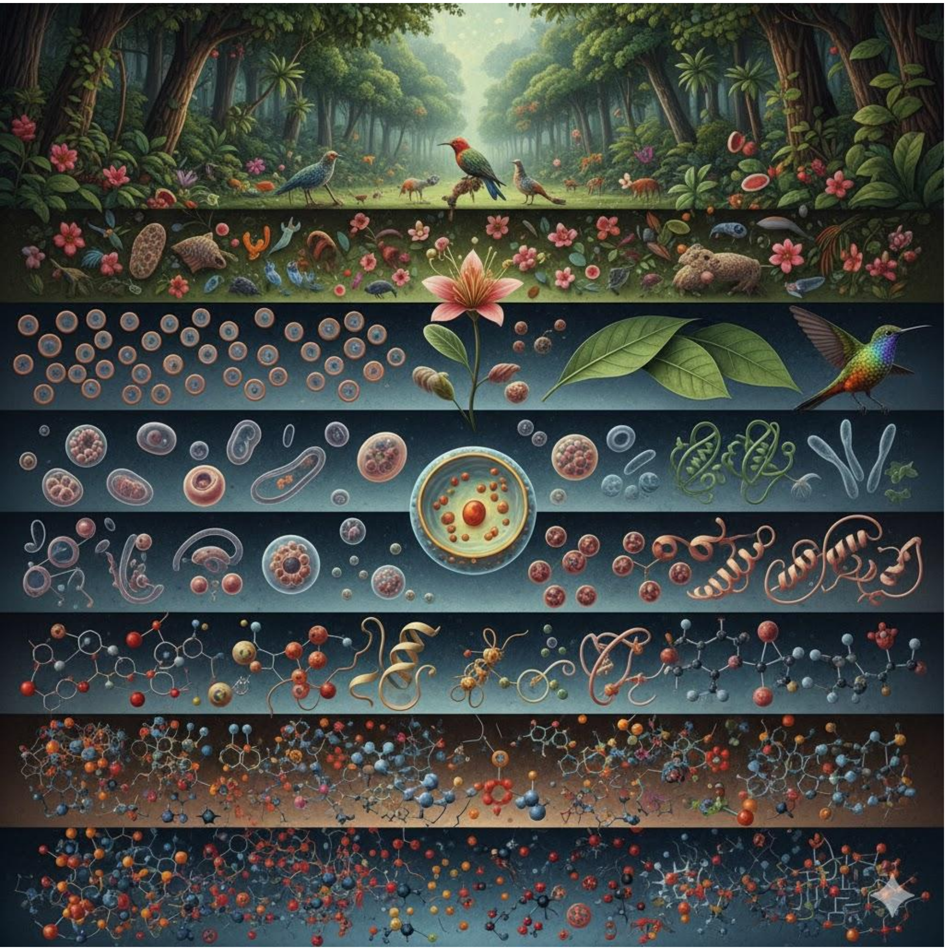
Wallenberg Initiative Materials Science for Sustainability

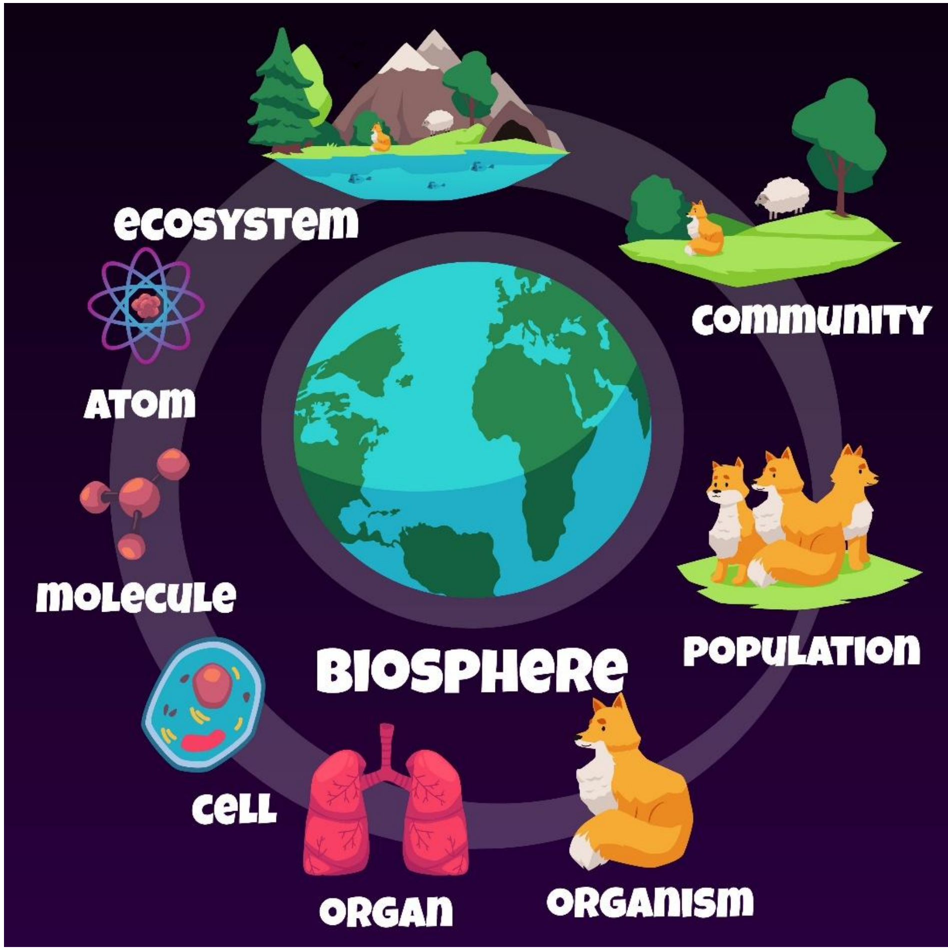
A philosophical statement

Knowledge begins, so to speak, in the middle, and leads into the unknown - both when moving upward, and when there is a downward movement. Our goal is to gradually dissipate the darkness in both directions, and the absolute foundation - this huge elephant carrying on his mighty back the tower of truth - it exists only in a fairy tales (Hermann Weyl)

The world is hierarchical

In biology:





Each next level of organization
Is essentially different from the
Previous one

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The world is hierarchical II

But also in physics, e.g., in magnetism: Electronic structure → Effective spin models → Atomistic spin simulations → LLG equations and micromagnetism

REVIEWS OF MODERN PHYSICS, VOLUME 95, JULY–SEPTEMBER 2023

Quantitative theory of magnetic interactions in solids

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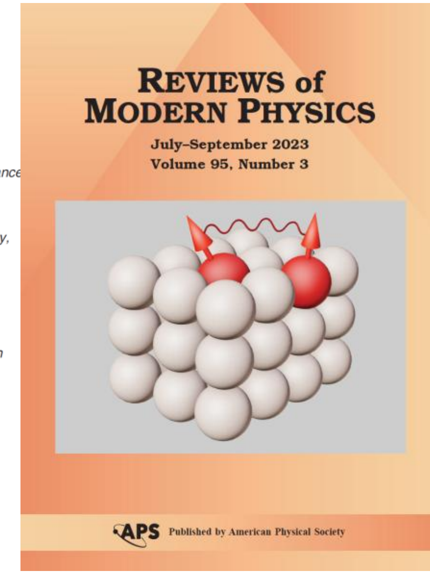
(published 11 September 2023)

