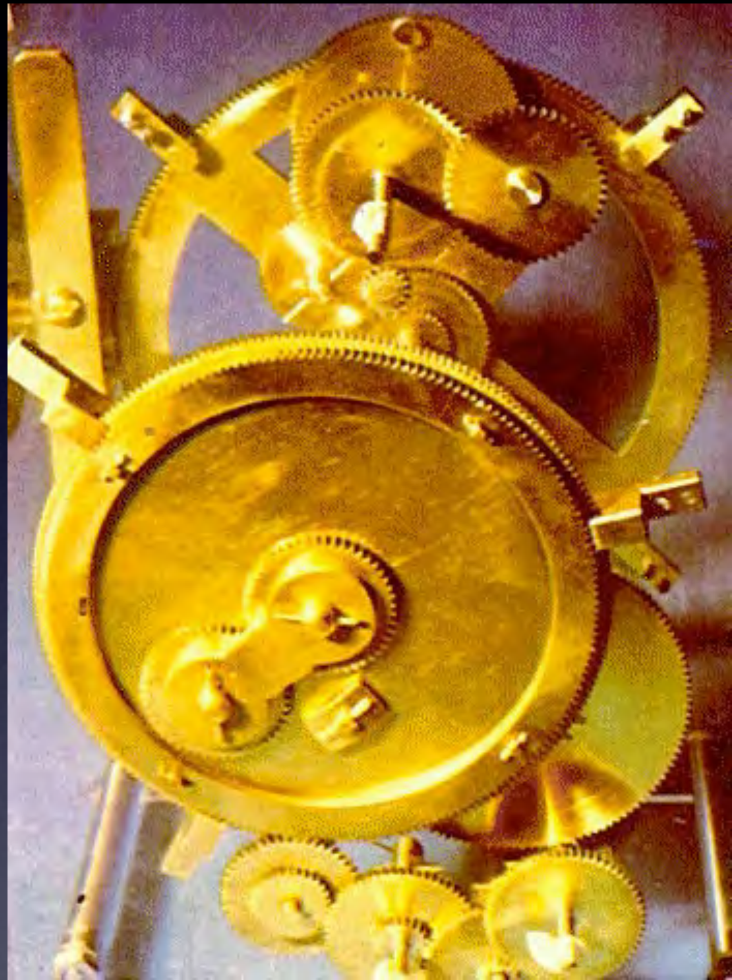
From the Atom to the Computer and Back Again
A 100 Year Round Trip

Charles Marcus,
Niels Bohr Institute

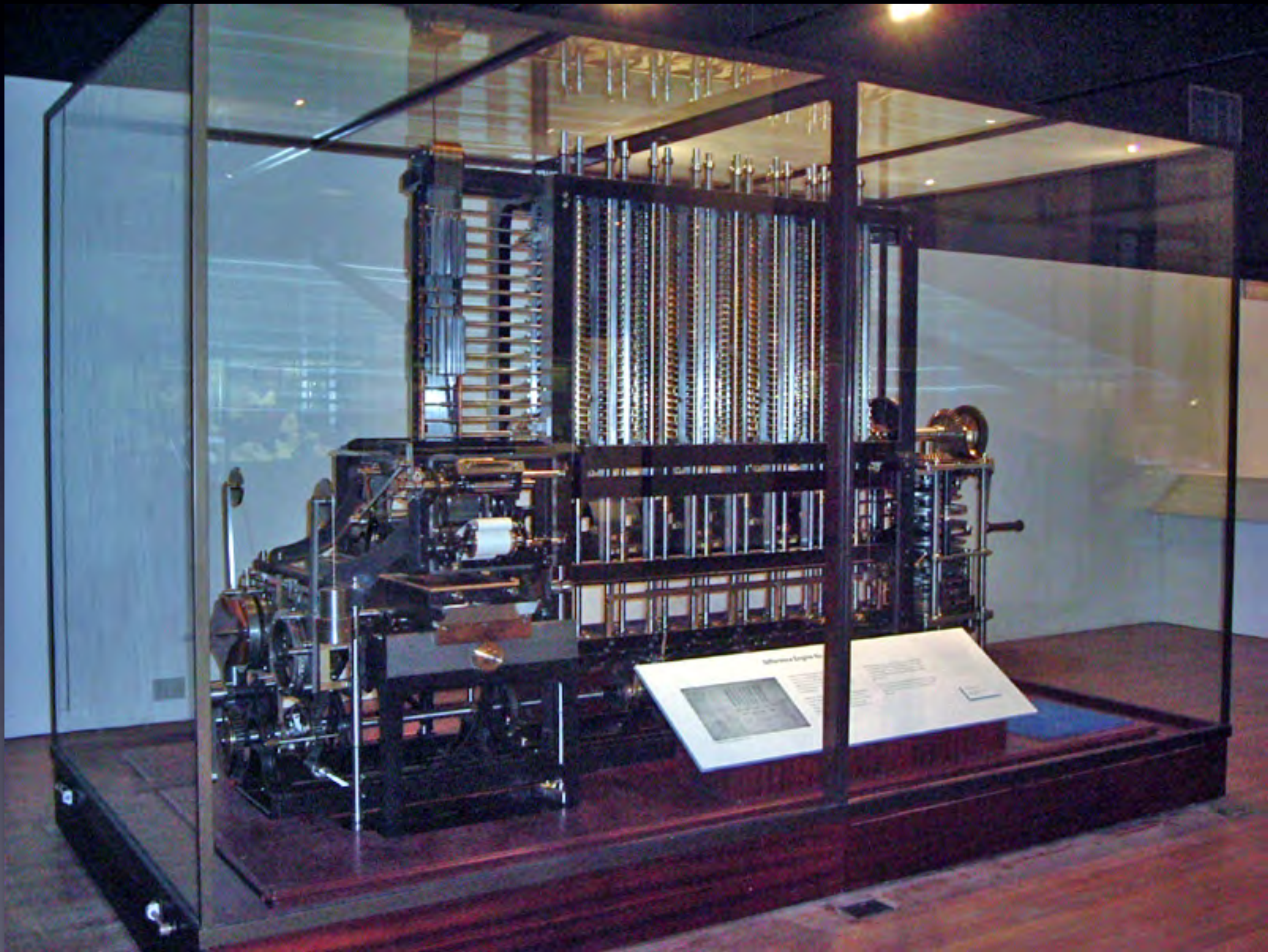
Antikythera mechanism

analog computer of astronomical information
~ 30 gears
dated to 150-100 BC

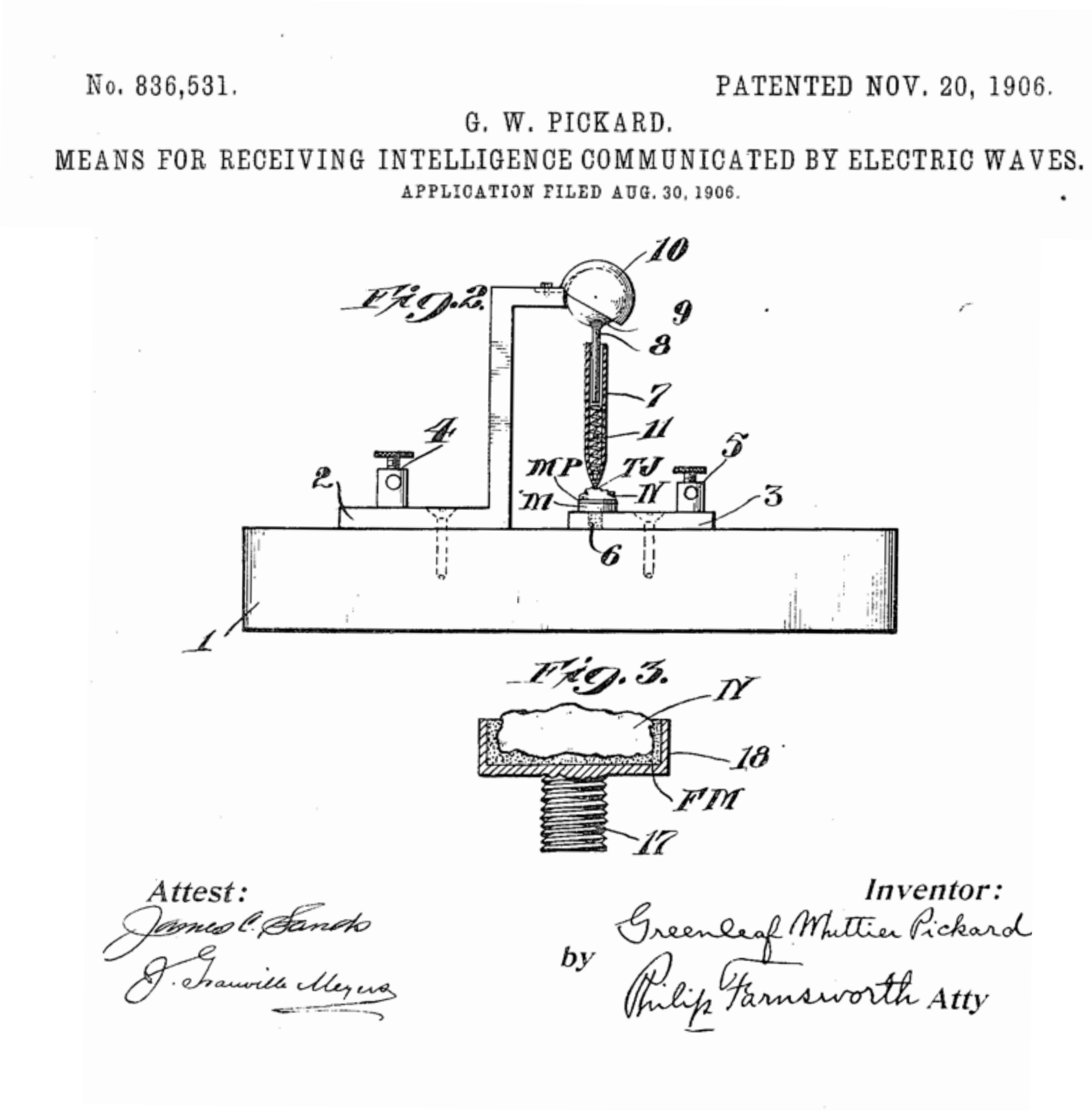


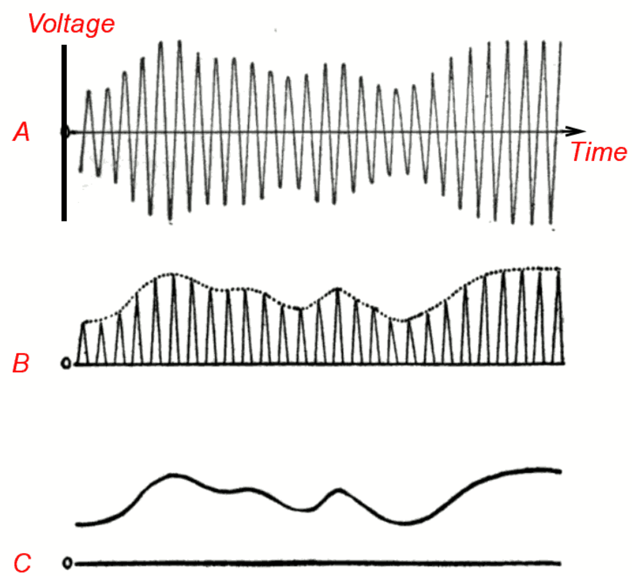
Babbage Difference Engine

designed to tabulate polynomial functions
~ 1837
never built, due to lack of funding



IBM Automatic Sequence Controlled Calculator (ASCC)
1937

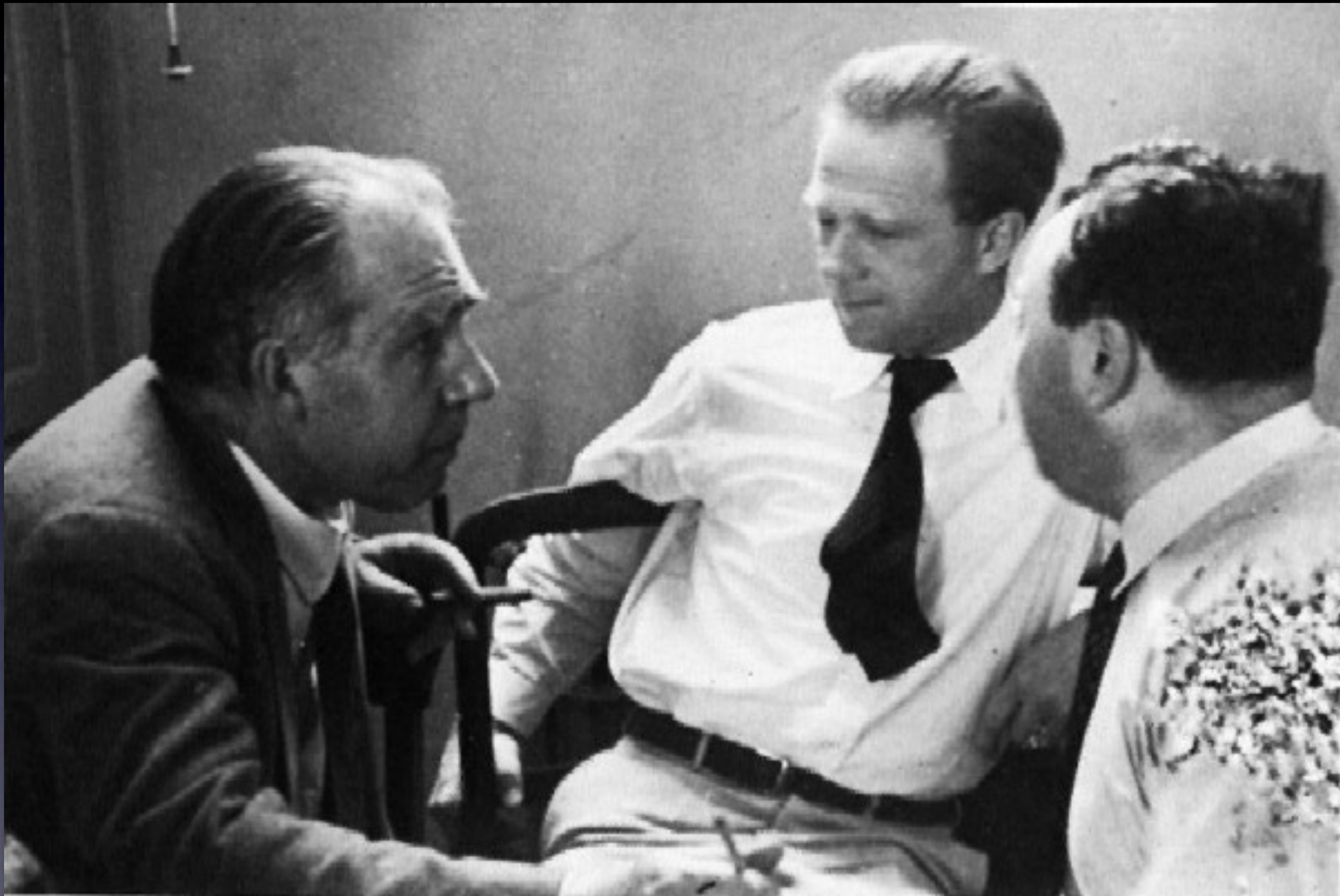




... the best results so far have been had with a non-metallic natural element, such as silicon, which possesses in a high degree the desired properties...

And there things remained, for 30 years

Sometimes, progress requires understanding.



The theory of a new kind of material: the semiconductor

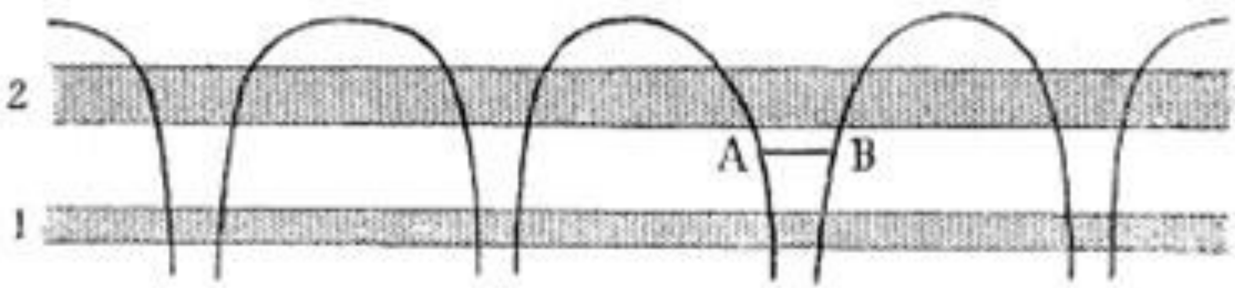
The Theory of Electronic Semi-Conductors.

By A. H. Wilson, Emmanuel College, Cambridge.

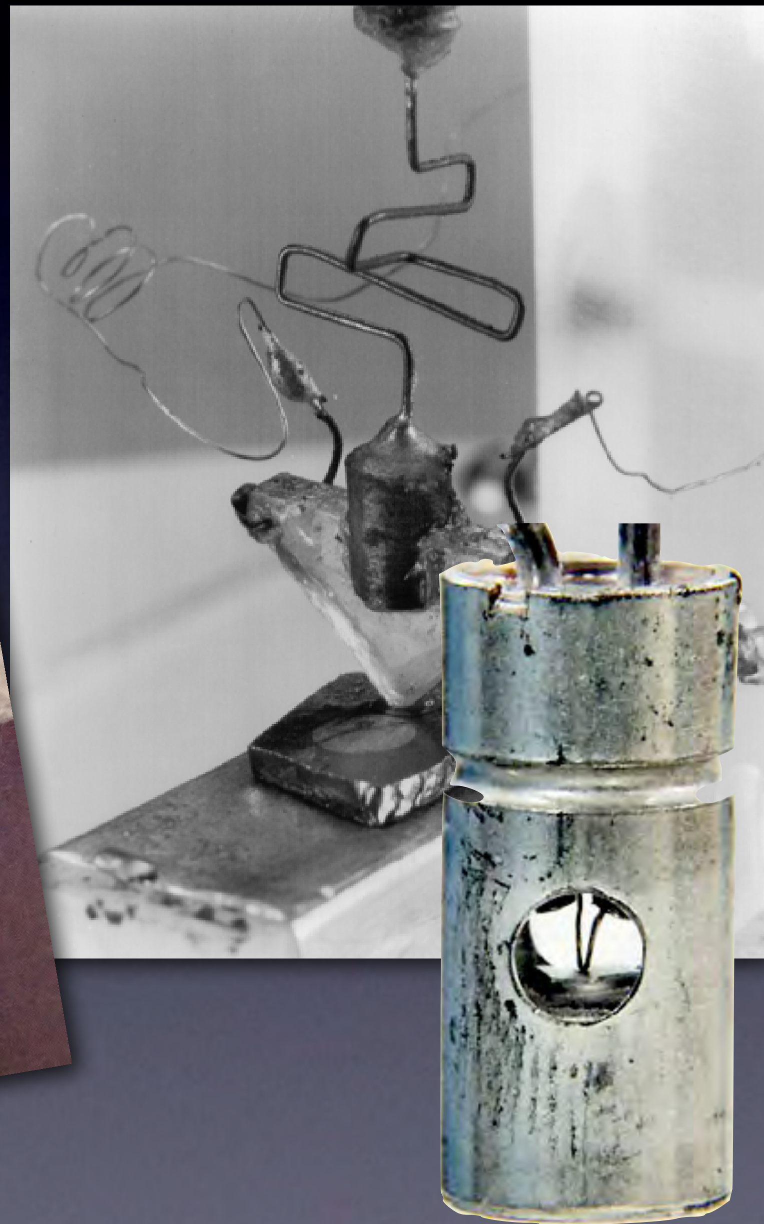
(Communicated by P. A. M. Dirac, F.R.S.—Received June 18, 1931.)

Introduction.