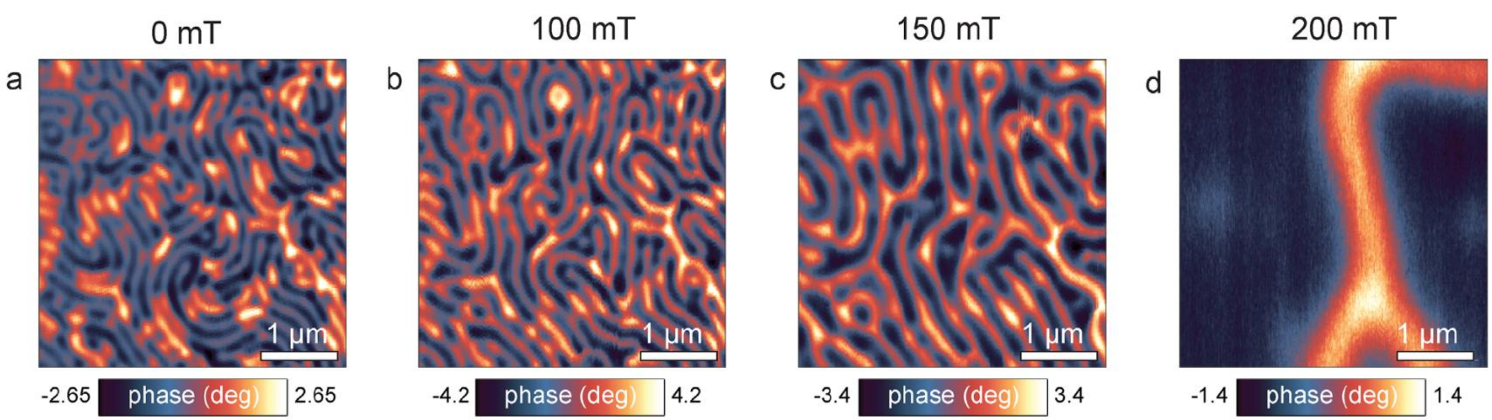


Correlations in Magnetic Sub-Domains as an Unconventional Phase Diagram for van der Waals Ferromagnets

Sergey Y. Grebenchuk, Magdalena Grzeszczyk, Zhaolong Chen, Makars Šiškins, Vladislav Borisov, Manuel Pereiro, Mikhail I. Katsnelson, Olle Eriksson, Kostya S. Novoselov, and Maciej Koperski**

Adv. Sci. **2025**, *12*, 2500562

From ab initio calculated magnetic interactions to simulations of complicated magnetic domains in $CrBr_3$

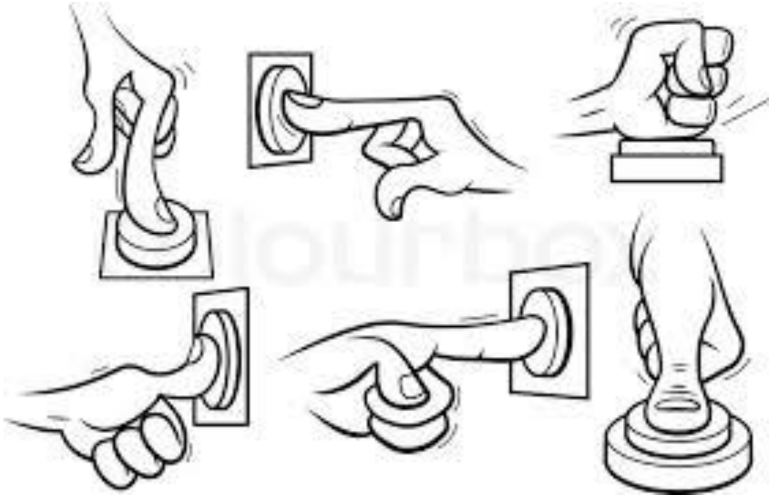


Two ways of thinking

I. Reductionism ("microscopic" approach)

Everything is from water/fire/earth/gauge fields/quantum space-time foam/strings... and the rest is your problem

II. Phenomenology: operating with "black boxes"



Microscopic vs phenomenological approaches

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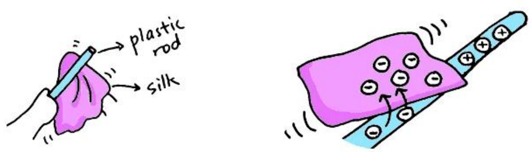
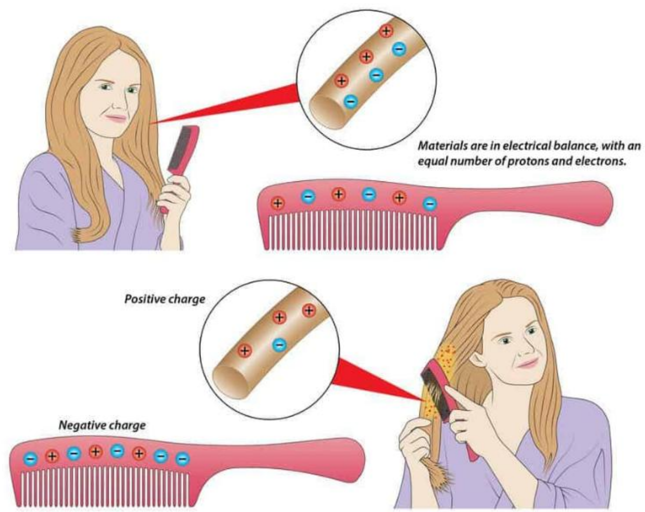
A very strong argument in favor of reductionism

The laws of "the world around us" are usually much more complicated than the worlds at microlevel





Example: electrification by friction – historically and pedagogically the first electromagnetic phenomena – we still do not have complete understanding!

Maxwell equations for vacuum are much simpler!

$$
\begin{aligned}
\nabla \cdot \mathbf{E} &= \frac{\rho}{\varepsilon_0} \\
\nabla \cdot \mathbf{B} &= 0 \\
\nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\
\nabla \times \mathbf{B} &= \mu_0 \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)
\end{aligned}
$$

What does it mean for condensed matter physics and materials science?

Everything follows from quantum mechanics
plus electrodynamics; QED is enough to explain
all properties of matter around us

$$\begin{aligned} \gamma^{\alpha}(\partial_{\alpha} - ieA_{\alpha})\psi + im\psi &= 0 \quad \text{where} \quad \alpha = 0, \ldots, 3 \\ F_{\alpha\beta} &= A_{\beta,\alpha} - A_{\alpha,\beta} \\ \partial^{\alpha} F_{\alpha\beta} &= -4\pi e j_{\beta} \\ \text{where} \quad j_{\alpha} &= \overline{\psi}\gamma_{\alpha}\psi. \end{aligned}$$

That is all. Please tell me why iridium is brittle and platinum is ductile, copper is red and silver is white, iron is ferromagnetic and vanadium is not... Not talking on biochemistry and biophysics!

Does it help?

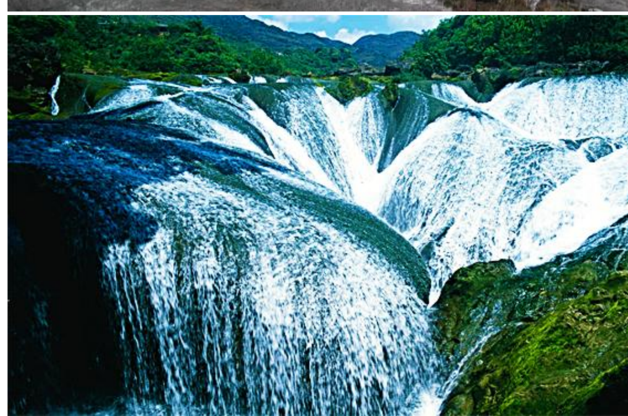
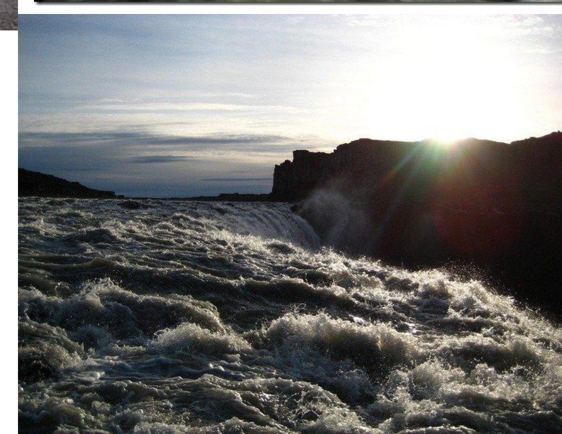
$$\nabla \cdot u = 0$$

$$\frac{\partial u}{\partial t} + u \cdot \nabla u = f + \mu \nabla^2 u - \nabla p$$

Navier-Stocks equations:
Turbulence is here!
Can you explain this?

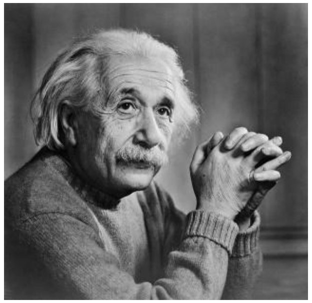




Is fundamental physics fundamental?

Classical thermodynamics is the only physical theory of universal content which I am convinced will never be overthrown, within the framework of applicability of its basic concepts (A. Einstein)



The laws describing our level of reality are essentially independent on the background laws. I wish our colleagues from *true* theory (strings, quantum gravity, etc....) all kind of success but either they will modify electrodynamics and quantum mechanics at atomic scale (and then they will be wrong) or they will not (and then I do not care). Our way is *down*

But how can we be sure that we are right?!

Why phenomenology is possible?

The simplest example: Newtonian classical mechanics

$$m_i \frac{d^2\vec{r}_i}{dt^2} = \vec{F}_i^{ext} + \sum_{j \neq i} \vec{F}_{ij}$$

$$\vec{F}_{ij} = -\vec{F}_{ji}$$

$$\vec{R} = \frac{\sum_i m_i \vec{r}_i}{\sum_i m_i}$$

$$M = \sum_i m_i$$

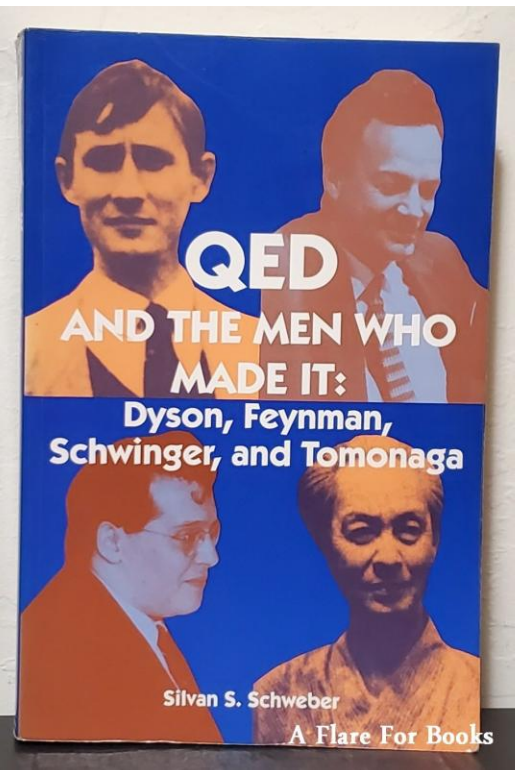
$$M \frac{d^2\vec{R}}{dt^2} = \vec{F}_{total}^{ext}$$

Thanks to third Newton's law, we do not need to know interactions between particles to determine the motion of inertia center

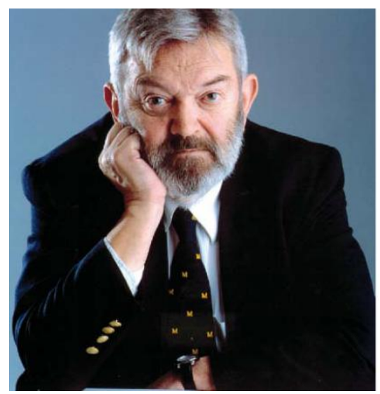
A bit deeper example: Renormalizability

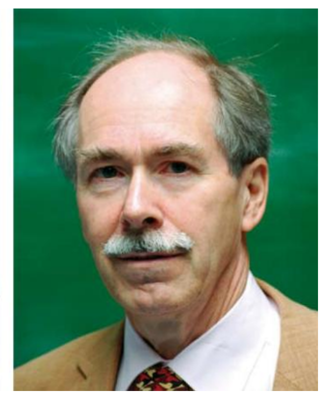
In quantum field theory there are "ultraviolet divergences", that is, all physical quantities are divergent due to large energy-momentum contribution

However, in QED this is not the case, actually: all high-energy processes can be put in effective parameters (e.g. electron mass and charge), and after that one can forget on what happens in ultraviolet (Tomonaga, Schwinger, Feynman, Dyson) - renormalizability



Weinberg-Salam model is also renormalizable (t'Hooft and Veldman)





Belief: fundamental physical theories should be renormalizable – but why?

Fundamental principles of evolution

Toward a theory of evolution as multilevel learning

PNAS 2022 Vol. 119 No. 6 e2120037119

Vitaly Vanchurin[a,b,1], Yuri I. Wolf[a], Mikhail I. Katsnelson[c], and Eugene V. Koonin[a,1]

What are the requirements for a universe to be observable? The possibility to make meaningful observations implies a degree of order and complexity in the observed universe emerging from evolutionary processes, and such evolvability itself seems to be predicated on several fundamental principles. It has to be emphasized that "observation" and "learning" here by no means imply "mind" or "consciousness" but a far more basic requirement. To learn and survive in an environment, a system (or observer) must predict, with some minimal but sufficient degree of accuracy, the response of that environment to various actions and to be able to choose such actions that are compatible with the observer's continued existence in that environment. In this sense, any life-form is an observer, and so are even inanimate systems endowed with the ability of feedback reaction. In this most general sense, observation is a prerequisite for evolution. We first formulate the basic principles underlying observability and evolvability and then, give the pertinent comments and explanations.