The application of quantum mechanics to the problem of metallic conduction has cleared up many of the difficulties which were so apparent in the free electron theories of Drude and Lorentz. Sommerfeld* assumed that the valency electrons of the metallic atoms formed an electron gas which obeyed the Fermi-Dirac statistics, instead of Maxwellian statistics, and, using in the main classical ideas, showed how the difficulty of the specific heat would be removed. He was, however, unable to determine the temperature dependence of the resistance, as his formulæ contained a mean free path about which little could be said.



1947. The revolution begins



The solid-state revolution, continued

1958 – Jack Kiby – first integrated circuit

Moore's Law

The experts look ahead

Cramming more components onto integrated circuits

With unit cost falling as the number of components per circuit rises, by 1975 economics may dictate squeezing as many as 65,000 components on a single silicon chip

By Gordon E. Moore

Director, Research and Development Laboratories, Fairchild Semiconductor division of Fairchild Camera and Instrument Corp.

The future of integrated electronics is the future of electronics itself. The advantages of integration will bring about a proliferation of electronics, pushing this science into many new areas.

Integrated circuits will lead to such wonders as home computers—or at least terminals connected to a central computer—automatic controls for automobiles, and personal portable communications equipment. The electronic wristwatch needs only a display to be feasible today.

But the biggest potential lies in the production of large systems. In telephone communications, integrated circuits in digital filters will separate channels on multiplex equipment. Integrated circuits will also switch telephone circuits and perform data processing.

Computers will be more powerful, and will be organized in completely different ways. For example, memories built of integrated electronics may be distributed throughout the machine instead of being concentrated in a central unit. In addition, the improved reliability made possible by integrated circuits will allow the construction of larger processing units. Machines similar to those in existence today will be built at lower costs and with faster turn-around.

Present and future

By integrated electronics, I mean all the various technologies which are referred to as microelectronics today as well as any additional ones that result in electronics functions supplied to the user as irreducible units. These technologies were first investigated in the late 1950's. The object was to miniaturize electronics equipment to include increasingly complex electronic functions in limited space with minimum weight. Several approaches evolved, including microassembly techniques for individual components, thin-film structures and semiconductor integrated circuits.

Each approach evolved rapidly and converged so that each borrowed techniques from another. Many researchers believe the way of the future to be a combination of the various approaches.

The advocates of semiconductor integrated circuitry are already using the improved characteristics of thin-film resistors by applying such films directly to an active semiconductor substrate. Those advocating a technology based upon films are developing sophisticated techniques for the attachment of active semiconductor devices to the passive film arrays.

Both approaches have worked well and are being used in equipment today.

The author

Dr. Gordon E. Moore is one of the new breed of electronic engineers, schooled in the physical sciences rather than in electronics. He earned a B.S. degree in chemistry from the University of California and a Ph.D degree in physical chemistry from the California Institute of Technology. He was one of the founders of Fairchild Semiconductor and has been director of the research and development laboratories since 1959.

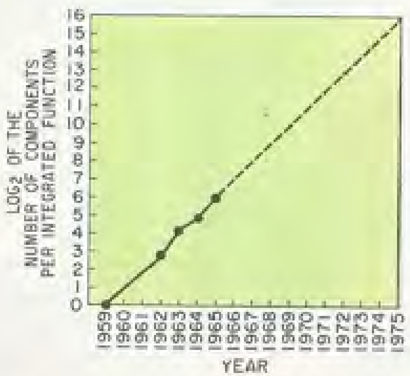
a few diodes. This allows at least 500 components per linear inch or a quarter million per square inch. Thus, 65,000 components need occupy only about one-fourth a square inch.

On the silicon wafer currently used, usually an inch or more in diameter, there is ample room for such a structure if the components can be closely packed with no space wasted for interconnection patterns. This is realistic, since efforts to achieve a level of complexity above the presently available integrated circuits are already underway using multilayer metalization patterns separated by dielectric films. Such a density of components can be achieved by present optical techniques and does not require the more exotic techniques, such as electron beam operations, which are being studied to make even smaller structures.

Increasing the yield

There is no fundamental obstacle to achieving device yields of 100%. At present, packaging costs so far exceed the cost of the semiconductor structure itself that there is no incentive to improve yields, but they can be raised as high as is economically justified. No barrier exists comparable to the thermodynamic equilibrium considerations that often limit yields in chemical reactions; it is not even necessary to do any fundamental research or to replace present processes. Only the engineering effort is needed.

In the early days of integrated circuitry, when yields were extremely low, there was such incentive. Today ordinary integrated circuits are made with yields comparable with those obtained for individual semiconductor devices. The same pattern will make larger arrays economical, if other considerations make such arrays desirable.



Heat problem

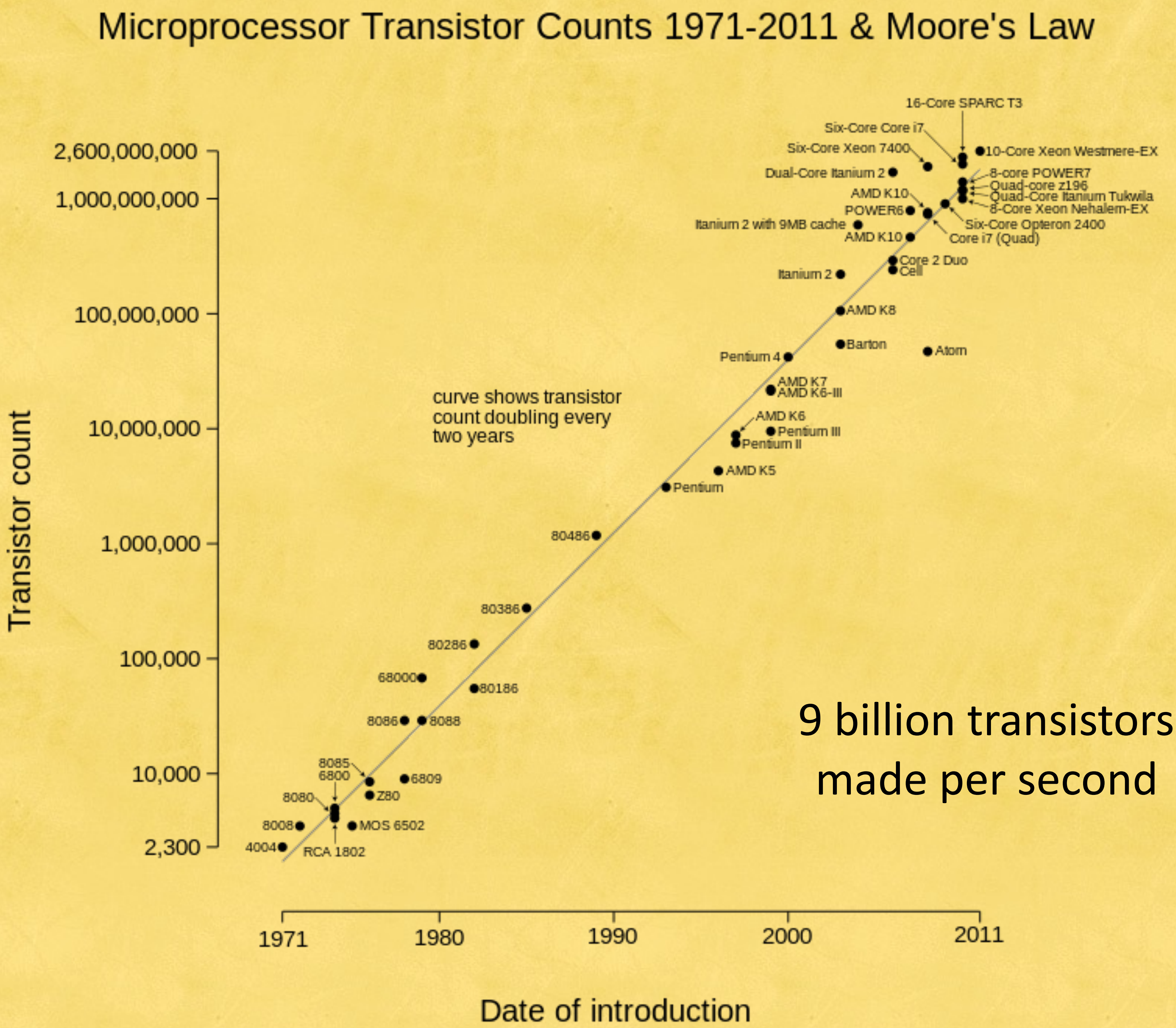
Will it be possible to remove the heat generated by tens of thousands of components in a single silicon chip?

If we could shrink the volume of a standard high-speed digital computer to that required for the components themselves, we would expect it to glow brightly with present power dissipation. But it won't happen with integrated circuits. Since integrated electronic structures are two-dimensional, they have a surface available for cooling close to each center of heat generation. In addition, power is needed primarily to drive the various lines and capacitances associated with the system. As long as a function is confined to a small area on a wafer, the amount of capacitance which must be driven is distinctly limited. In fact, shrinking dimensions on an integrated structure makes it possible to operate the structure at higher speed for the same power per unit area.

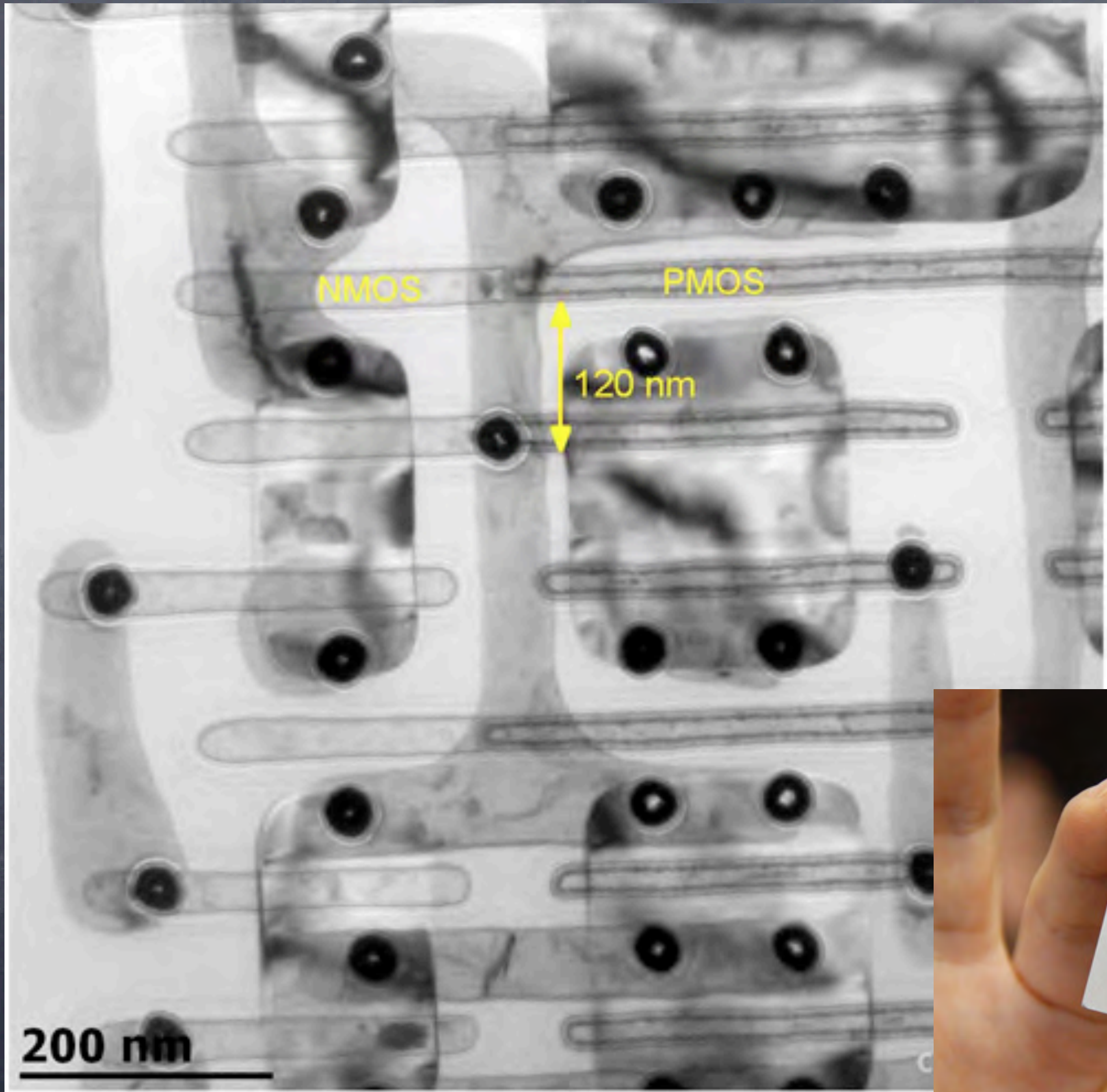
Day of reckoning

Clearly, we will be able to build such component-crammed equipment. Next, we ask under what circumstances we should do it. The total cost of making a particular system function must be minimized. To do so, we could amortize the engineering over several identical items, or evolve flexible techniques for the engineering of large functions so that no disproportionate expense need be borne by a particular array. Perhaps newly devised design automation procedures could translate from logic diagram to technological realization without any special engineering.

It may prove to be more economical to build large systems out of smaller functions, which are

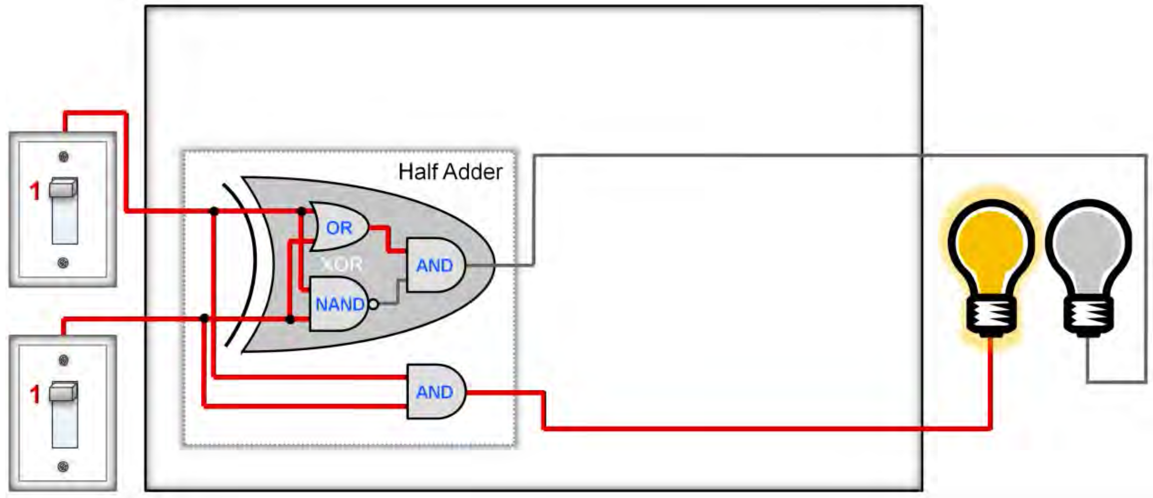


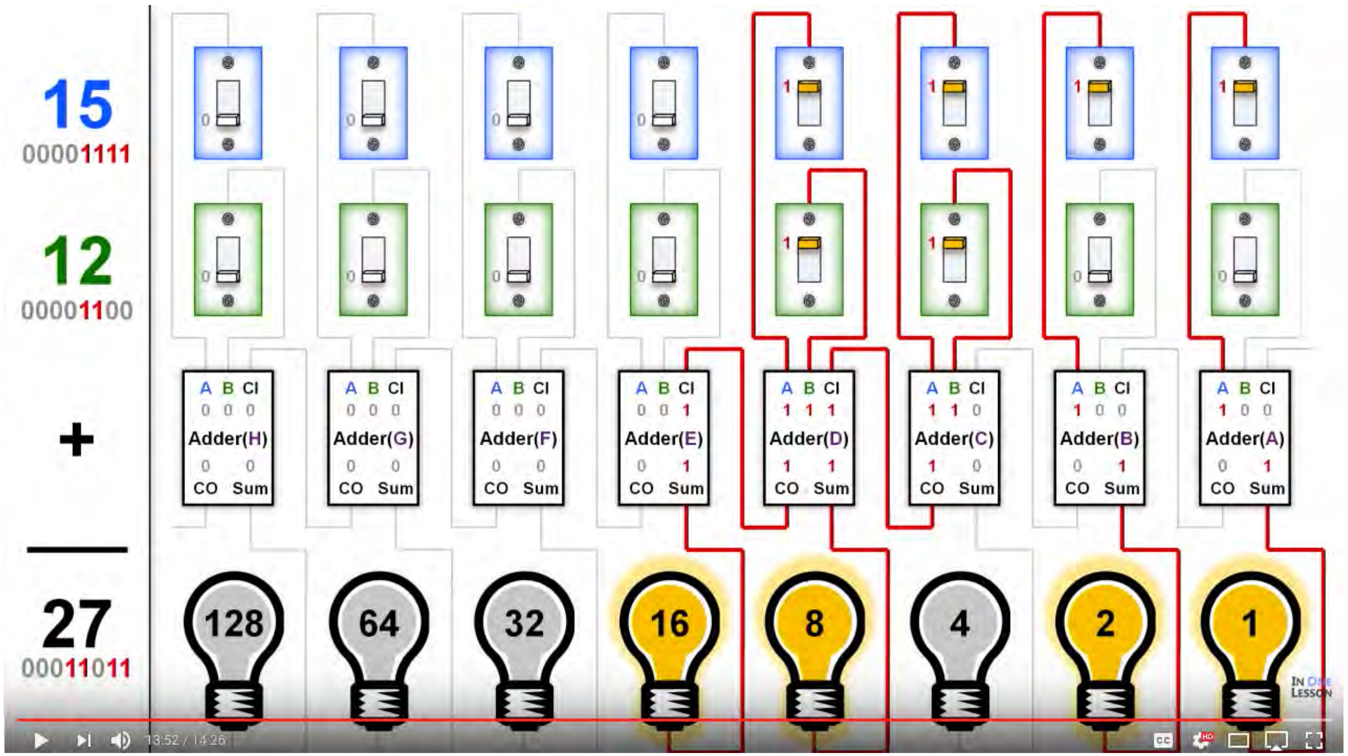
9 billion transistors made per second


NMOS
PMOS
120 nm
200 nm

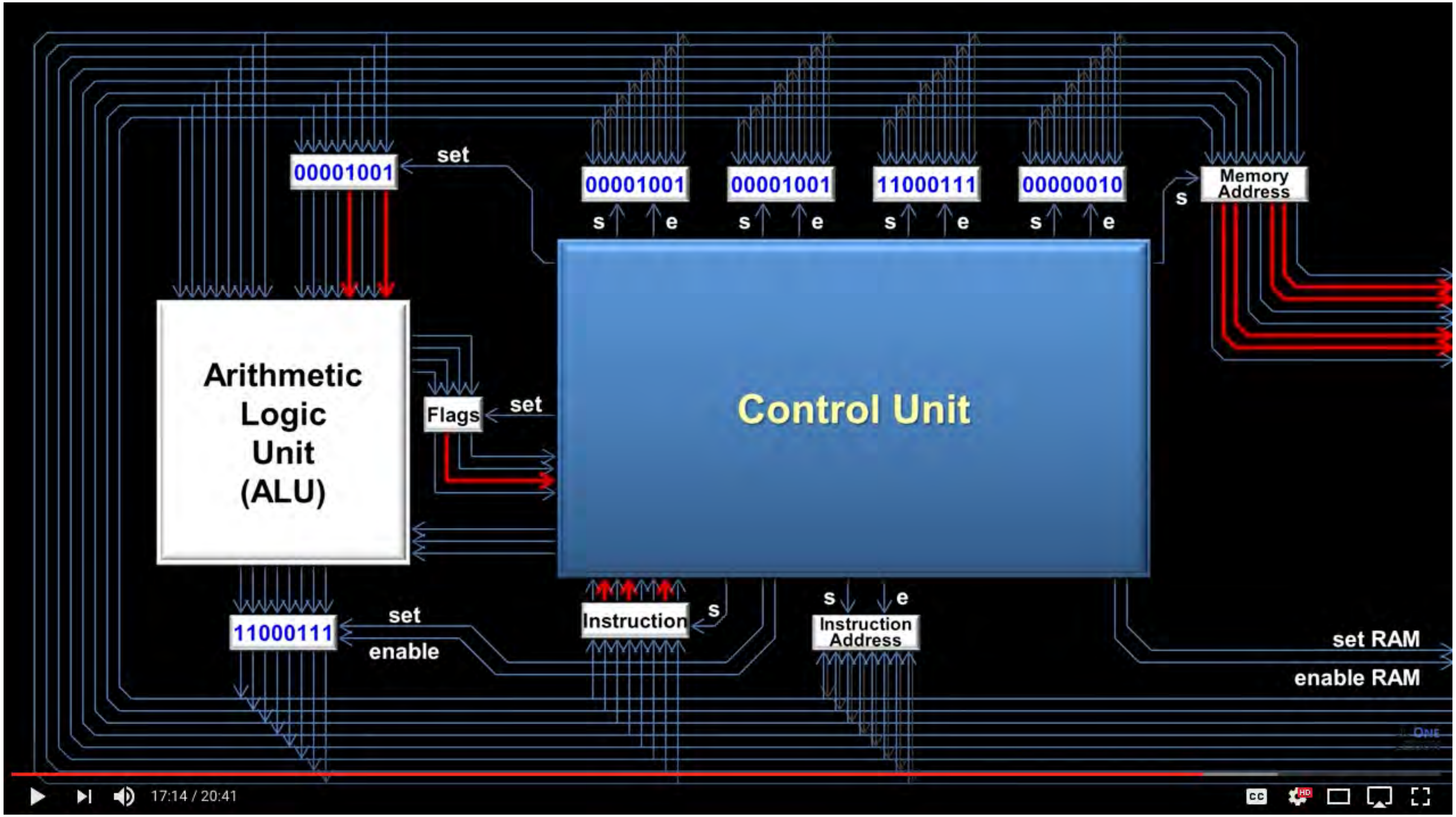

XILINX
KINTEX-7
XC7K325T
FFG900ACX1109
DC20475A/N6C848-1
ESLAB
TAIWAN

YouTube: “How Computers Add Numbers In One Lesson”