P1. Loss function. In any evolving system, there exists a loss function of time-dependent variables that is minimized during evolution.

P2. Hierarchy of scales. Evolving systems encompass multiple dynamical variables that change on different temporal scales (with different characteristic frequencies).

P3. Frequency gaps. Dynamical variables are split among distinct levels of organization separated by sufficiently wide frequency gaps.

P4. Renormalizability. Across the entire range of organization of evolving systems, a statistical description of faster-changing (higher-frequency) variables is feasible through the slower-changing (lower-frequency) variables.

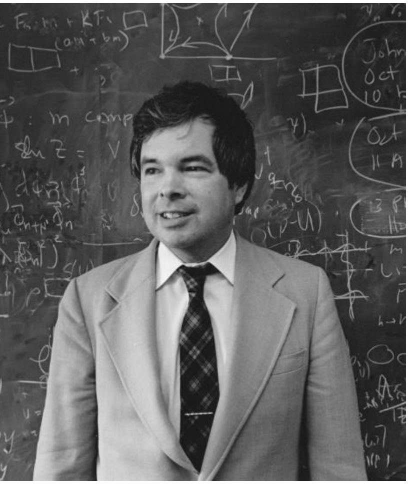
P5. Extension. Evolving systems have the capacity to recruit additional variables that can be utilized to sustain the system and the ability to exclude variables that could destabilize the system.

P6. Replication. In evolving systems, replication and elimination of the corresponding information-processing units (IPUs) can take place on every level of organization.

P7. Information flow. In evolving systems, slower-changing levels absorb information from faster-changing levels during learning and pass information down to the faster levels for prediction of the state of the environment and the system itself.

Generalized anthropic principle: in the world where fundamental physics is not renormalizable fox cannot catch hare and hare cannot escape from fox without studying first quantum gravity

Renormalizability in condensed matter and emergent phenomena



Kenneth Wilson

Very successful applications of idea of renormalization to critical phenomena and to "Kondo problem"

The concept of "universality classes": microscopically different ("ultraviolet" different) systems behave in the same way at large scale (at "infrared")

Emergent phenomena

4 August 1972, Volume 177, Number 4047 SCIENCE

More Is Different

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

P. W. Anderson

The reductionist hypothesis may still be a topic for controversy among philosophers, but among the great majority of active scientists I think it is accepted without question. The workings of our minds and bodies, and of all the animate or inanimate matter of which we have any detailed knowledge, are assumed to be controlled by the same set of fundamental laws, which except under certain extreme conditions we feel we know pretty well.

It seems inevitable to go on uncritically to what appears at first sight to be an obvious corollary of reductionism: that if everything obeys the same fundamental laws, then the only scientists who are studying anything really fundamental are those who are working on those laws. In practice, that amounts to some astrophysicists, some elementary particle physicists, some logicians and other mathematicians, and few others. This point of view, which it is the main purpose of this article to oppose, is expressed in a rather well-known passage by Weisskopf (1):

Looking at the development of science in the Twentieth Century one can distinguish two trends, which I will call "intensive" and "extensive" research, lacking a better terminology. In short: intensive research goes for the fundamental laws, extensive research goes for the explanation of phenomena in terms of known fundamental laws. As always, distinctions of this kind are not unambiguous, but they are clear in most cases. Solid state physics, plasma physics, and perhaps also biology are extensive. High energy physics and a good part of nuclear physics are intensive. There is always much less intensive research going on than extensive. Once new fundamental laws are discovered, a large and ever increasing activity begins in order to apply the discoveries to hitherto unexplained phenomena. Thus, there are two dimensions to basic research. The frontier of science extends all along a long line from the newest and most modern intensive research, over the extensive research recently spawned by the intensive research of yesterday, to the broad and well developed web of extensive research activities based on intensive research of past decades.

The effectiveness of this message may be indicated by the fact that I heard it quoted recently by a leader in the field of materials science, who urged the participants at a meeting dedicated to "fundamental problems in condensed matter physics" to accept that there were few or no such problems and that nothing was left but extensive science, which he seemed to equate with device engineering.

The main fallacy in this kind of thinking is that the reductionist hypothesis does not by any means imply a "constructionist" one: The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe. In fact, the more the elementary particle physicists tell us about the nature of the fundamental laws, the less relevance they seem to have to the very real problems of the rest of science, much less to those of society.

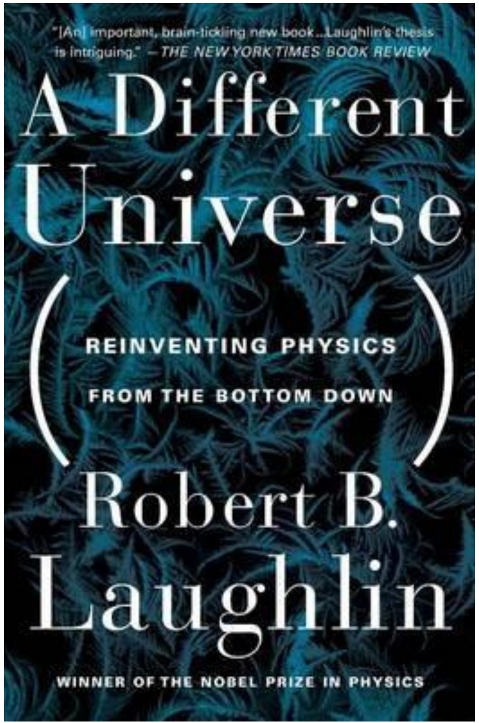
The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity. The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other. That is, it seems to me that one may array the sciences roughly linearly in a hierarchy, according to the idea: The elementary entities of science X obey the laws of science Y.

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.

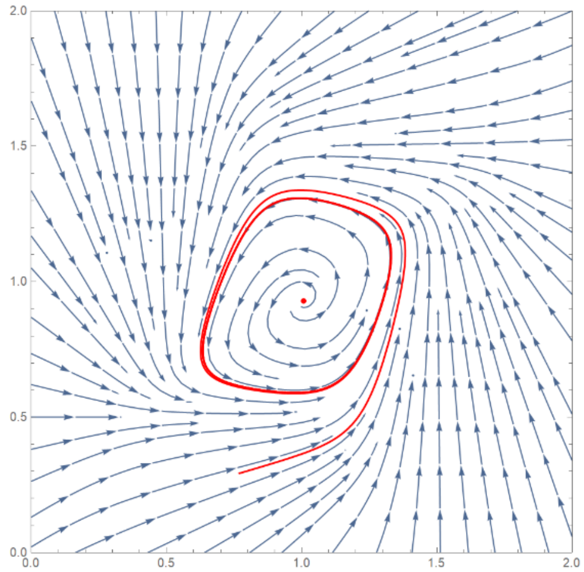
In my own field of many-body physics, we are, perhaps, closer to our fundamental, intensive underpinnings than in any other science in which nontrivial complexities occur, and as a result we have begun to formulate a general theory of just how this shift from quantitative to qualitative differentiation takes place. This formulation, called the theory of "broken symmetry," may be of help in making more generally clear the breakdown of the constructionist converse of reductionism. I will give an elementary and incomplete explanation of these ideas, and then go on to some more general speculative comments about analogies at

The author is a member of the technical staff of the Bell Telephone Laboratories, Murray Hill, New Jersey 07974, and visiting professor of theoretical physics at Cavendish Laboratory, Cambridge, England. This article is an expanded version of a Regents' Lecture given in 1967 at the University of California, La Jolla.

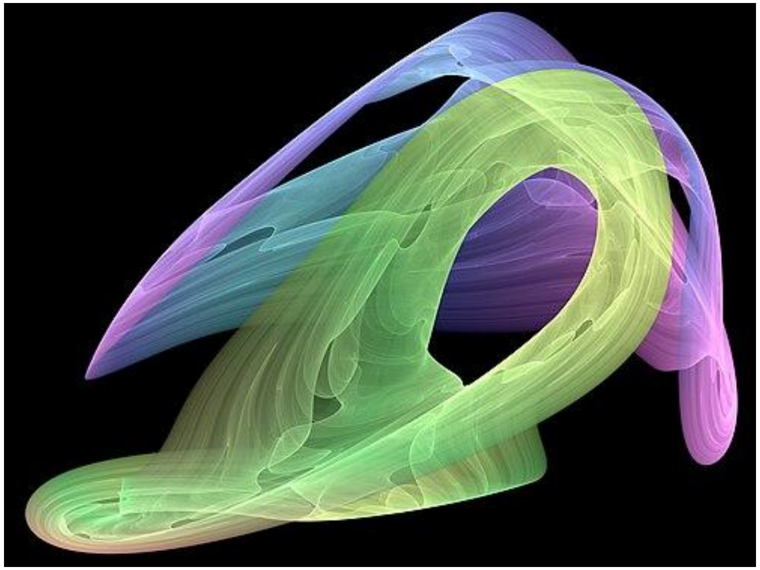


Systems and elements

Much earlier: the concept of equifinality (e.g. in "general system theory" of L. von Bertalanffy) and attractor (in theory of classical dynamical systems)



Limit cycle (self-oscillations)



Strange attractor (chaos)

Universality classes are related to attractors of renormalizaton flow (in the simplest case: just fixed points)

Logical inference approach – a machine to produce phenomenological theories

Quantum theory as the most robust description of reproducible experiments

Hans De Raedt[a], Mikhail I. Katsnelson[b], Kristel Michielsen[c,d,*]

Annals of Physics 347 (2014) 45–73

Quantum theory as a description of robust experiments: Derivation of the Pauli equation

Hans De Raedt[a], Mikhail I. Katsnelson[b], Hylke C. Donker[b], Kristel Michielsen[c,d,*]

Annals of Physics 359 (2015) 166–186

Logical inference approach to relativistic quantum mechanics: Derivation of the Klein–Gordon equation

H.C. Donker[a,*], M.I. Katsnelson[a], H. De Raedt[b], K. Michielsen[c]

Annals of Physics 372 (2016) 74–82

Hans De Raedt, RUG

Kristel Michielsen, Julich

and me

(a continuation)

Logical inference derivation of the quantum theoretical description of Stern–Gerlach and Einstein–Podolsky–Rosen–Bohm experiments

Annals of Physics 396 (2018) 96–118

Hans De Raedt [a], Mikhail I. Katsnelson [b], Kristel Michielsen [c,d,*]

Quantum theory as plausible reasoning applied to data obtained by robust experiments

PHILOSOPHICAL TRANSACTIONS A

H. De Raedt[1], M. I. Katsnelson[2] and K. Michielsen[3,4]

Cite this article: De Raedt H, Katsnelson MI, Michielsen K. 2016 Quantum theory as plausible reasoning applied to data obtained by robust experiments. *Phil. Trans. R. Soc. A* **374**: 20150233.

Einstein–Podolsky–Rosen–Bohm experiments: A discrete data driven approach

Annals of Physics 453 (2023) 169314

Hans De Raedt [a,b,*], Mikhail I. Katsnelson [c], Manpreet S. Jattana [a,d], Vrinda Mehta [a,e], Madita Willsch [a], Dennis Willsch [a], Kristel Michielsen [a,e], Fengping Jin [a]

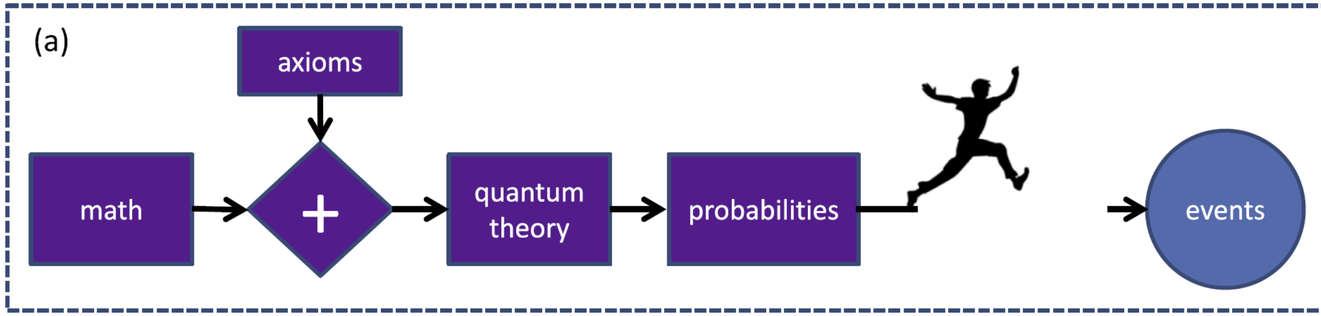
Can foreign exchange rates violate Bell inequalities?

Annals of Physics 469 (2024) 169742

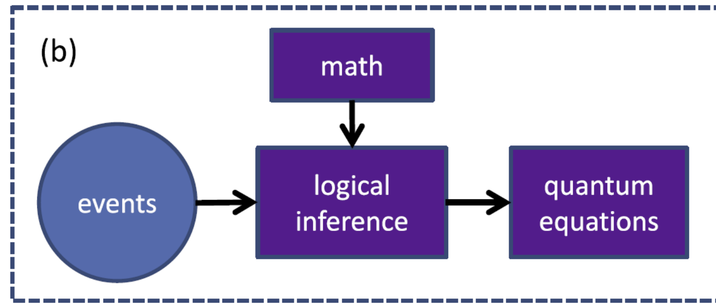
Hans De Raedt [a,*], Mikhail I. Katsnelson [b], Manpreet S. Jattana [c], Vrinda Mehta [a], Madita Willsch [a], Dennis Willsch [a], Kristel Michielsen [a,d], Fengping Jin [a]

Logical inference approach – a machine to produce phenomenological theories II

Traditional approach



LI approach



(1) Start with data sets produced by black boxes
(2) Require robustness of description (leads to Fischer entropy etc.)
(3) Add physical assumptions (symmetry requirements, correctness of classical mechanics at the average, etc.)