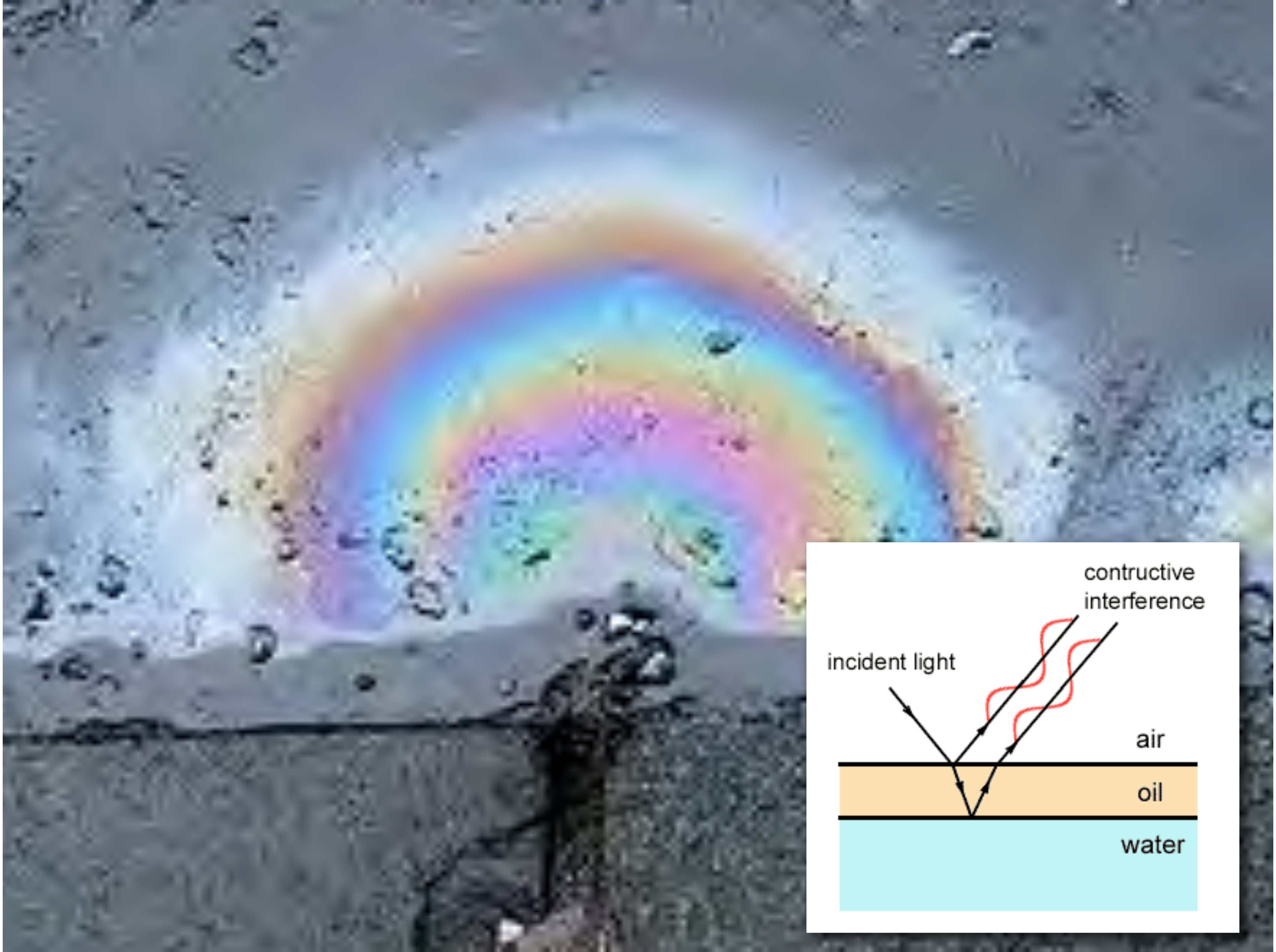


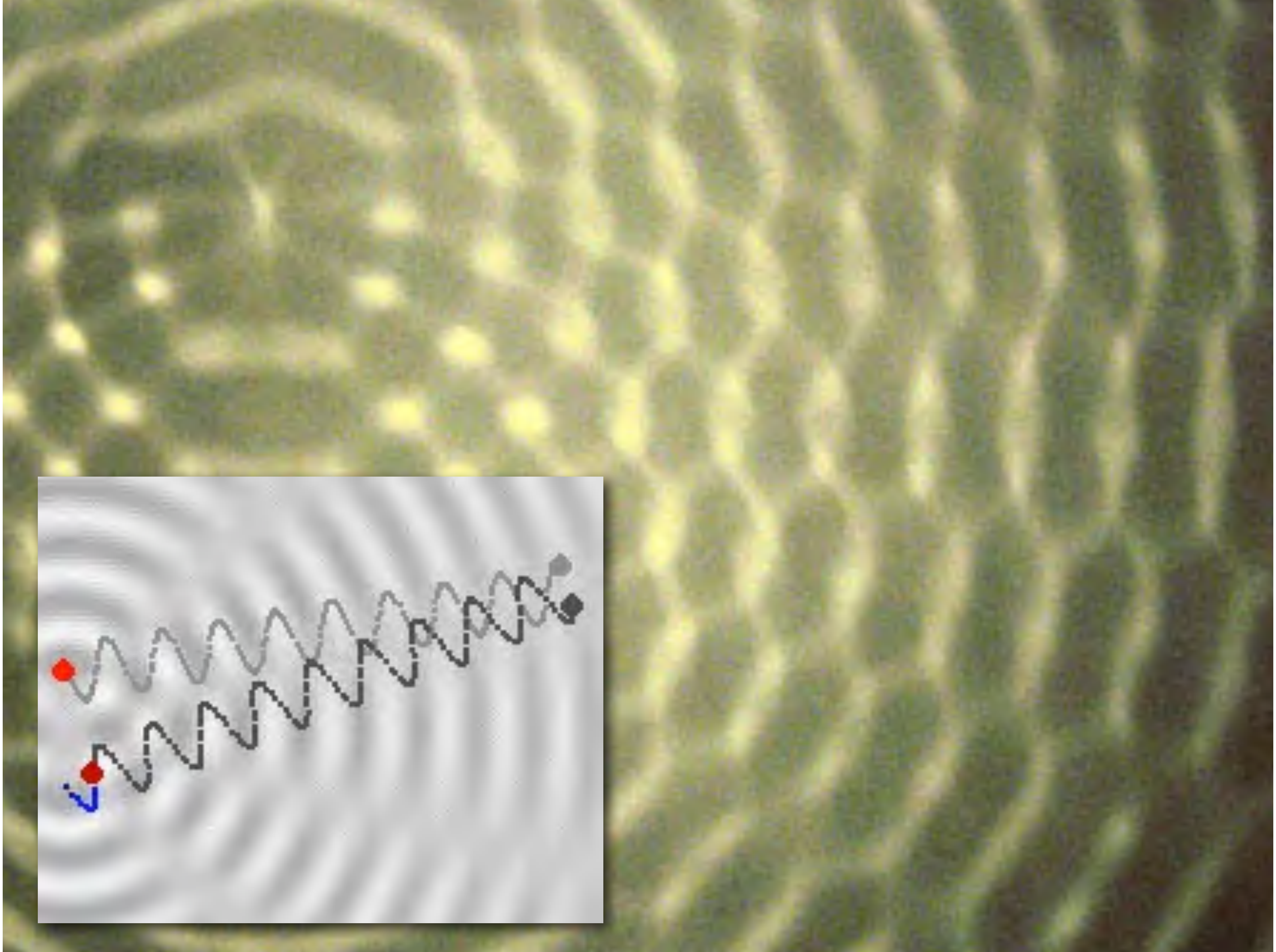


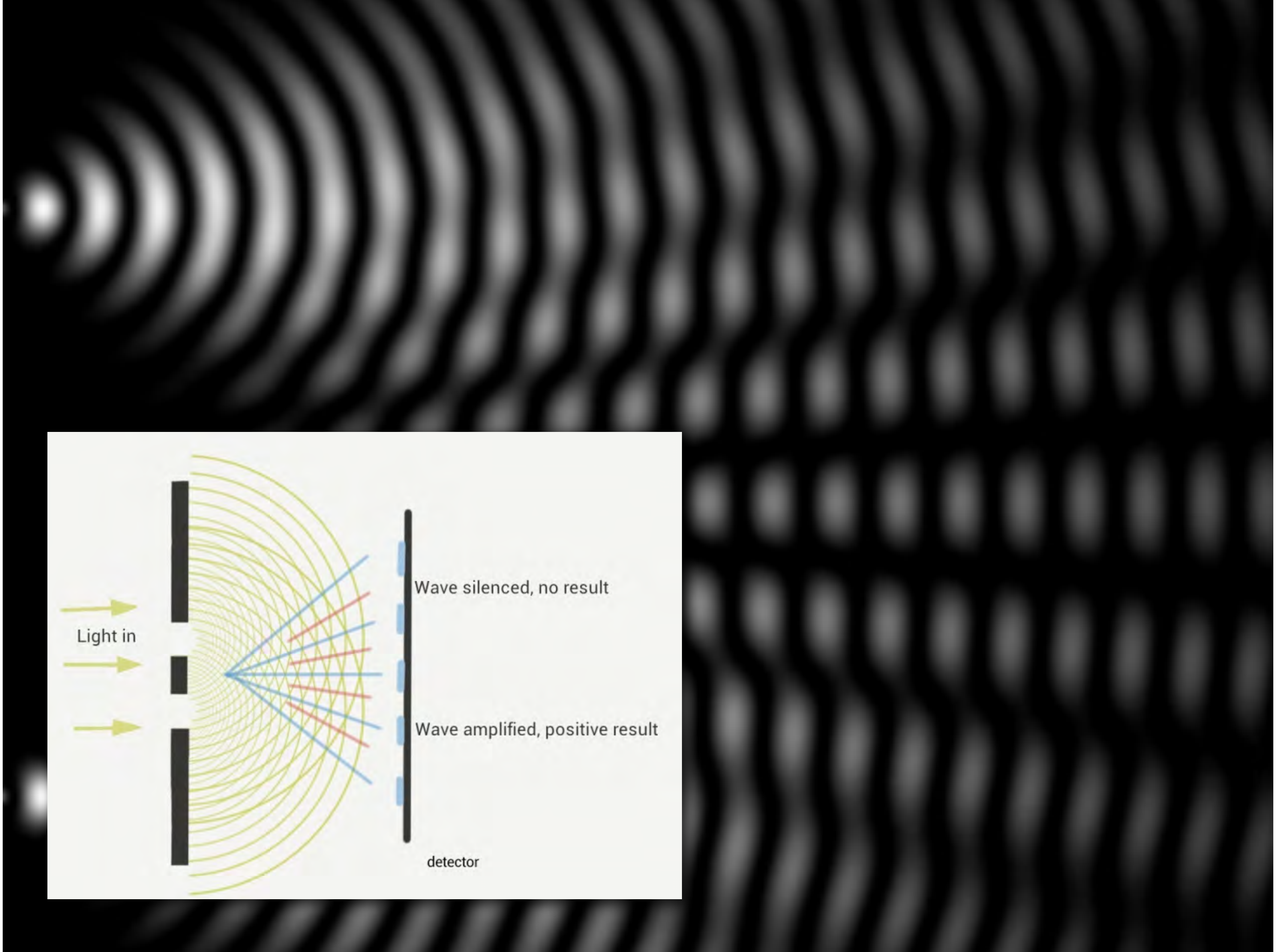
YouTube: “How a CPU Works”



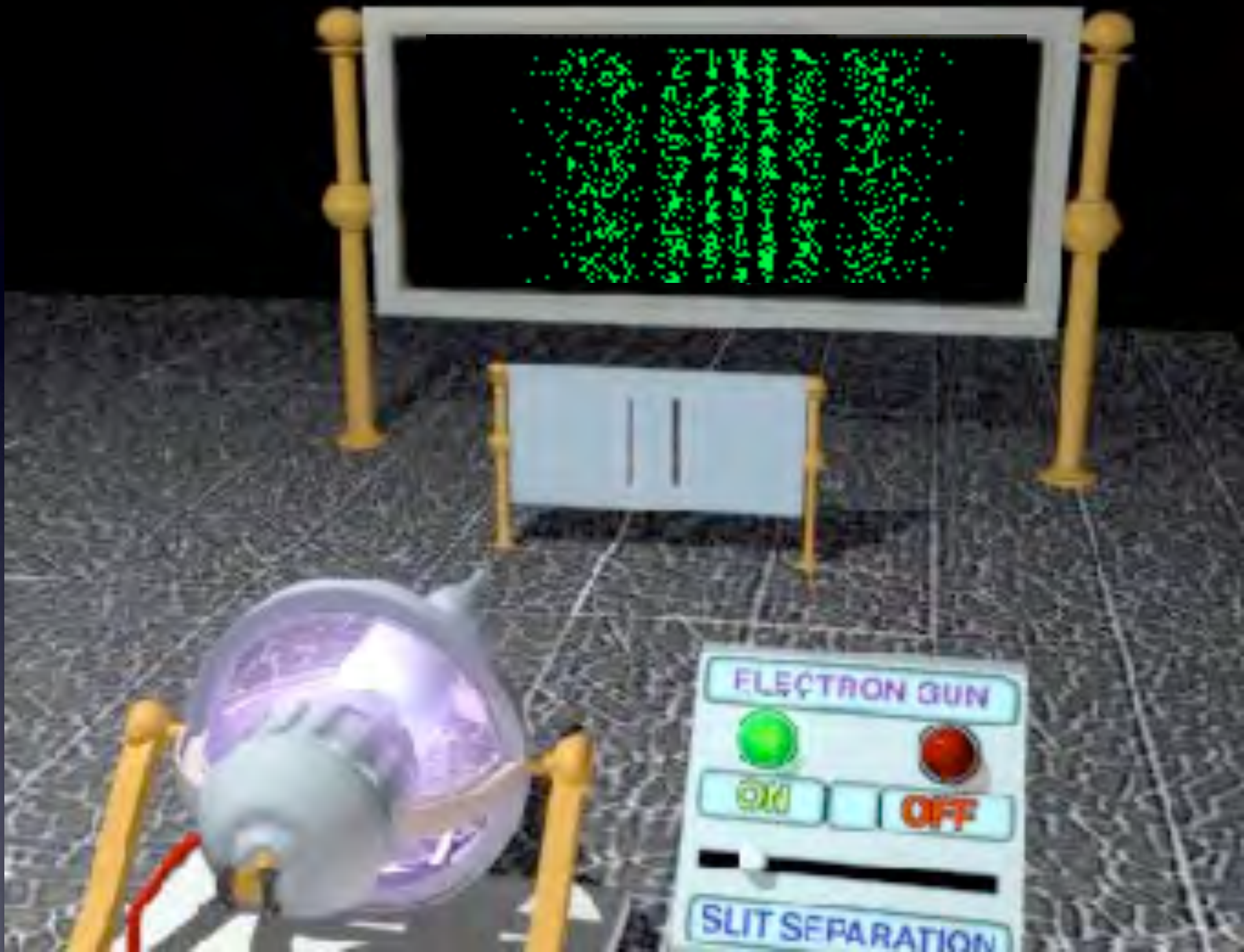
What was bothering these men?


contructive
interference
incident light
air
oil
water

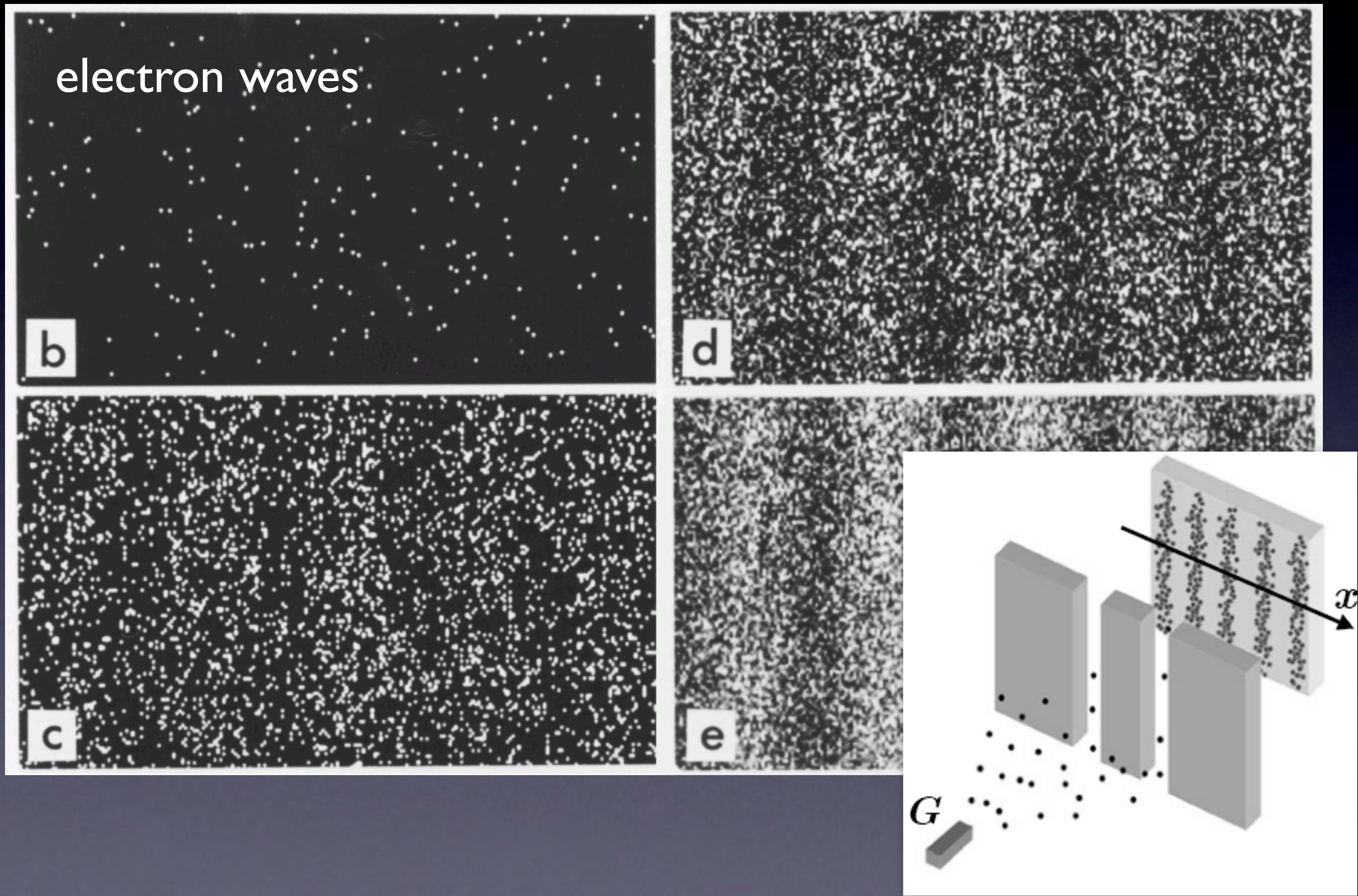



Light in
Wave silenced, no result
Wave amplified, positive result
detector

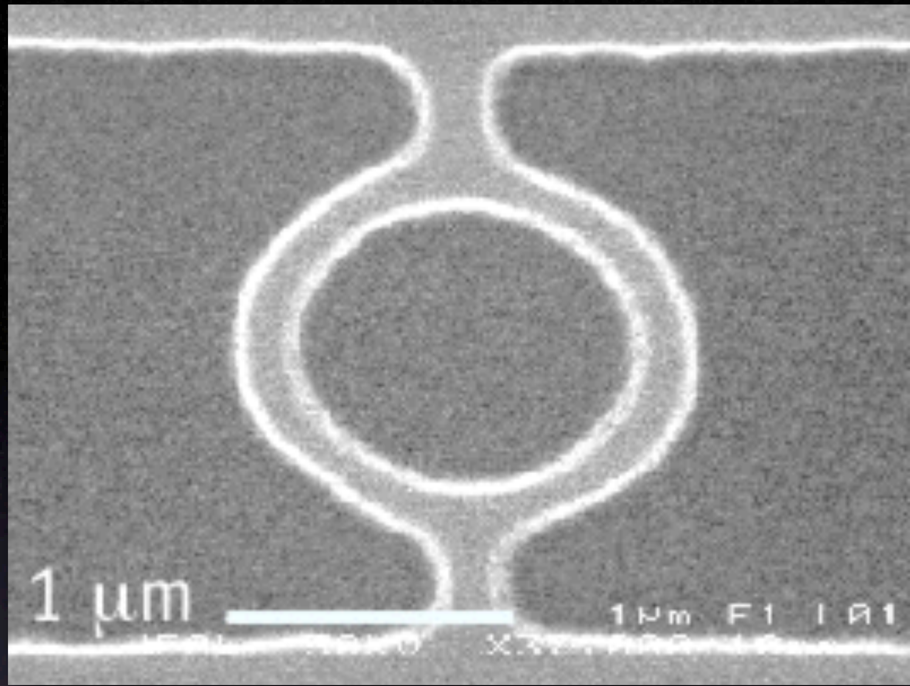
The quantum age

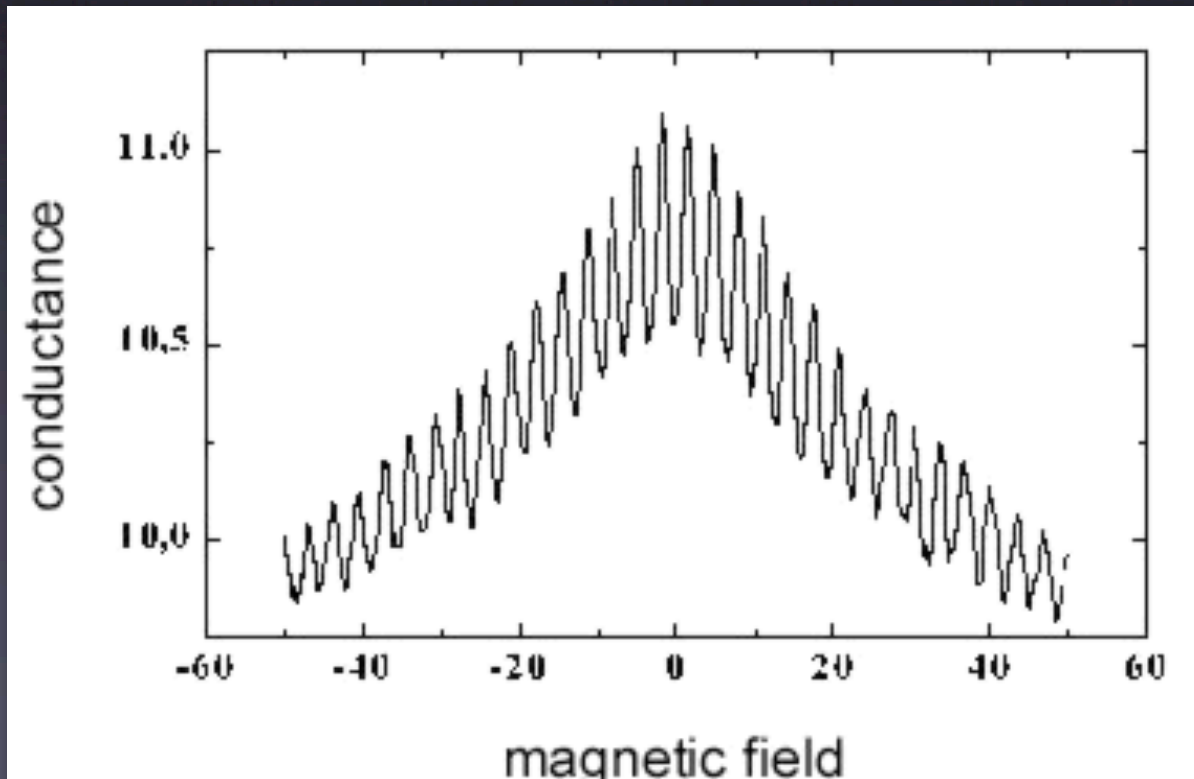


Particles also show interference (?!)

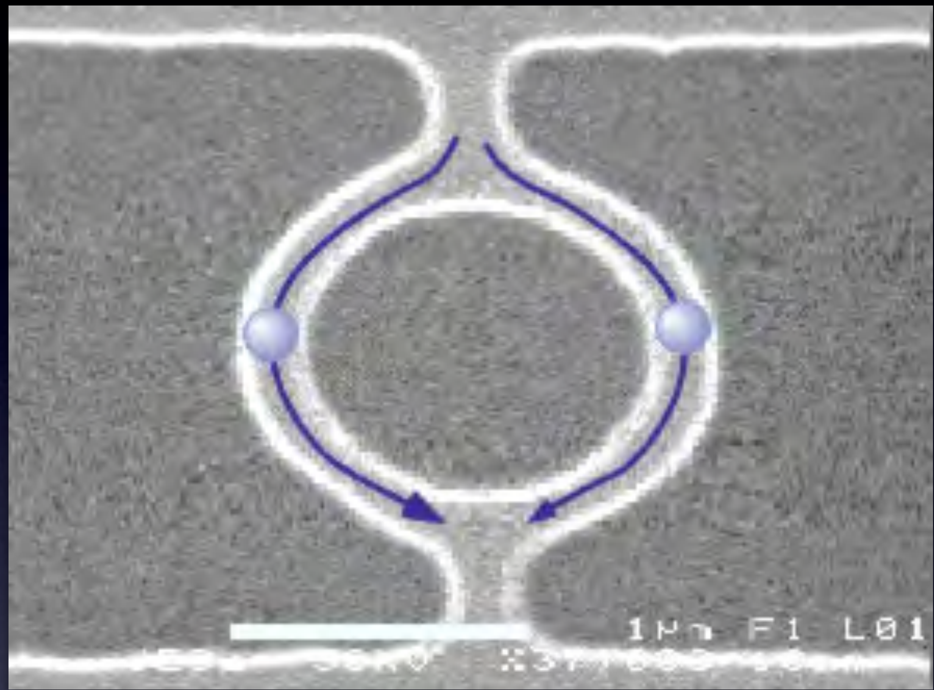


Quantum Circuits
small electronics at low temperatures





Mesoscopic Electronics and Quantum Interference

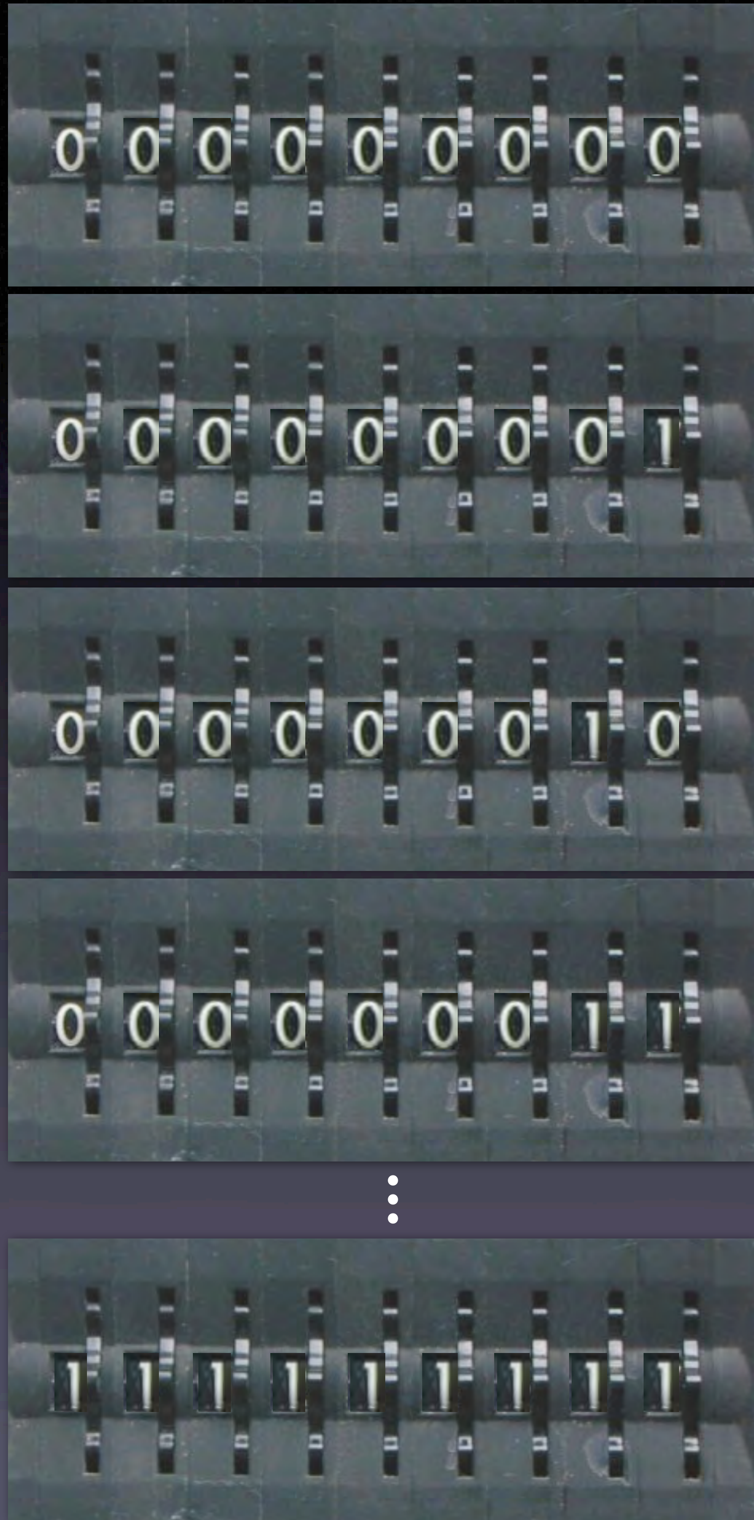


A transistor is a switch controlled by a voltage.

If the transistor can be in more than one state at a time, then it can control another switch that can be in more than one state at a time, etc.

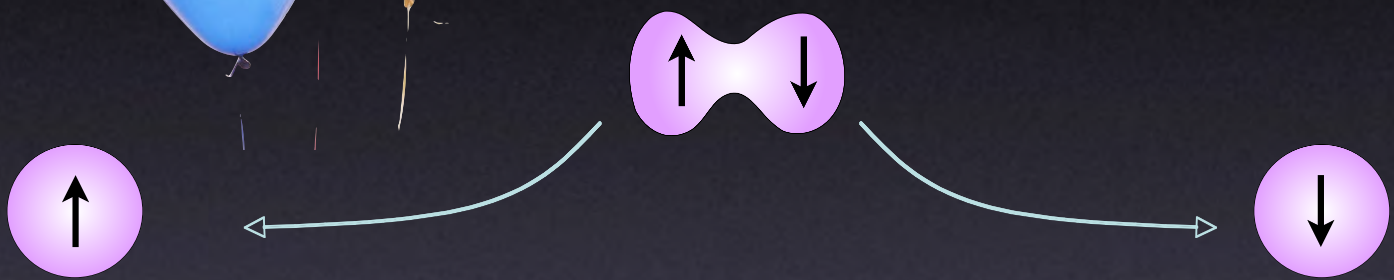
superposition as
quantum
parallelism

$$|\psi\rangle = \left\{ \right.$$

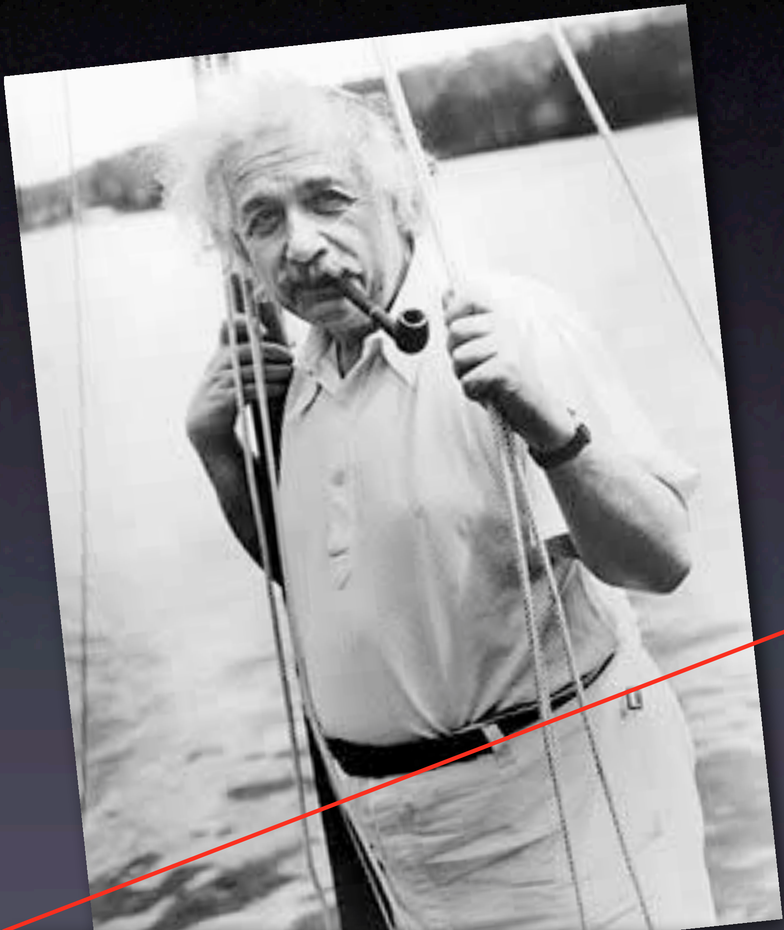


Quantum Entanglement: “Spooky Action at a Distance”

$$|S\rangle = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$



The Challenge



of lanthanum is 7/2, hence the nuclear magnetic moment as determined by this analysis is 2.5 nuclear magnetons. This is in fair agreement with the value 2.8 nuclear magnetons determined from La III hyperfine structures by the writer and N. S. Grace.[9]

[9] M. F. Crawford and N. S. Grace, Phys. Rev. **47**, 536 (1935).

This investigation was carried out under the supervision of Professor G. Breit, and I wish to thank him for the invaluable advice and assistance so freely given. I also take this opportunity to acknowledge the award of a Fellowship by the Royal Society of Canada, and to thank the University of Wisconsin and the Department of Physics for the privilege of working here.

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. Einstein, B. Podolsky and N. Rosen, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

1.

Any serious consideration of a physical theory must take into account the distinction between the objective reality, which is independent of any theory, and the physical concepts with which the theory operates. These concepts are intended to correspond with the objective reality, and by means of these concepts we picture this reality to ourselves.

In attempting to judge the success of a physical theory, we may ask ourselves two questions: (1) "Is the theory correct?" and (2) "Is the description given by the theory complete?" It is only in the case in which positive answers may be given to both of these questions, that the concepts of the theory may be said to be satisfactory. The correctness of the theory is judged by the degree of agreement between the con- ... ence. ... make ... the ... the ... re, as

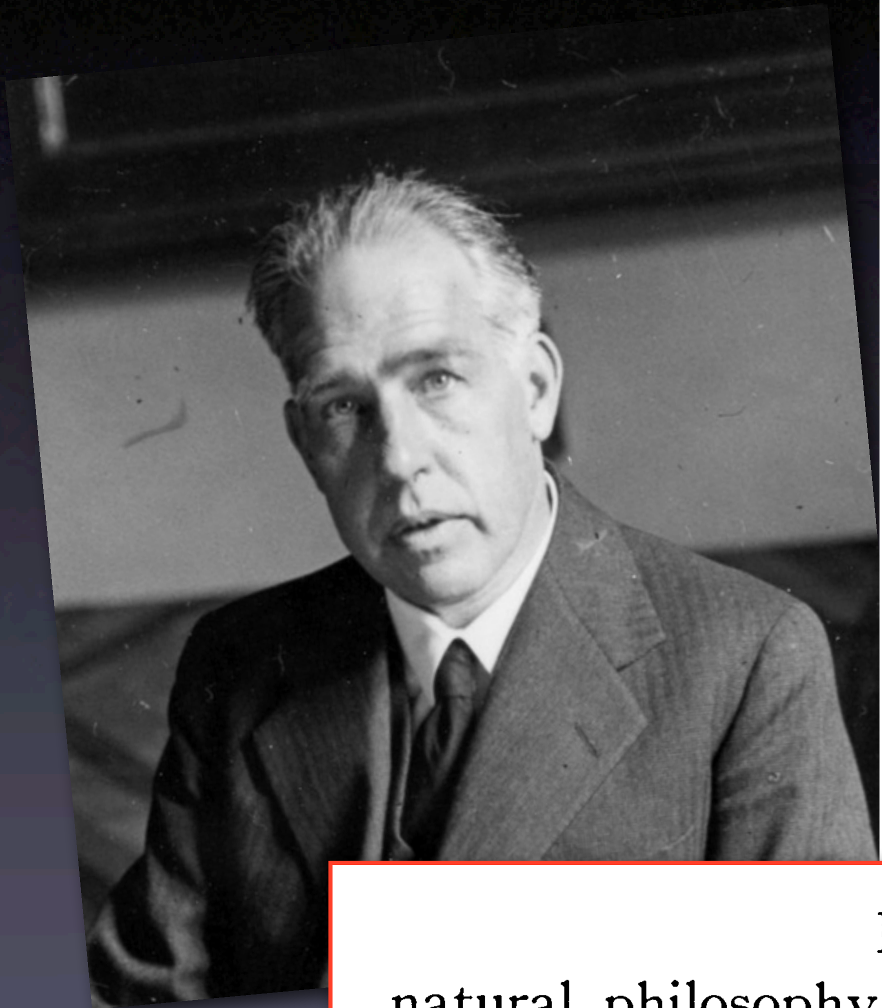
Whatever the meaning assigned to the term *complete*, the following requirement for a complete theory seems to be a necessary one: *every element of the physical reality must have a counterpart in the physical theory*. We shall call this the condition of completeness. The second question is thus easily answered, as soon as we are able to decide what are the elements of the physical reality.