Nonrelativistc QM is not derived from relativistic QM in the limit $c \to \infty$,
They are derived independently via different choice of requirements in (3)

Back effect of “physics around us” on “fundamental” physics

The origin of fundamental constants: how we define electron charge e and Planck constant h?

Google

metrology of h and e now

- **Defining Units:** Instead of being measured, these constants are now used to define the base SI units:
  - The **kilogram** is defined by the fixed numerical value of the Planck constant (h).
  - The **ampere** (unit of electric current) is defined in terms of the fixed elementary charge (e).
- **Focus Shift:** The role of metrology has shifted from precisely measuring these constants to accurately *realizing* the units (like the kilogram or ampere) in practice, using methods tied to these fixed values.

Quantum Metrology Triangle

A core aspect of this new system for electrical metrology is the **quantum metrology triangle**. This concept links the values of h and e through three quantum effects:

1. **Josephson effect:** Relates voltage to frequency via the Josephson constant, $K_J = 2e/h$.
2. **Quantum Hall effect:** Relates resistance to the von Klitzing constant, $R_K = h/e^2$.
3. **Single-electron tunneling (SET) effect:** (Historically relevant, though the first two are more central to current practical standards) allows for the direct measurement of e.

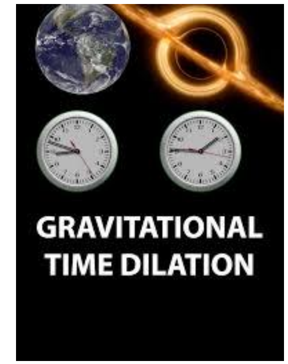
The triangle is now used as a **consistency test** of quantum theory, allowing scientists to cross-verify measurements of current, voltage, and resistance using any two of the effects to determine the third. Any discrepancy would indicate a problem with the underlying physical principles or experimental equipment calibration.

The most accurate data are from Josephson and quantum Hall effects, both are solid state

Back effect of "physics around us" on "fundamental" physics II

General relativity theory is fundamental physics

First observation in Earth condition: Pound and Rebka experiment, long before discovery of black holes etc.



VOLUME 3, NUMBER 9 PHYSICAL REVIEW LETTERS NOVEMBER 1, 1959

the results of reference 1 required by these considerations is easily made. The matrix element appropriate to a collision in which the (K, p) system in a state $\psi_{n,l}$ is changed to a state $\psi_{n,l-1}$, which can be the products of the $K-p$ interaction, is

$$\langle U_{L+1}^{*}\psi_{n,l-1}^{*}|H|U_2\psi_{n,l}\rangle,$$

where the U are the plane wave functions representing the relative (K, p) atom and proton coordinates and H, the Hamiltonian, will be equal to $(e^2/|R-r_p|)-(e^2/|R-r_k|)$, where R is the vector coordinate of the colliding proton and r_p and r_k are the coordinates of the proton and K meson in the atom. For $|R|>|r|$ a multipole expansion of H can be made. Setting $R=a_0$ as in reference 1, the matrix element can be rewritten as

$$\langle V_{L+1}^{*}(a_0)|V_L(a_0)\rangle\langle\psi_{n,l-1}^{*}|H'|\psi_{n,l}\rangle,$$

where, with appropriate averaging of geometric factors, the second term is precisely that evaluated by Day et al. In the first factor V represents the radial part of the wave functions U, and the square of this term has a value of 1/5 for S to P transitions which are the most favorable. Changes of more than one unit of angular momentum are much more strongly forbidden. These corrections modify the conclusions of reference 1 concerning the $n=6$ state in the following way. The depopulation of the P level in any collision is essentially unaffected but the reshuffling of other states is much reduced and their direct depopulation is largely forbidden. This greatly reduces the transfer into the P level and the average atomic lifetime is considerably increased, enhancing the importance of radiative transitions. Calculations of the same kind as reported in reference 1 lead then to the result that about 20% of atoms in a $n=6$ state reach the $2P$ state instead of the 1.4% stated in reference 1.

The uncertainties involved in the estimates made in this note, and also in reference 1, are quite large, and the conclusions reached in these calculations are not presented with the intention of establishing that P-wave capture is large, or that the Stark effect is unimportant. But we believe that these results do indicate the necessity of a more detailed examination of the problem.

[1]Day, Snow, and Sucher, Phys. Rev. Letters 3, 61 (1959).

[2]L. B. Okun' and I. A. Pomeranchuk, J. Exptl. Theoret. Phys. U.S.S.R. 34, 997 (1958) [translation: Soviet Phys. JETP 34, 688 (1958)].

GRAVITATIONAL RED-SHIFT IN NUCLEAR RESONANCE

R. V. Pound and G. A. Rebka, Jr.
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts

(Received October 15, 1959)

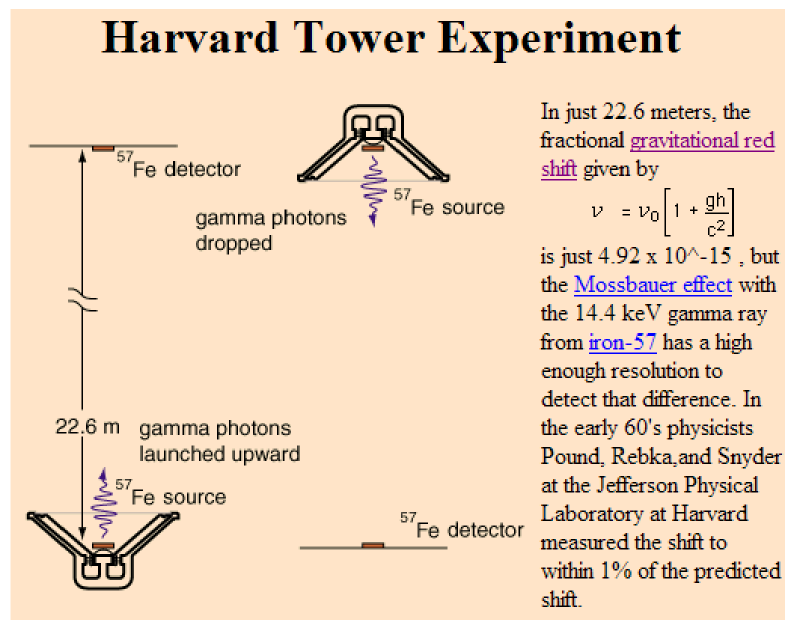
It is widely considered desirable to check experimentally the view that the frequencies of electromagnetic spectral lines are sensitive to the gravitational potential at the position of the emitting system. The several theories of relativity predict the frequency to be proportional to the gravitational potential. Experiments are proposed to observe the timekeeping of a "clock" based on an atomic or molecular transition, when held aloft in a rocket-launched satellite, relative to a similar one kept on the ground. The frequency ν_h and thus the timekeeping at height h is related to that at the earth's surface ν_0 according to

$$\Delta\nu_h=\nu_h-\nu_0=\nu_0 gh/c^2(1+h/R)$$
$$\approx\nu_0 h\times(1.09\times10^{-18}),$$

where R is the radius of the earth and h is the altitude measured in cm. Very high accuracy is required of the clocks even with the altitudes available with artificial satellites. Although several ways of obtaining the necessary frequency stability look promising, it would be simpler if a way could be found to do the experiment between fixed terrestrial points. In particular, if an accuracy could be obtained allowing the measurement of the shift between points differing as little as one to ten kilometers in altitude, the experiment could be performed between a mountain and a valley, in a mineshaft, or in a borehole.