The elements of the physical reality cannot be determined by *a priori* philosophical considerations, but must be found by an appeal to results of experiments and measurements. A comprehensive definition of reality is, however, unnecessary for our purpose. We shall be satisfied with the following criterion, which we regard as reasonable. *If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.* It seems to us that this criterion, while far from exhausting all possible ways of recognizing a physical reality, at least provides us with one

One is thus led to conclude that the description of reality as given by a wave function is not complete.

The Response:

Same year, same title,
Radically different viewpoint.



OCTOBER 15, 1935 PHYSICAL REVIEW VOLUME 48

Can Quantum-Mechanical Description of Physical Reality be Considered Complete?

N. Bohr, *Institute for Theoretical Physics, University, Copenhagen*

(Received July 13, 1935)

It is shown that a certain "criterion of physical reality" formulated in a recent article with the above title by A. Einstein, B. Podolsky and N. Rosen contains an essential ambiguity when it is applied to quantum phenomena. In this connection a viewpoint termed "complementarity" is explained from which quantum-mechanical description of physical phenomena would seem to fulfill, within its scope, all rational demands of completeness.

In a recent article[1] under the above title A. Einstein, B. Podolsky and N. Rosen have presented arguments which lead them to answer the question at issue in the negative. The trend of their argumentation, however, does not seem to me adequately to meet the actual situation with which we are faced in atomic physics. I shall therefore be glad to use this opportunity to explain in somewhat greater detail a general viewpoint, conveniently termed "complementarity," which I have indicated on various previous occasions,[2] and from which quantum mechanics within its scope would appear as a completely rational description of physical phenomena, such as we meet in atomic processes.

The extent to which an unambiguous meaning can be attributed to such an expression as "physical reality" cannot of course be deduced from *a priori* philosophical conceptions, but—as the authors of the article cited themselves emphasize—must be founded on a direct appeal to experiments and measurements. For this purpose they propose a "criterion of reality" formulated as follows: "If, without in any way disturbing a system, we can predict with certainty the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity." By means of an interesting example, to which we shall return below, they next proceed to show that in quantum mechanics, just as in classical

interaction with the system under investigation. According to their criterion the authors therefore want to ascribe an element of reality to each of the quantities represented by such variables. Since, moreover, it is a well-known feature of the present formalism of quantum mechanics that it is never possible, in the description of the state of a mechanical system, to attach definite values to both of two canonically conjugate variables, they consequently deem this formalism to be incomplete, and express the belief that a more satisfactory theory can be developed.

Such an argumentation, however, would hardly seem suited to affect the soundness of quantum-mechanical description, which is based on a coherent mathematical formalism covering automatically any procedure of measurement like that indicated.* The apparent contradiction in

* The deductions contained in the article cited may in this respect be considered as an immediate consequence of the transformation theorems of quantum mechanics, which perhaps more than any other feature of the formalism contribute to secure its mathematical completeness and its rational correspondence with classical mechanics. In fact, it is always possible in the description of a mechanical system, consisting of two partial systems (1) and (2), interacting or not, to replace any two pairs of canonically conjugate variables (q_1p_1), (q_2p_2) pertaining to systems (1) and (2), respectively, and satisfying the usual commutation rules

$$[q_1p_1]=[q_2p_2]=ih/2\pi,$$
$$[q_1q_2]=[p_1p_2]=[q_1p_2]=[q_2p_1]=0,$$

by two pairs of new conjugate variables (Q_1P_1), (Q_2P_2) related to the first variables by a simple orthogonal transformation, corresponding to a rotation of angle θ in the

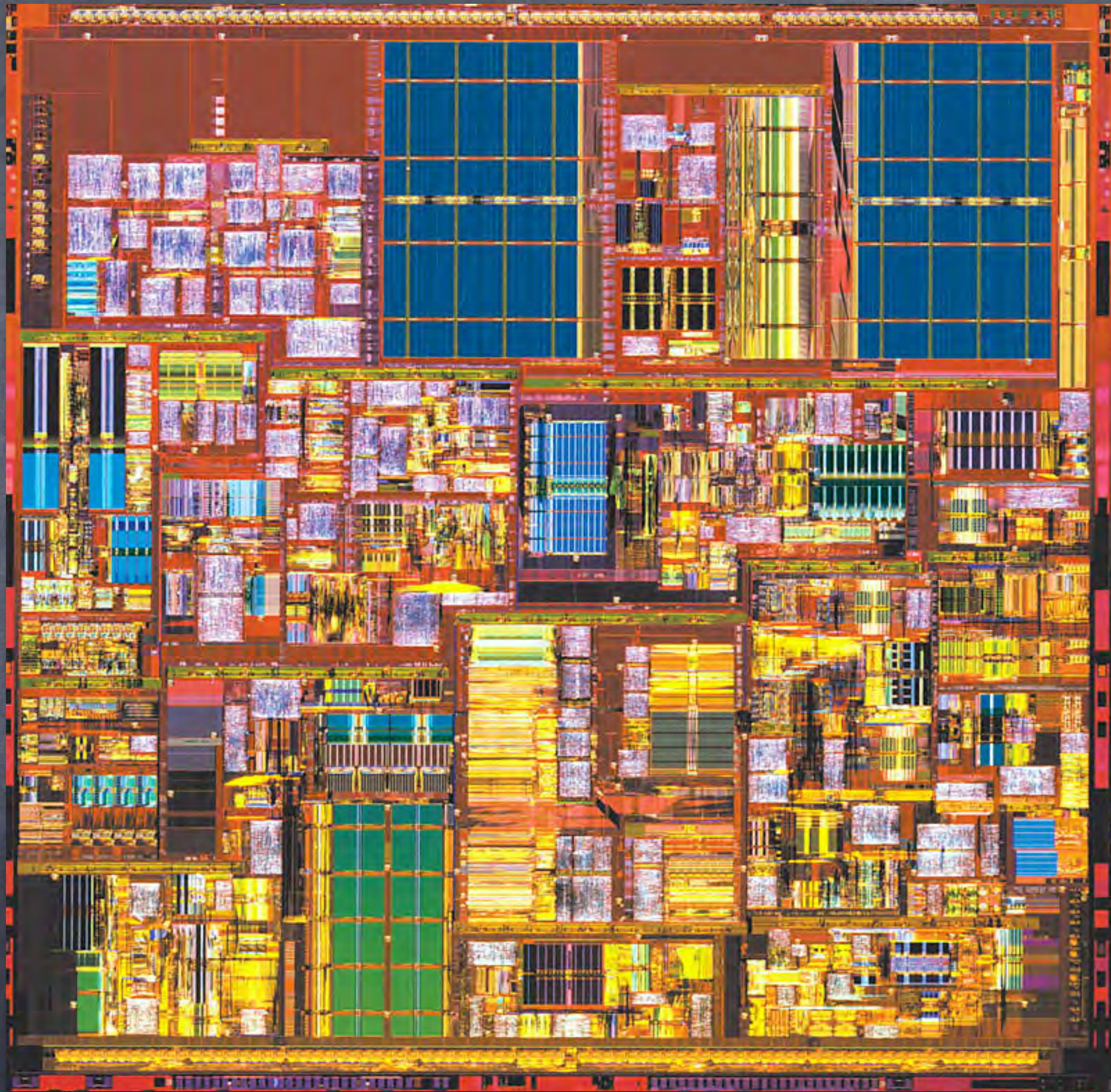
$P_1\cos\theta-P_2\sin\theta$
$P_1\sin\theta+P_2\cos\theta.$

nalogous commutation

$Q_1P_2]=0,$

f the state of the com-
values may not be as-
we may clearly assign

> In fact this new feature of natural philosophy means a radical revision of our attitude as regards physical reality



Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer*

Peter W. Shor†

A digital computer is generally believed to be an efficient universal computing device; that is, it is believed able to simulate any physical computing device with an increase in computation time by at most a polynomial factor. This may not be true when quantum mechanics is taken into consideration. This paper considers factoring integers and finding discrete logarithms, two problems which are generally thought to be hard on a classical computer and which have been used as the basis of several proposed cryptosystems. Efficient randomized algorithms are given for these two problems on a hypothetical quantum computer. These algorithms take a number of steps polynomial in the input size, e.g., the number of digits of the integer to be factored.

Quantum Algorithms - Putting Engtanglement to Work:
Factoring and Internet Security

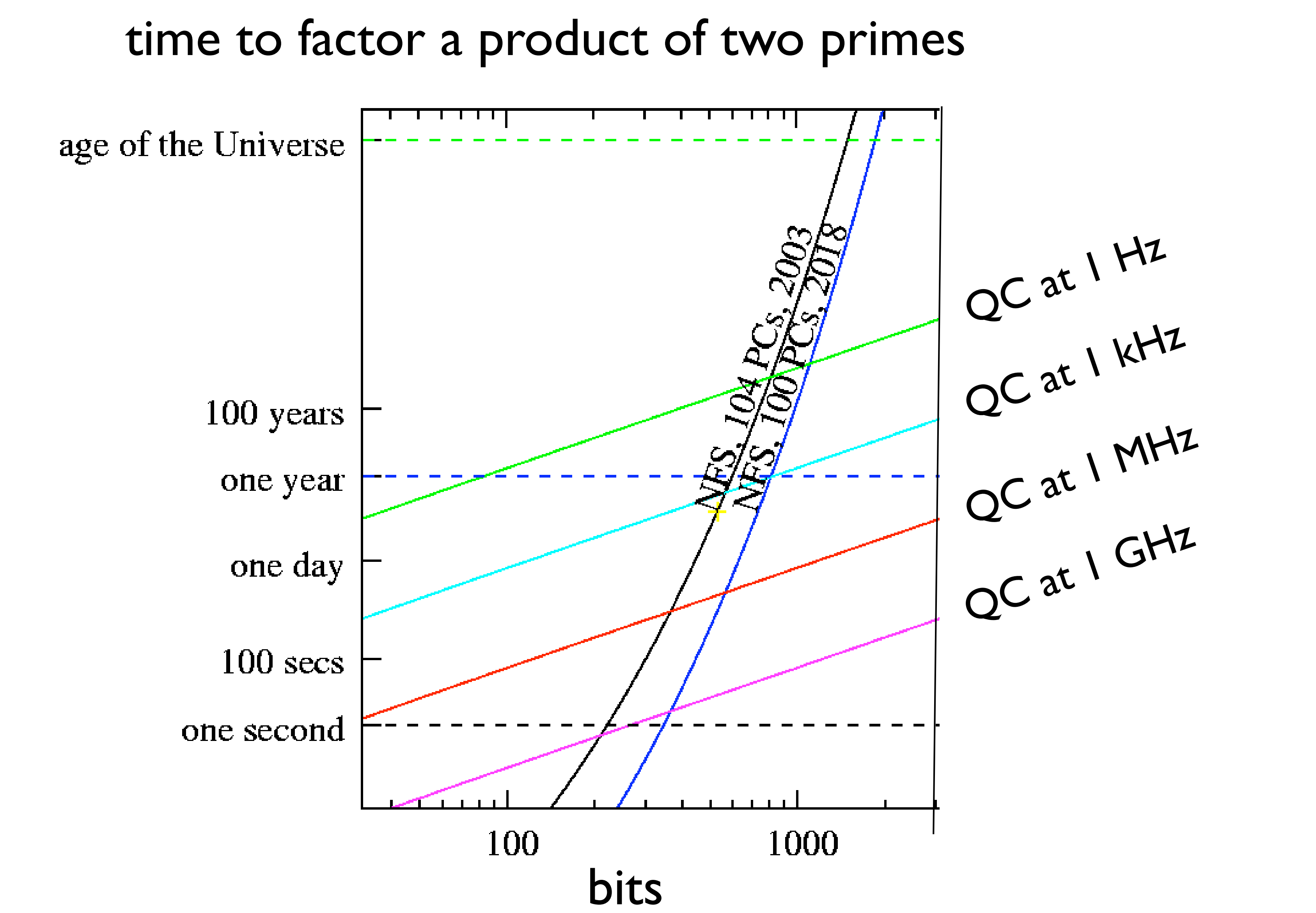
$$15 = \boxed{5} \times \boxed{3}$$

$$4633 = \boxed{41} \times \boxed{113}$$

RSA-129

114381625757888867669235779976146612010218296721242362562561842935706935245733897830597123563958705058989075147599290026879543541 =
3490529510847650949147849619903898133417764638493387843990820577 x 32769132993266709549961988190834461413177642967992942539798288533

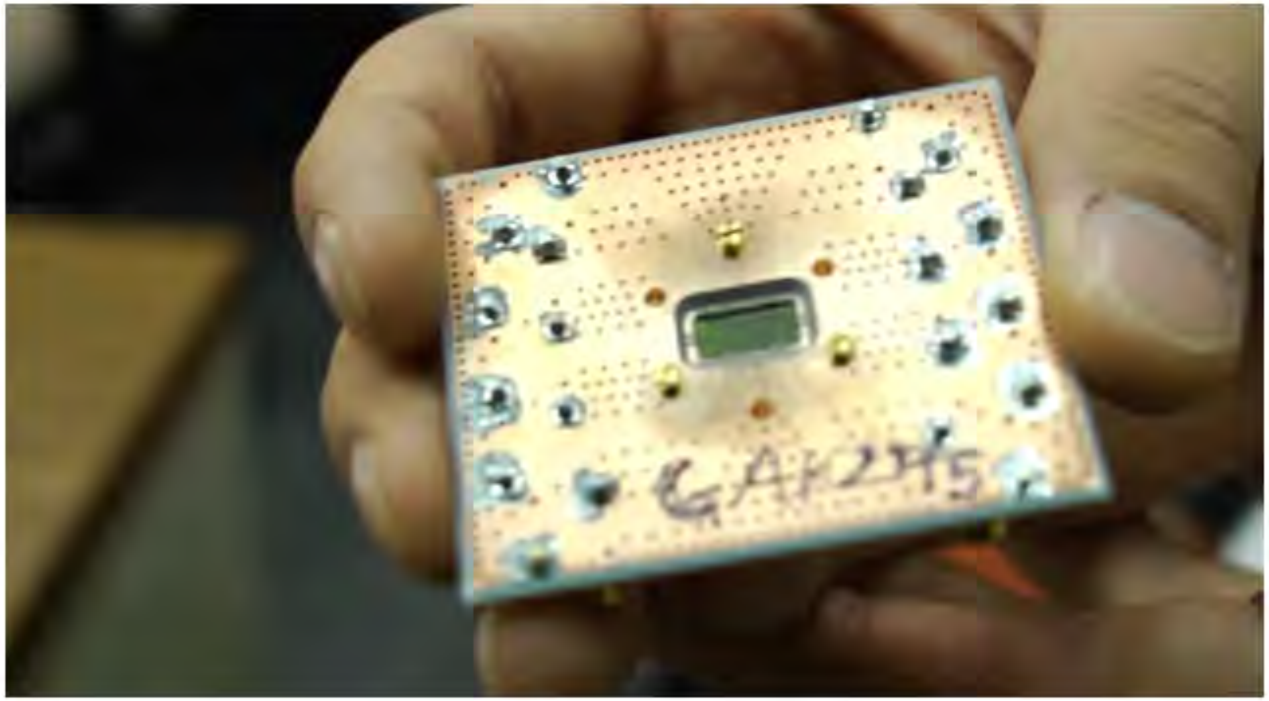
Comparing quantum and classical computation



van Meter et al 2006

IBM shows off quantum computing advances, says practical qubit computers are close

By Sebastian Anthony on February 28, 2012 at 7:03 am | **20 Comments**



Quantum scientists at IBM Research have announced major advances in quantum computing that could place real, practical quantum computers in businesses and homes within the next 10 years.

The main breakthrough revolves around the long-term integrity of qubits. To perform quantum computing, you need to be able to reliably store and interrogate qubits — but qubits are incredibly flighty creatures that readily change their state through *decoherence*. IBM has created a high-coherence 3D qubit that retains its state for up to 100 microseconds, or 0.1 milliseconds. This is stable enough that engineers can now shift their focus to scaling up the number of qubits to create a quantum logic computer.

The New York Times

Microsoft Makes Bet Quantum Computing Is Next Breakthrough

By **JOHN MARKOFF** JUNE 23, 2014

Michael Freedman, Sankar Das Sarma and Chetan Nayak proposed a computing model in 2005 that can be used to construct qubits, the foundation of quantum computing. Emily Berl for The New York Times

SANTA BARBARA, Calif. — Modern computers are not unlike the looms of the industrial revolution: They follow programmed instructions to weave intricate patterns. With a loom, you see the result in a cloth or carpet. With a computer, you see it on an electronic display.

Now a group of physicists and computer scientists funded by Microsoft is trying to take the analogy of interwoven threads to what some believe will be the next great leap in computing, so-called quantum computing.

If the scientists are right, their research could lead to the design of computers that are far more powerful than today's supercomputers and could solve problems in fields as diverse as chemistry, material science, artificial intelligence and code-breaking.

Google Launches Effort to Build Its Own Quantum Computer

Google's crack at a quantum computer is a bid to change computing forever.

By Tom Simonite on September 3, 2014

Google is about to begin designing and building hardware for a quantum computer, a type of machine that can exploit quantum physics to solve problems that would take a conventional computer millions of years.

Since 2009, Google has been working with controversial startup D-Wave Systems, which claims to make "the first commercial quantum computer." And last year Google purchased one of D-Wave's machines. But independent tests published earlier this year found no evidence that D-Wave's computer uses quantum physics to solve problems more efficiently than a conventional machine.

Quantum core: Techniques developed at the University of California, Santa Barbara, to build this device, known as a qubit, will be used to try to build a working quantum computer at Google.

Now John Martinis, a professor at University of California, Santa Barbara, has joined Google to establish a new quantum hardware lab near the university. He will try to make his own versions of the kind of chip inside a D-Wave machine.

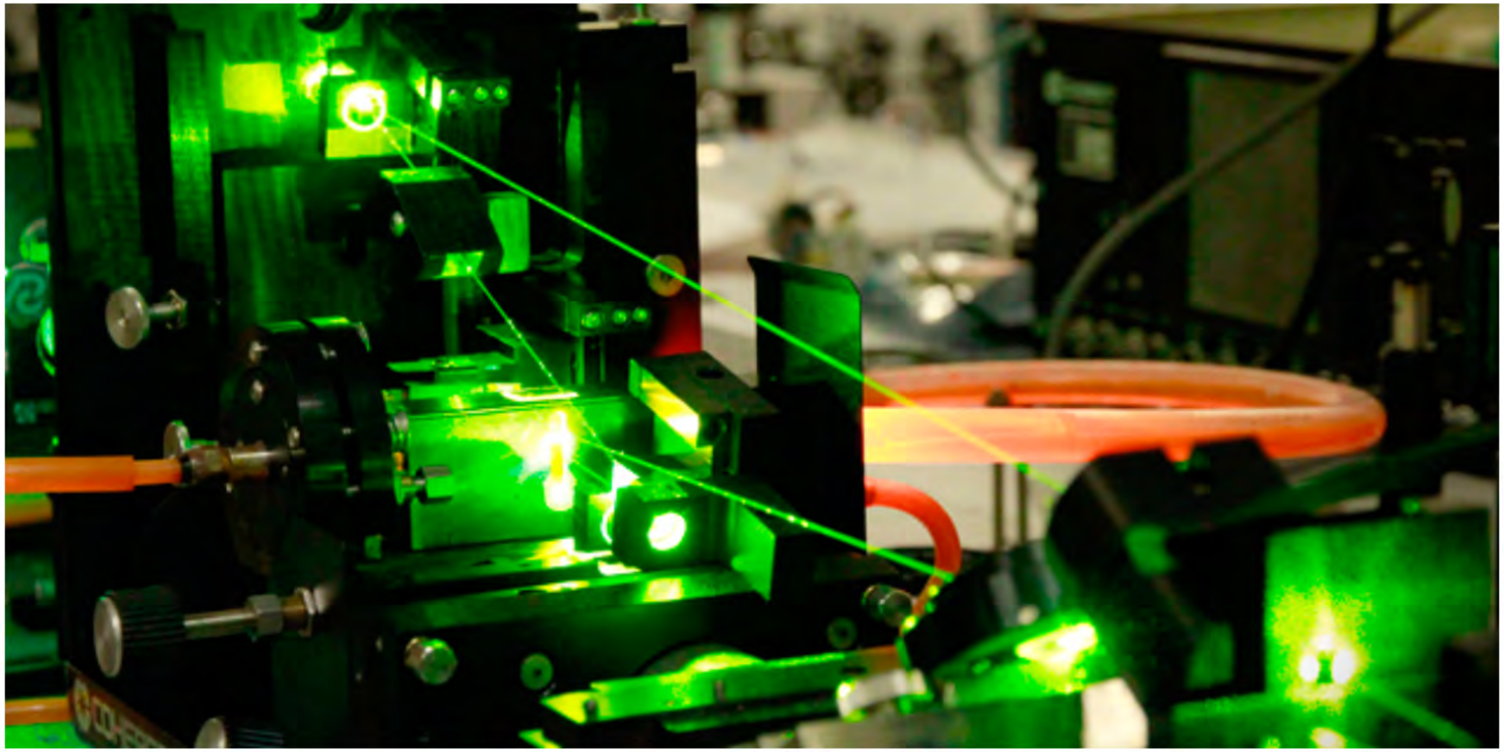
Martinis has spent more than a decade working on a more proven approach to quantum computing, and built some of the largest, most error-free systems of qubits, the basic building blocks that encode information in a quantum computer.

WHY IT MATTERS

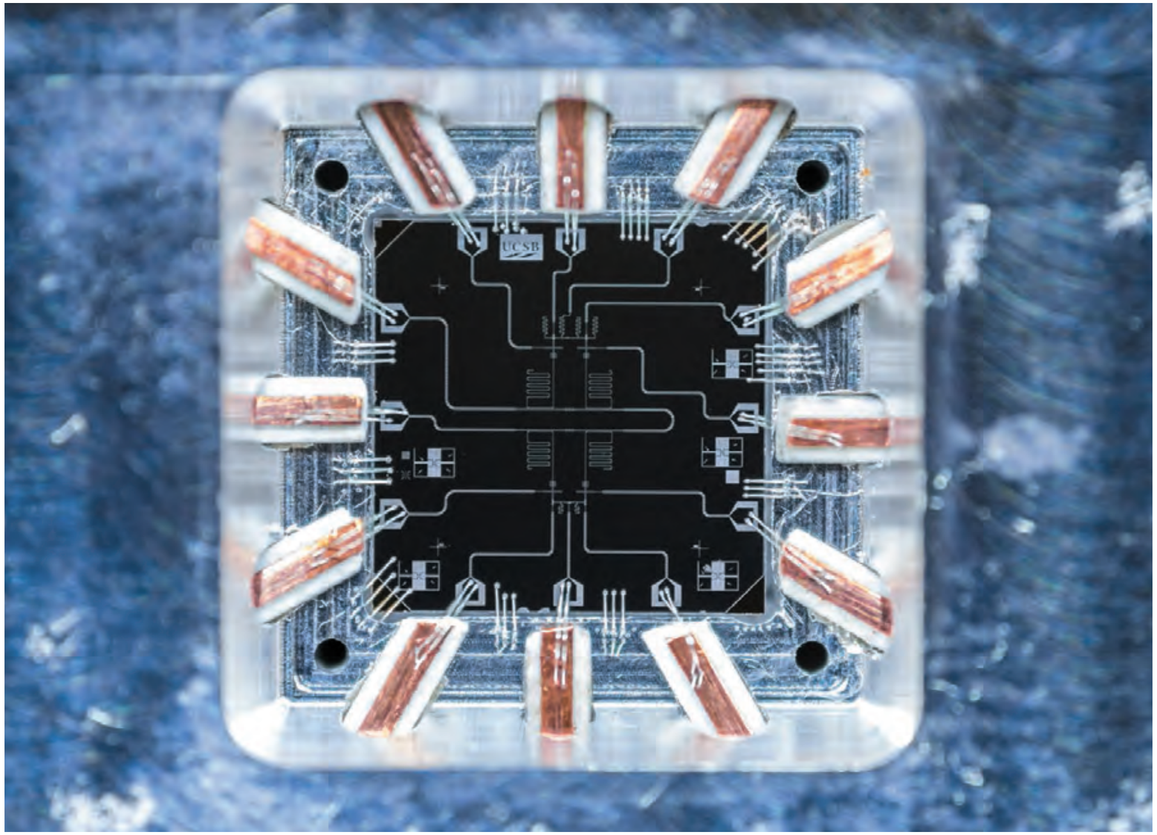
Practical quantum computers could solve problems that would take conventional machines millions of years.

Historic investment sends Denmark towards new quantum leaps

Denmark as the world centre of modern quantum technology - this is the ambition of Innovation Fund Denmark's new and so far largest investment of DKK 80m. The massive investment in leading Danish knowledge will pave the way for new products in the years to come and ensure that Danish companies are created based on quantum technology knowledge. So far18 companies have agreed to collaborate with the new Danish centre for quantum technology.



Pressrelease 2016.07.04


MICHAEL FANG / MARTINIS GROUP

A €1-billion (US$1.1-billion) European flagship project could advance the state of quantum computing.

FUNDING

Billion-euro boost for quantum tech

Third European Union flagship project will be similar in size and ambition to graphene and human-brain initiatives.

development of such technologies, which the commission calls part of a "second quantum revolution" (the first was the unearthing of the rules of the quantum realm, which led to the invention of tools such as lasers and transistors).

The initiative will include support for relatively near-to-market systems, such as quantum-communication networks, ultra-sensitive cameras and quantum simulators that could help to design new materials. It will also look long term, pushing more-futuristic visions such as all-purpose quantum computers and high-precision sensors that fit into mobile phones.

Success will be judged by how well the flagship boosts industry take up of the technologies and seeds investment in the field, says Calarco: "If this doesn't happen, it will be a failure. But everyone is very confident it will".

Quantum-technology projects already exist in a few individual European Union countries, such as the UK Quantum Technologies Programme and the Netherlands' QuTech initiative, notes Marco Genovese, a quantum physicist at the Italian National Institute of Metrological Research in Turin. But to reach commercial level in the near future, an EU-wide initiative is essential, he says. "At the moment, EU industry is still only marginally involved," he says.

Europe's graphene and brain-project flagships were announced with great fanfare in 2013, after a multiyear competition, but the latest initiative has had a much quieter birth. Calarco says that it was driven by an 18-month dialogue between the commission and a group of researchers who, at the organization's request, produced the manifesto.

Not everyone is pleased with this approach. Choosing flagships on the basis of bilateral discussions and manifestos risks turning them into "a competition of lobbying, rather than

Information Assurance

- About IA at NSA
- IA Client and Partner Support
- IA News
- IA Events
- IA Mitigation Guidance
- IA Academic Outreach
- IA Business and Research
- IA Programs
  - Commercial Solutions for Classified Program
  - Global Information Grid
  - High Assurance Platform
  - Inline Media Encryptor
  - **Suite B Cryptography**
  - NSA Mobility Program

Cryptography Today

In the current global environment, rapid and secure information sharing is important to protect our Nation, its citizens and its interests. Strong cryptographic algorithms and secure protocol standards are vital tools that contribute to our national security and help address the ubiquitous need for secure, interoperable communications.

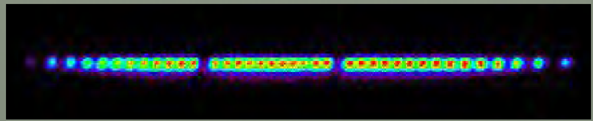
Currently, Suite B cryptographic algorithms are specified by the National Institute of Standards and Technology (NIST) and are used by NSA's Information Assurance Directorate in solutions approved for protecting classified and unclassified National Security Systems (NSS). Below, we announce preliminary plans for transitioning to quantum resistant algorithms.

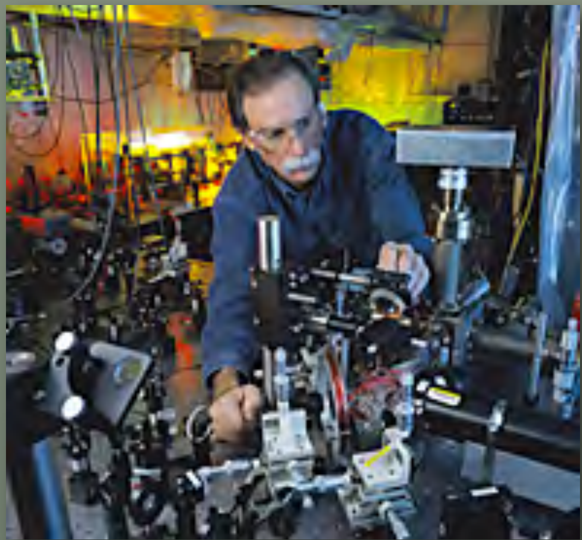
Background

IAD will initiate a transition to quantum resistant algorithms in the not too distant future. Based on experience in deploying Suite B, we have determined to start planning and communicating early about the upcoming transition to quantum resistant algorithms. Our ultimate goal is to provide cost effective security against a potential quantum computer. We are working with partners across the USG, vendors, and standards bodies to ensure there is a clear plan for

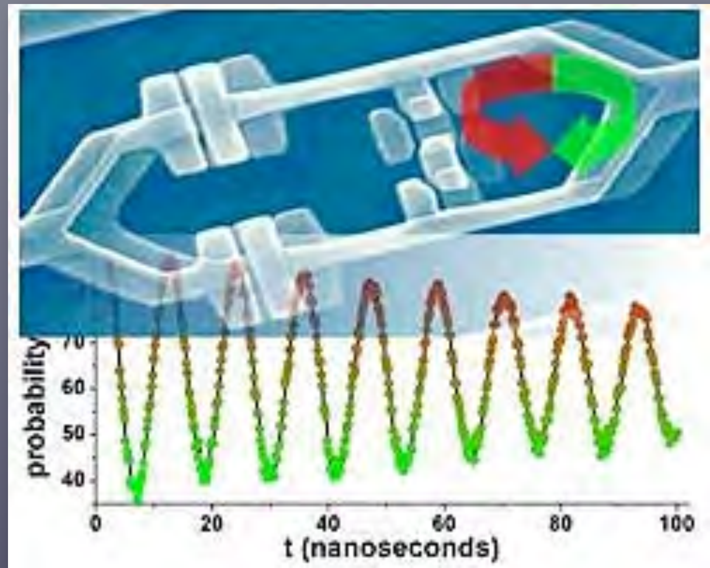
making controllable qubits

ion traps

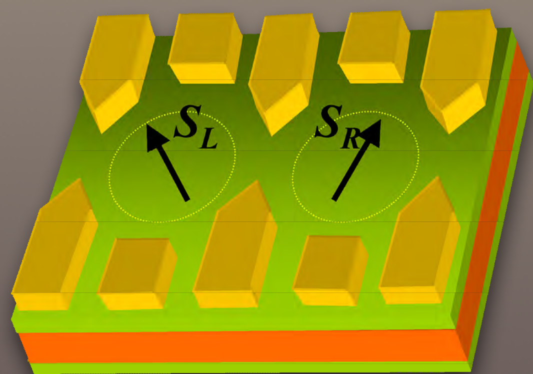




Josephson devices



Electron Spins in Dots



PHYSICAL REVIEW A VOLUME 57, NUMBER 1 JANUARY 1998

Quantum computation with quantum dots

Daniel Loss[1,2,*] and David P. DiVincenzo[1,3,†]
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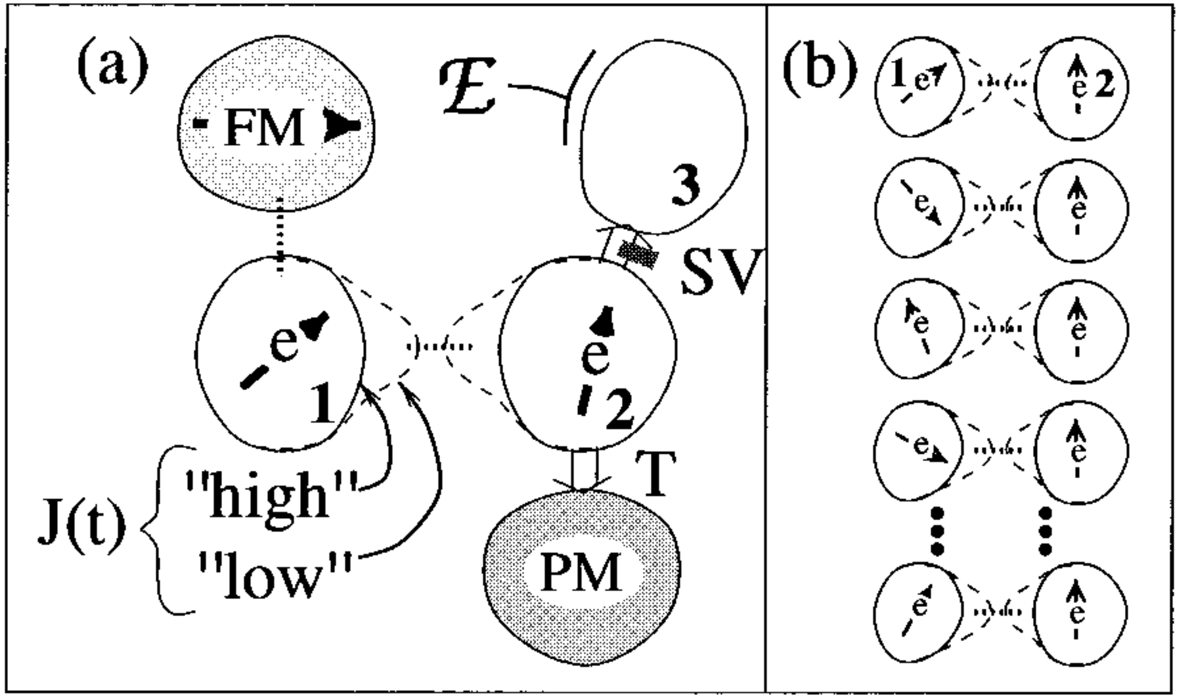
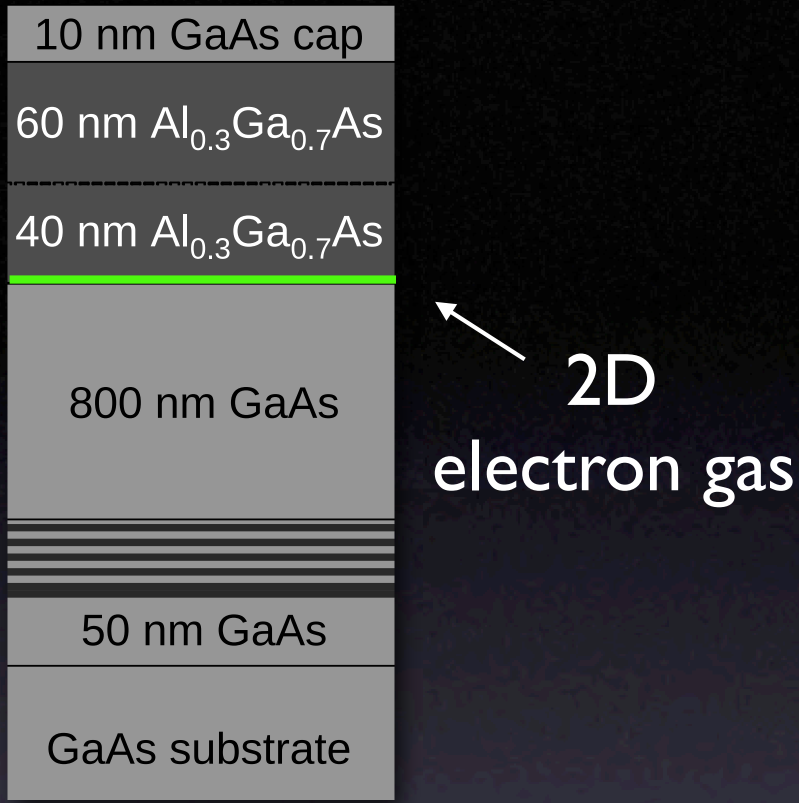
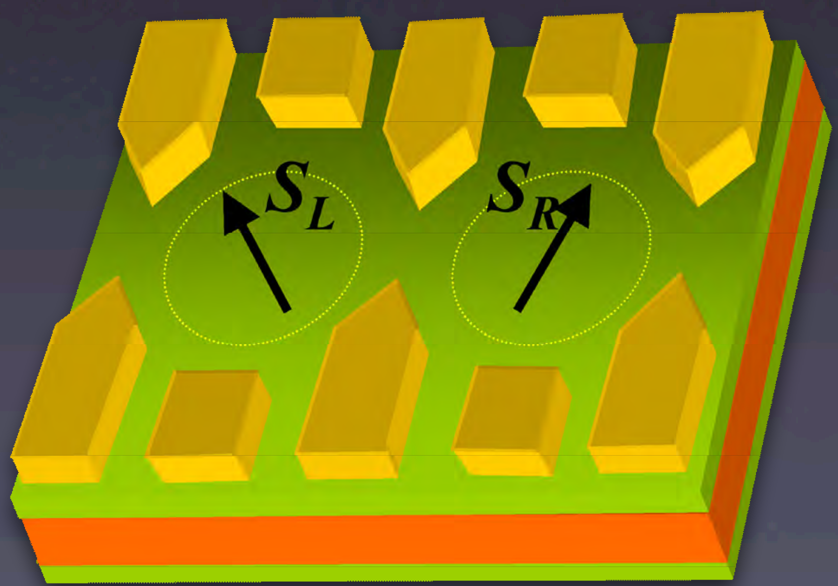
(Received 9 January 1997; revised manuscript received 22 July 1997)