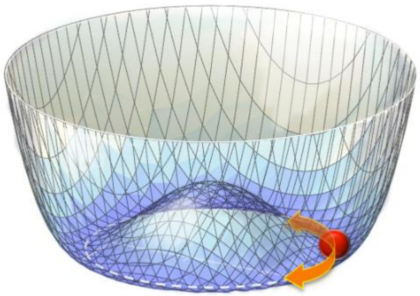
Recently Mössbauer has discovered[1] a new aspect of the emission and scattering of γ rays by nuclei in solids. A certain fraction f of γ rays of the nuclei of a solid are emitted without

They used Mössbauer effect, another solid-state phenomenon



Back effect of "physics around us" on "fundamental" physics III

Last not least: the concept of spontaneous symmetry breaking



First introduced by Landau in his theory of second-order phase transitions

Developed and discussed in detail in the context of superconductivity

Mathematically rigorously studied first by Bogoliubov ("quasi-averages", or anomalous averages)

Plays absolutely fundamental role in modern quantum field theory and high energy physics (Goldstone-Nambu bosons, Higgs boson, the basis of Weinberg-Salam model, the basis of Standard Model…)

Should physical theory be mathematically beautiful?

It is more important to have beauty in one's equations than to have them fit experiment
(P.A.M. Dirac)

REVIEWS OF MODERN PHYSICS, VOLUME 83, OCTOBER–DECEMBER 2011

Topological insulators and superconductors

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the Einstein-Dirac approach has been successful in searching for the fundamental laws of nature: logical reasoning and mathematical equations guided and predicted subsequent experimental discoveries. The success of theoretical predictions in the field of topological insulators shows that this powerful approach works equally well in condensed matter physics, inspiring many more examples to come.

Should physical theory be mathematically beautiful? II

You can get much further with a *kind word* and a *gun* than you can with a *kind word* alone
(Al Capone)

You can get much further with an insight from experiment and mathematics than you can with mathematics alone

My own experience do confirm this (graphene, Nd, …)

Graphene: Predicted and confirmed

Chiral tunnelling and the Klein paradox in graphene

M. I. KATSNELSON[1]*, K. S. NOVOSELOV[2] AND A. K. GEIM[2]*

nature physics | VOL 2 | SEPTEMBER 2006

nature physics LETTERS
PUBLISHED ONLINE: 1 FEBRUARY 2009 | DOI: 10.1038/NPHYS1198

Quantum interference and Klein tunnelling in graphene heterojunctions

Andrea F. Young and Philip Kim*

LETTERS nature physics
PUBLISHED ONLINE: 27 SEPTEMBER 2009 | DOI: 10.1038/NPHYS1420

Energy gaps and a zero-field quantum Hall effect in graphene by strain engineering

F. Guinea[1]*, M. I. Katsnelson[2] and A. K. Geim[3]*

Strain-Induced Pseudo–Magnetic Fields Greater Than 300 Tesla in Graphene Nanobubbles

N. Levy,[1,2]*† S. A. Burke,[1]*‡ K. L. Meaker,[1] M. Panlasigui,[1] A. Zettl,[1,2] F. Guinea,[3] A. H. Castro Neto,[4] M. F. Crommie[1,2]§

30 JULY 2010 VOL 329 SCIENCE

PRL 99, 236801 (2007) PHYSICAL REVIEW LETTERS week ending 7 DECEMBER 2007

Vacuum Polarization and Screening of Supercritical Impurities in Graphene

A. V. Shytov,[1] M. I. Katsnelson,[2] and L. S. Levitov[3]

PRL 99, 246802 (2007) PHYSICAL REVIEW LETTERS week ending 14 DECEMBER 2007

Atomic Collapse and Quasi–Rydberg States in Graphene

A. V. Shytov,[1] M. I. Katsnelson,[2] and L. S. Levitov[3]

Observing Atomic Collapse Resonances in Artificial Nuclei on Graphene

Yang Wang,[1,2]* Dillon Wong,[1,2]* Andrey V. Shytov,[3] Victor W. Brar,[1,2] Sangkook Choi,[1] Qiong Wu,[1,2] Hsin-Zon Tsai,[1] William Regan,[1,2] Alex Zettl,[1,2] Roland K. Kawakami,[5] Steven G. Louie,[1,2] Leonid S. Levitov,[4] Michael F. Crommie[1,2]†

10 MAY 2013 VOL 340 SCIENCE

Self-induced spin glass state in elemental Nd

PHYSICAL REVIEW B **93**, 054410 (2016)

Stripe glasses in ferromagnetic thin films

Alessandro Principi* and Mikhail I. Katsnelson

PHYSICAL REVIEW B **109**, 144414 (2024)

Frustrated magnets in the limit of infinite dimensions: Dynamics and disorder-free glass transition

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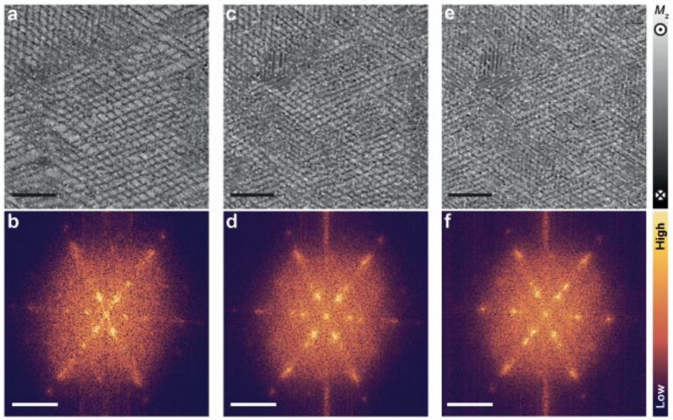
(Received 16 November 2023; accepted 27 March 2024; published 18 April 2024)

PRL **117**, 137201 (2016) PHYSICAL REVIEW LETTERS week ending 23 SEPTEMBER 2016

Self-Induced Glassiness and Pattern Formation in Spin Systems Subject to Long-Range Interactions

Alessandro Principi* and Mikhail I. Katsnelson



Self-induced spin glass state in elemental and crystalline neodymium

Umut Kamber, Anders Bergman, Andreas Eich, Diana Iuşan, Manuel Steinbrecher, Nadine Hauptmann, Lars Nordström, Mikhail I. Katsnelson, Daniel Wegner*, Olle Eriksson, Alexander A. Khajetoorians*