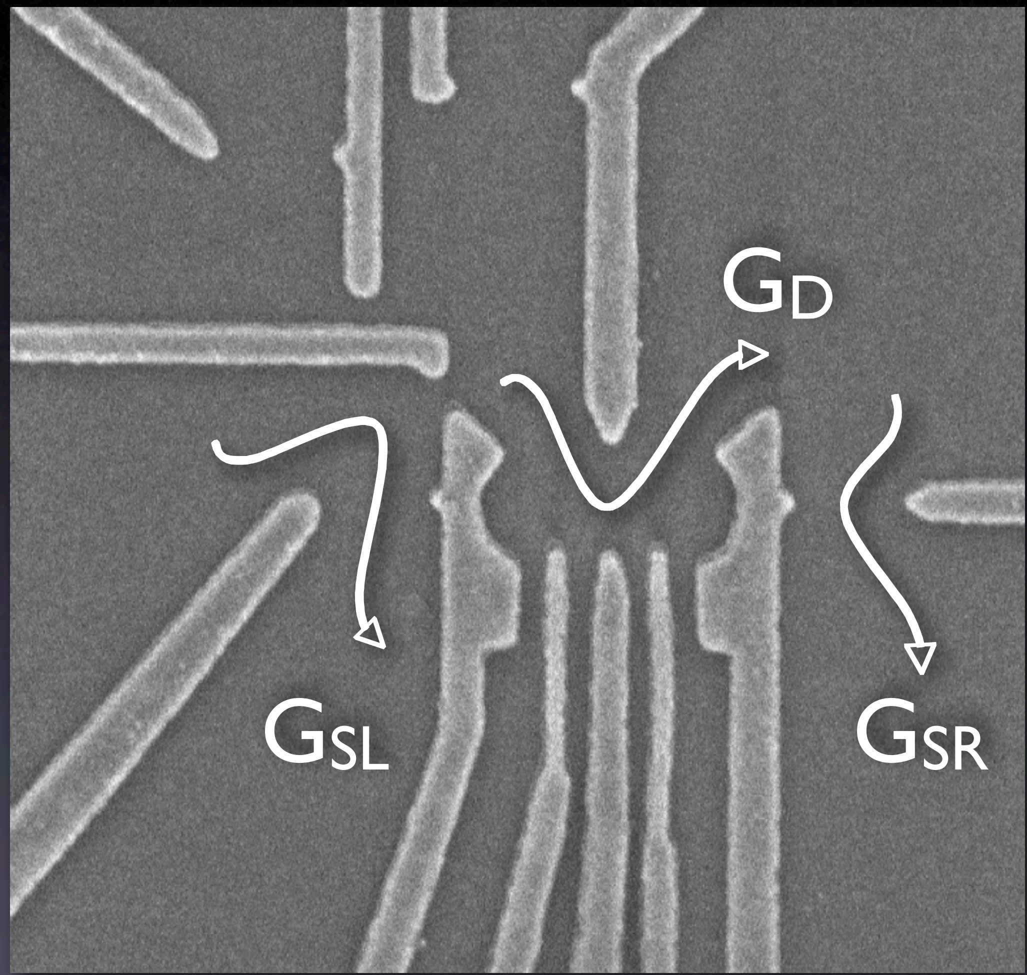
We propose an implementation of a universal set of one- and two-quantum-bit gates for quantum computation using the spin states of coupled single-electron quantum dots. Desired operations are effected by the gating of the tunneling barrier between neighboring dots. Several measures of the gate quality are computed within a recently derived spin master equation incorporating decoherence caused by a prototypical magnetic environment. Dot-array experiments that would provide an initial demonstration of the desired nonequilibrium spin dynamics are proposed. [S1050-2947(98)04501-6]



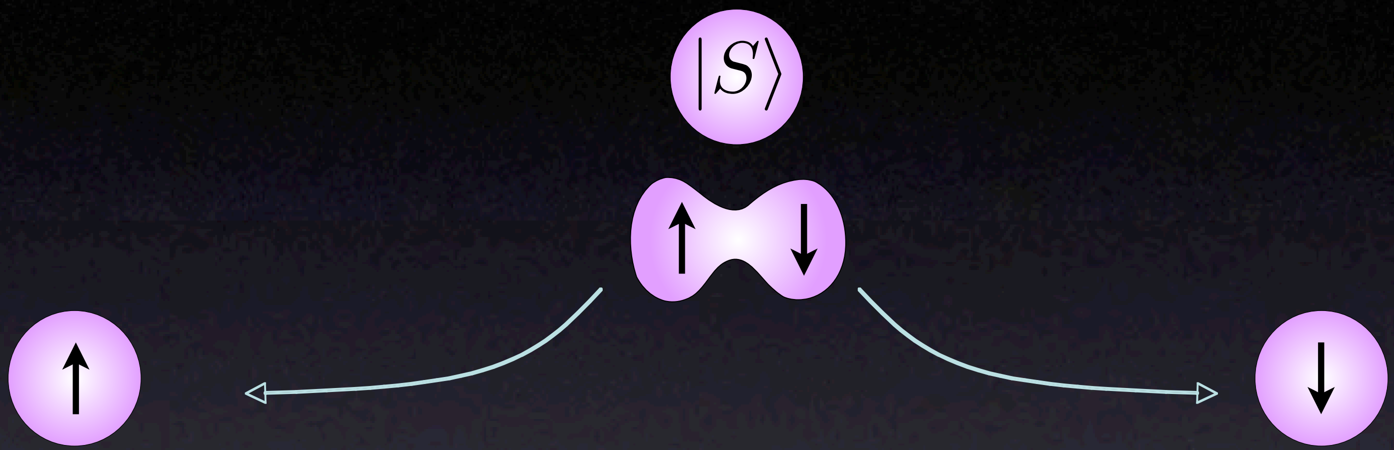
Semiconductor Double Dot Device

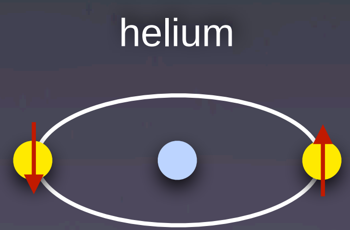




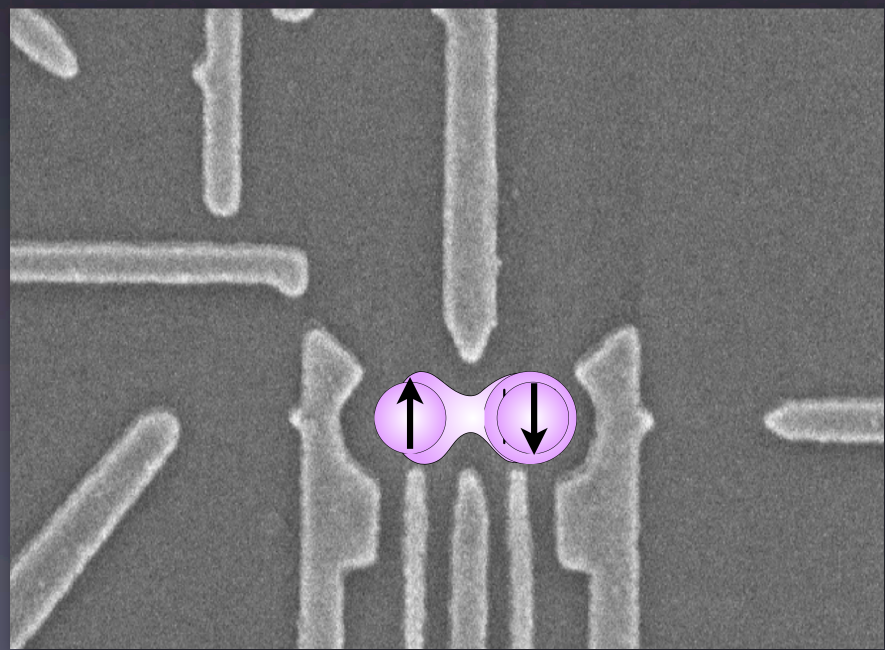


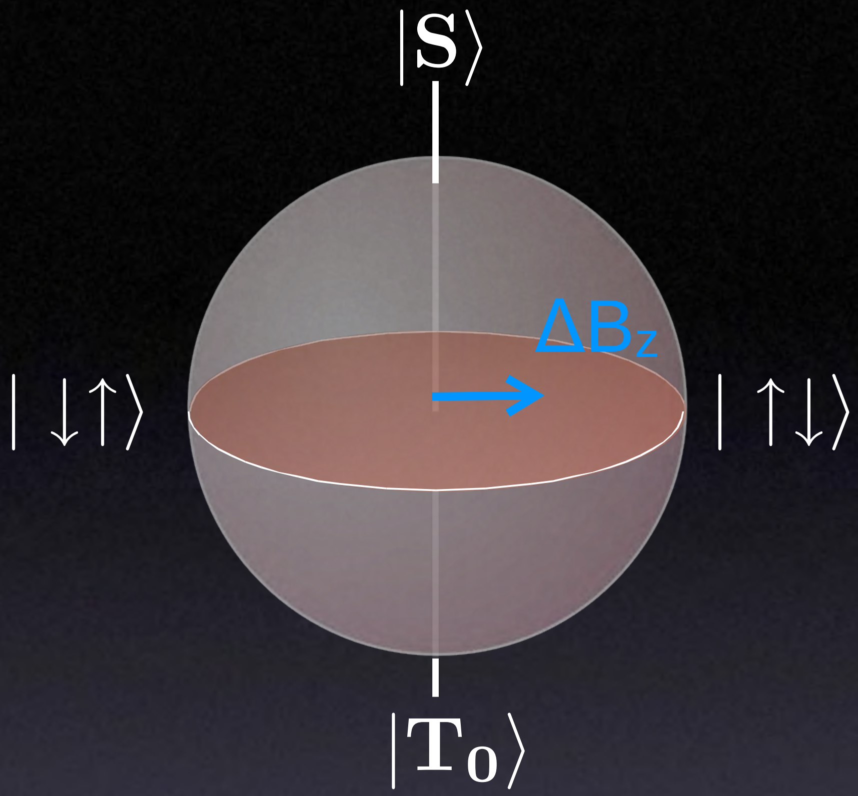
Artificial Helium Atom - Hydrogen Molecule:
An entanglement generator





$$|S\rangle = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

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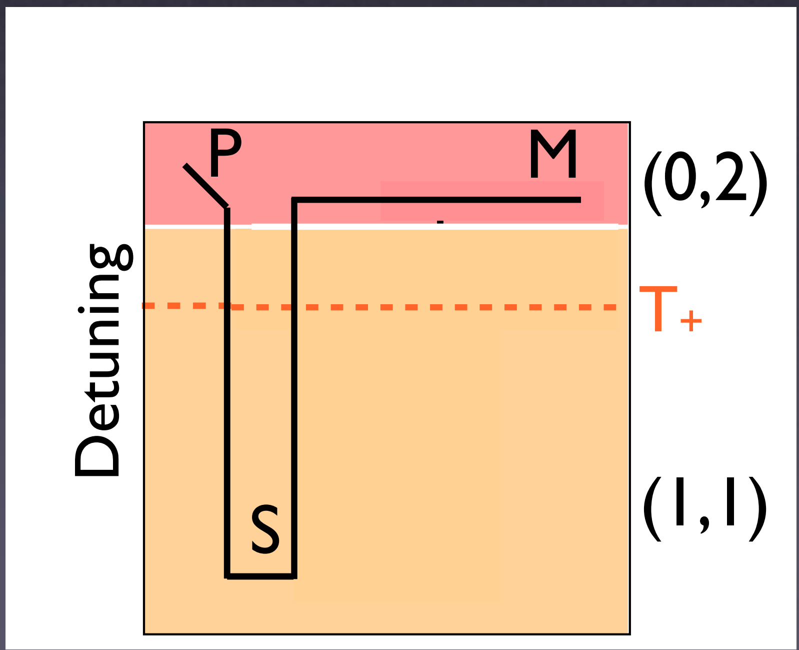
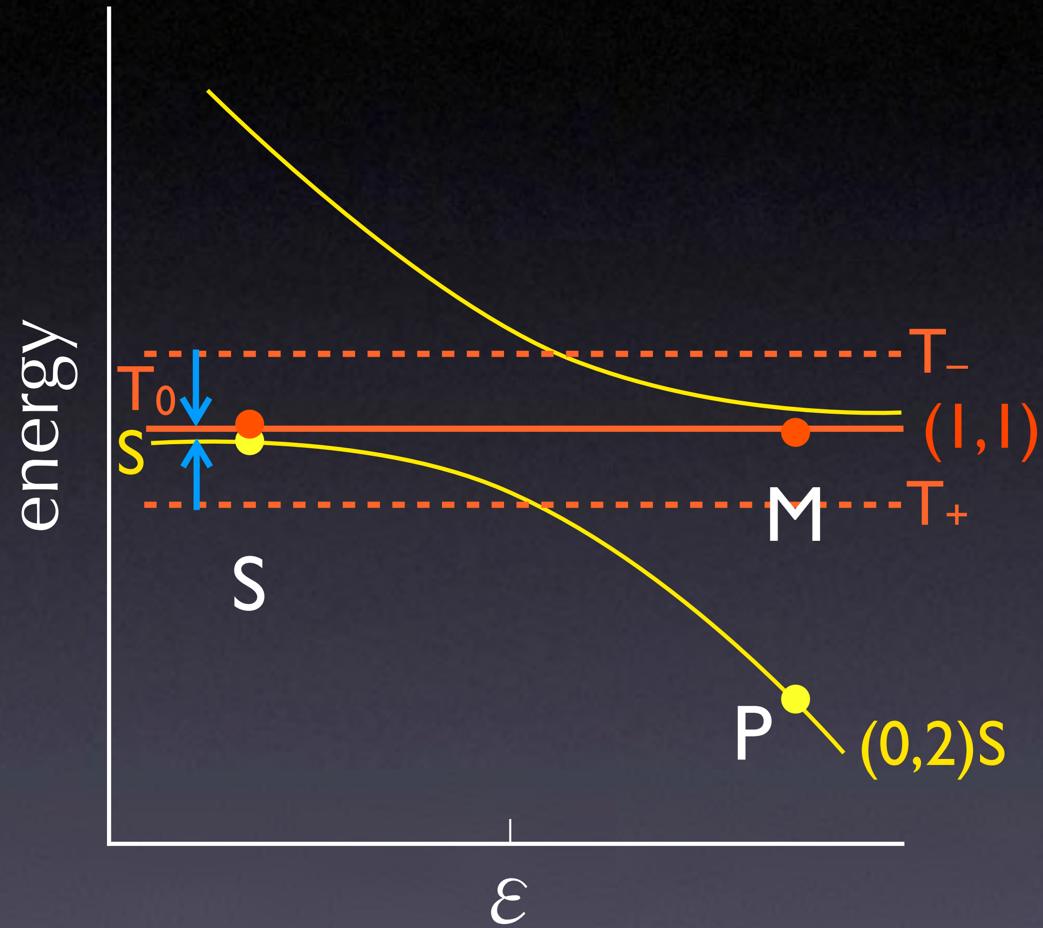
ΔBz
| ↓↑⟩
| ↑↓⟩
|T0⟩


P
M
(0,2)
Detuning
T+
S
(1,1)


energy
T–
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(1,1)
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T+
S
P
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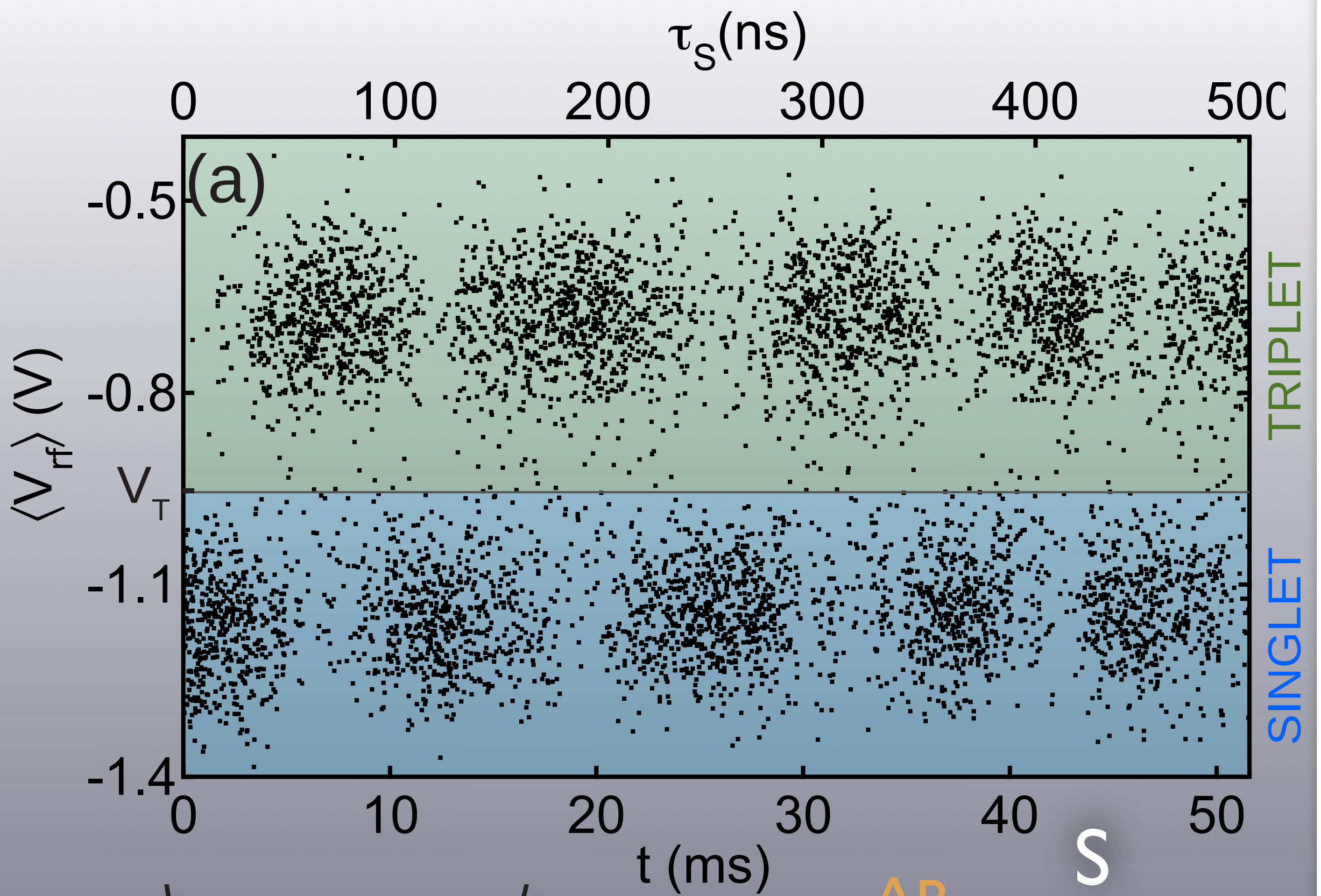
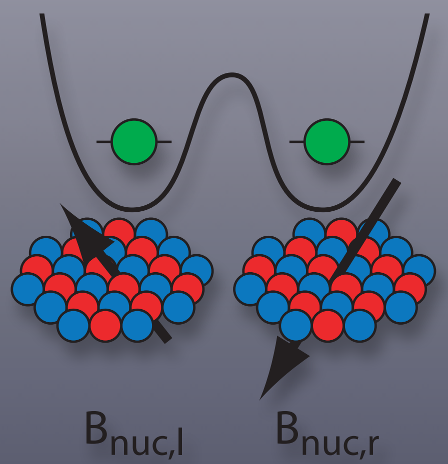
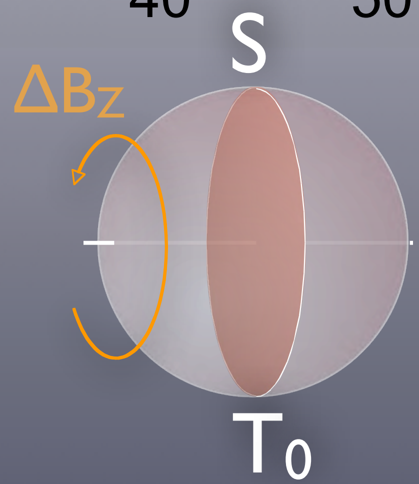
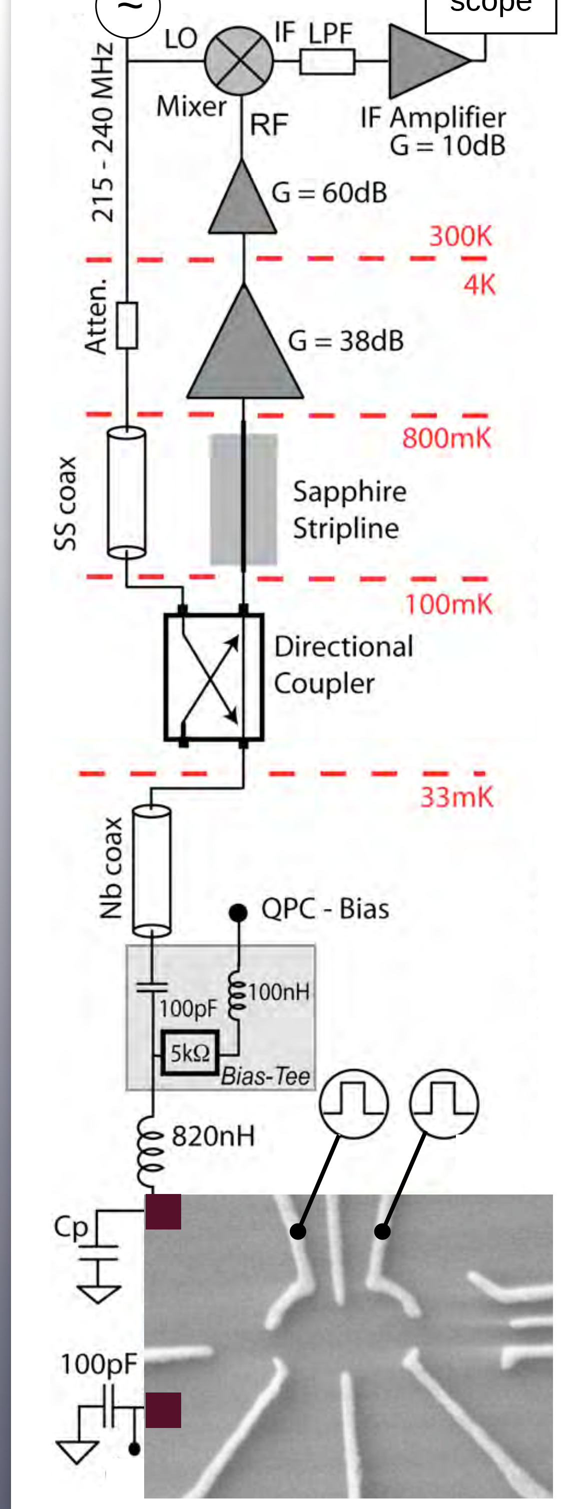
ε