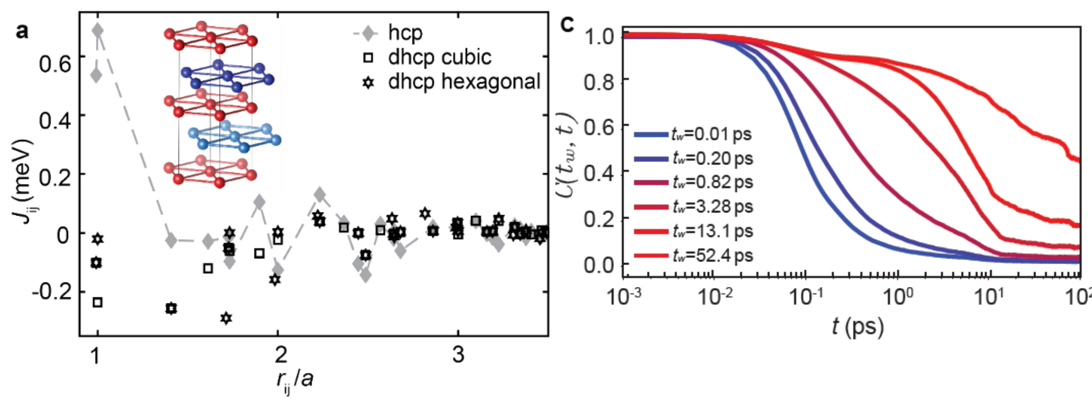
Science **368**, 966 (2020)

The most important observation: aging. At thermocycling (or cyling magnetic field) the magnetic state is not exactly reproduced

Thermally induced magnetic order from glassiness in elemental neodymium

Benjamin Verlhac[1], Lorena Niggli[1], Anders Bergman[2], Umut Kamber[1], Andrey Bagrov[1,2], Diana Iuşan[2], Lars Nordström[2], Mikhail I. Katsnelson[1], Daniel Wegner[1], Olle Eriksson[2,3] and Alexander A. Khajetoorians[1]✉

NATURE PHYSICS | VOL 18 | AUGUST 2022 | 905–911



Should physical theory be mathematically beautiful? (continuation)

What about fundamental physics itself (e.g. high energy physics)?

$$\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$
$$M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) -$$
$$igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu -$$
$$W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu -$$
$$Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w(A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 -$$
$$\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h -$$
$$g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) -$$
$$\tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) -$$
$$gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H -$$
$$\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) +$$
$$\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) +$$
$$M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- -$$
$$W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) -$$
$$\tfrac{1}{4}g^2 W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-\right) -$$
$$\tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial +$$
$$m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) +$$
$$\tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) +$$
$$(\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) +$$
$$\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) +$$
$$\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) +$$
$$\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) -$$
$$\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa -$$
$$\tfrac{1}{4}\overline{\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa} + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) +$$
$$\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) -$$
$$\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu +$$
$$\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- -$$
$$\partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 -$$
$$\partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ -$$
$$\partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ -$$
$$\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM\left(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-\right) +$$
$$\tfrac{1}{2c_w}igM\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + igMs_w\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) +$$
$$\tfrac{1}{2}igM\left(\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0\right).$$

Is Lagrangian of the Standard Model beautiful? I think it depends…

Well… it is not fundamental (yet).
Then what? Strings?!
Experts have different opinion
(mildly speaking)

Polyakov: String Theory is Crazy

Posted on July 26, 2004 by woit

Alexander Polyakov is one of the most prominent figures in theoretical physics and one of the most well-known string theorists at Princeton. He has written a review of his career and of his efforts to understand the relation between gauge theory and string theory. His penultimate paragraph goes as follows:

"In my opinion, string theory in general may be too ambitious. We know too little about string dynamics to attack the fundamental questions of the 'right' vacua, hierarchies, to choose between anthropic and misanthropic principles, etc. The lack of control from the experiment makes going astray almost inevitable. I hope that gauge/string duality somewhat improves the situation. There we do have some control, both from experiment and from numerical simulations. Perhaps it will help to restore the mental health of string theory."

Should physical theory be mathematically beautiful? (personal experience)

Dual fermions A. Rubtsov, MIK, A. Lichtenstein, PRB **77**, 033101 (2008)

Simple and beautiful Hubbard model

$$\mathcal{H} = \sum_{ij,\sigma} t_{ij} c_{i\sigma}^{\dagger} c_{j\sigma} + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

Simple and beautiful action in Grassmann path integral

$$\mathcal{S}[c^+, c] = \sum_{\mathbf{k}\nu\sigma} [-i\nu + \varepsilon_{\mathbf{k}} - \mu] c_{\mathbf{k}\nu\sigma}^+ c_{\mathbf{k}\nu\sigma} + U \sum_i \int_0^\beta d\tau c_{i\uparrow}^+(\tau) c_{i\uparrow}(\tau) c_{i\downarrow}^+(\tau) c_{i\downarrow}(\tau).$$

Functional analog of Fourier transformation

$$Z[\eta^+, \eta, \tilde{\eta}^+, \tilde{\eta}] = \int D[c^+, c] \exp\left[-\mathcal{S}_{\text{loc}}[c^+, c] - \sum_{\mathbf{k}\nu\sigma} [\varepsilon_{\mathbf{k}} - \Delta_\nu] C_{\mathbf{k}\nu\sigma}^+ C_{\mathbf{k}\nu\sigma} + \sum_{\mathbf{k}\nu\sigma} c_{\mathbf{k}\nu\sigma}^+ \eta_{\mathbf{k}\nu\sigma} + \eta_{\mathbf{k}\nu\sigma}^+ c_{\mathbf{k}\nu\sigma} \right]$$

After integration you have ugly infinite series with terms expressed in terms of quite complicated diagrams

Should physical theory be mathematically beautiful? (personal experience) II

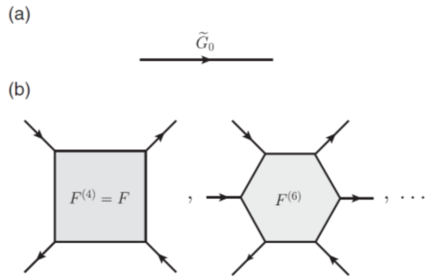
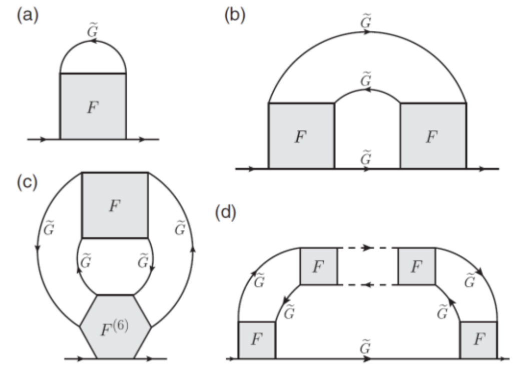


FIG. 13. Diagrammatic elements of the DF approach: (a) The bare DF propagator $\tilde{G}_0$ [Eq. (39)] given by the purely nonlocal Green's function and (b) the DF interaction represented by the local connected n-particle vertex functions $F^{(2n)}$.



But:

(1) Very good zero-order approximation interpolating between weak and strong coupling

(2) Effective computation algorithms

Transformation of a beautiful princess to an ugly frog

Made by Google Gemini

Sometimes there are much less problems with a frog than with a princess…

Concluding statement

The essence of physics is a historically reached subtle balance between theory and experiment. In "fundamental physics" experiments are too expensive and thus too rare, nothing can really stop a flight of fantasy of theorists. In condensed matter and similar kind of physics the ratio of experiment to theory seems to be more healthy. Therefore I expect more progress for our science in general from there.

MANY THANKS FOR YOUR ATTENTION