Single-shot S-T detection









C. Barthel et al., Phys. Rev. Lett. 103, 160503 (2009).

Gate fidelity and coherence of an electron spin in an Si/SiGe quantum dot with micromagnet

Erika Kawakami[a,b], Thibaut Jullien[a,b,1], Pasquale Scarlino[a,b], Daniel R. Ward[c], Donald E. Savage[c], Max G. Lagally[c], Viatcheslav V. Dobrovitski[d], Mark Friesen[c], Susan N. Coppersmith[c,2], Mark A. Eriksson[c], and Lieven M. K. Vandersypen[a,b,e,2]

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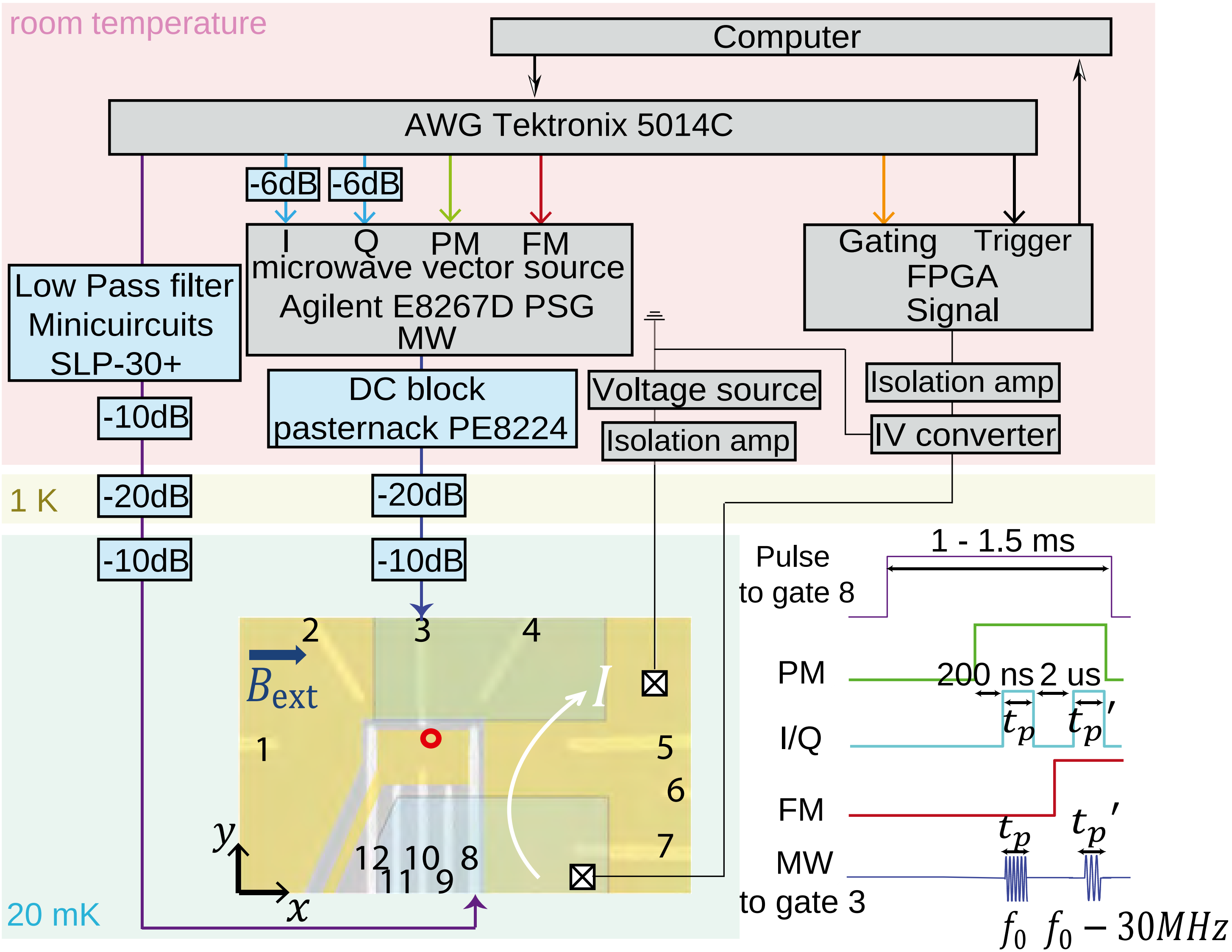

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journal homepage: www.elsevier.com/locate/ssc

Towards 0.99999 ^{28}Si

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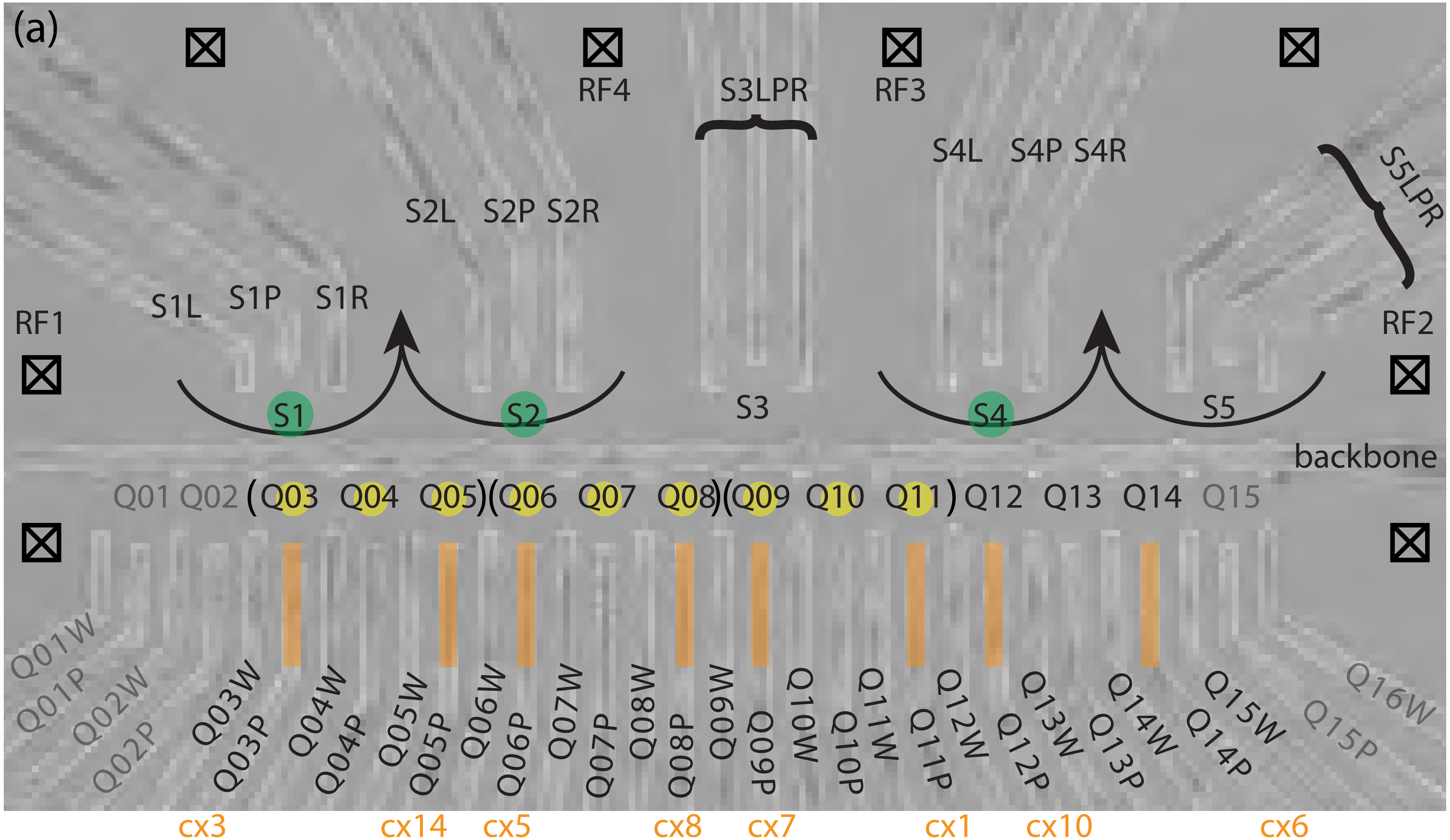
E. ECR discharge
E. PECVD

ABSTRACT

A new approach for producing high-purity silicon with isotopic enrichment of ^{28}Si isotope is reported. The methods of centrifugal enrichment were modified to obtain the initial gaseous silicon tetrafluoride with a record-breaking enrichment of 0.99999664(11) with respect to ^{28}Si. The effective conversion of silicon tetrafluoride into elementary silicon with minimal isotopic dilution was achieved in an electron cyclotron resonance discharge plasma, sustained by gyrotron microwave radiation with a frequency of 24 GHz. We have experimentally demonstrated the deposition of the layers of microcrystalline ^{28}Si with enrichment of 0.999986 ± 0.000003, which is the best result at the present time.

The Full Monty



built: 15 dots, 5 sensors

wired and operating: 13 dots, 3 multiplexed fast sensors,

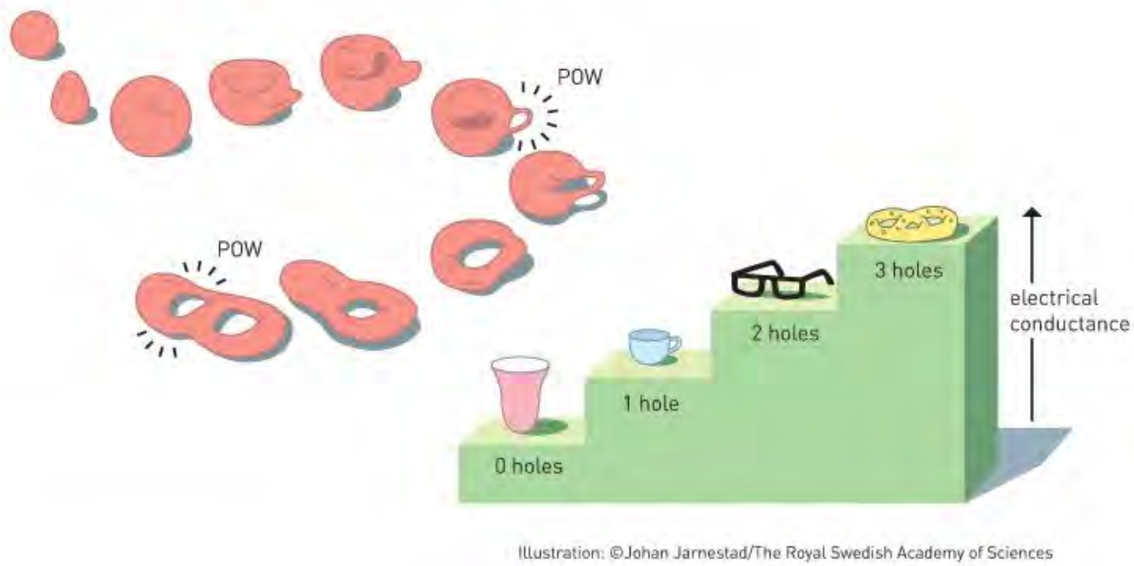
8 synchronized AWG channels

Nobelpris i fysik: Topologisk forståelse kan føre til nye materialer og kvantecomputere

Teoretiske opdagelser fra 1970'erne og 1980'erne af betydning for nye elektroniske produkter og kvantecomputere belønnes med dette års Nobelpris i fysik.

Af Jens Ramskov 4. okt 2016 kl. 12:54

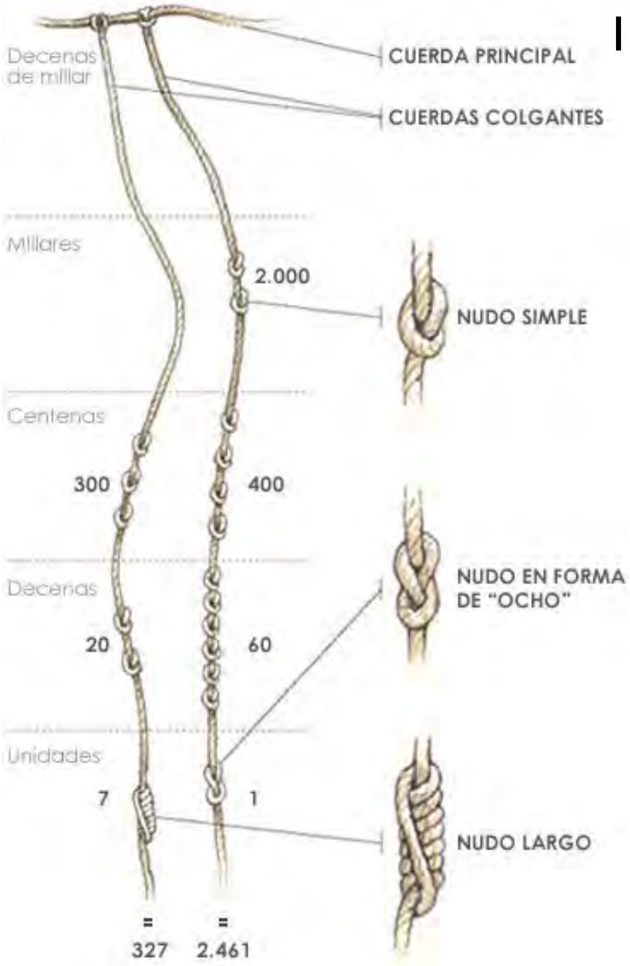
Årets Nobelprismodtagere i fysik: David Thouless, Duncan Haldane og Michael Kosterlitz (Ill: Nobelprize.org)



Topologi: En bold kan gradvist omformes til en kop uden hank, de er topologisk ens. Men det kræver en trinvis ændring at sætte hank på koppen, som nu er topologisk forskellig fra bolden. Det kræver endnu en trinvis ændring at lave et par briller osv. (Grafik Nobelprize.org)

Storing Information in Knots

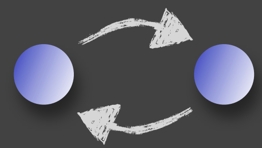
1590



quipu: a 5000 year old technology

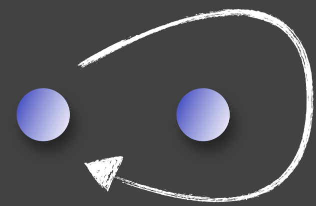
In reduced dimension, particle histories can be tied in knots (they say.)

3 dimensions



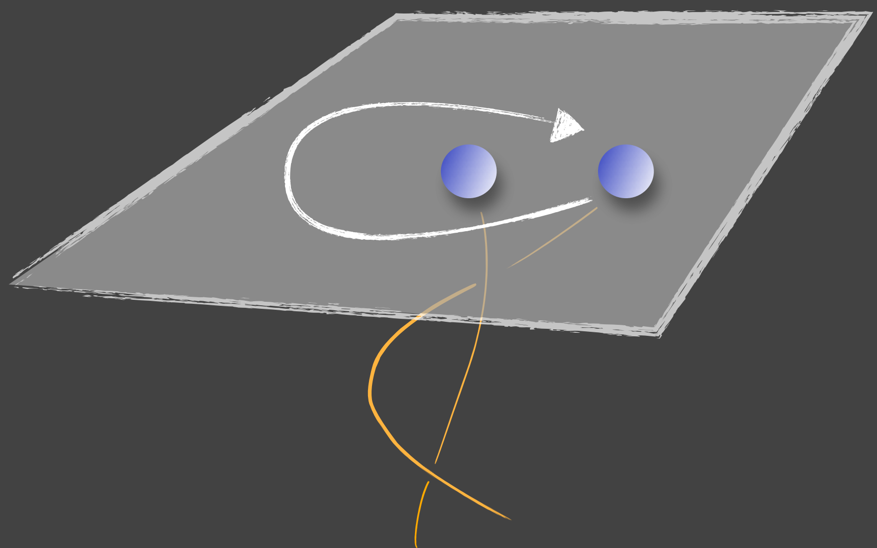
$$|\psi\rangle \longrightarrow |\psi\rangle$$ Bosons

$$|\psi\rangle \longrightarrow -|\psi\rangle$$ Fermions



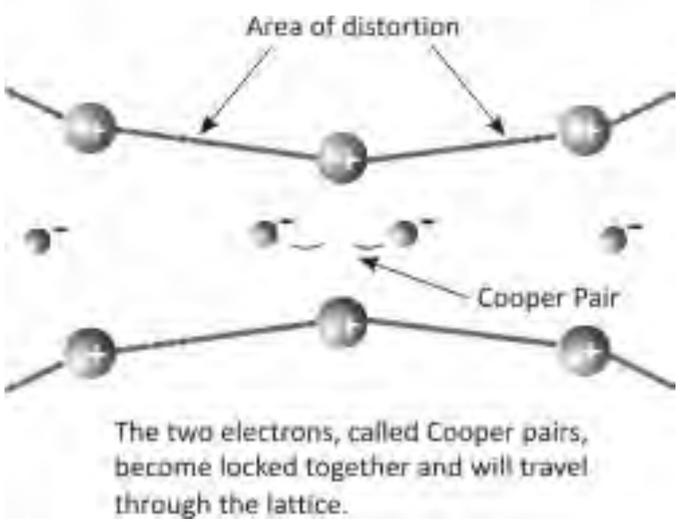
$$|\psi\rangle \longrightarrow |\psi\rangle$$

2 dimensions

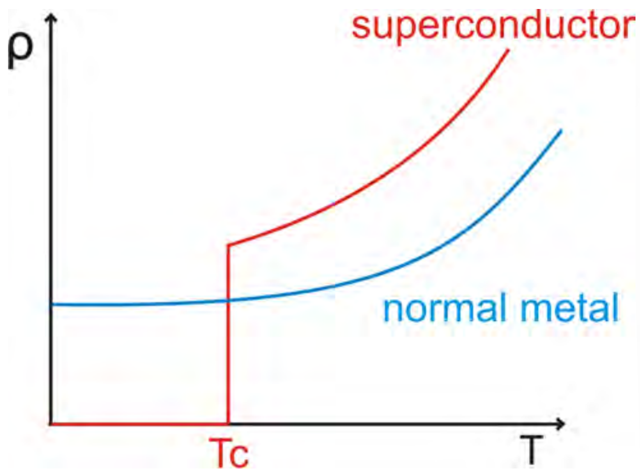


$$|\psi_1\rangle \longrightarrow |\psi_2\rangle$$

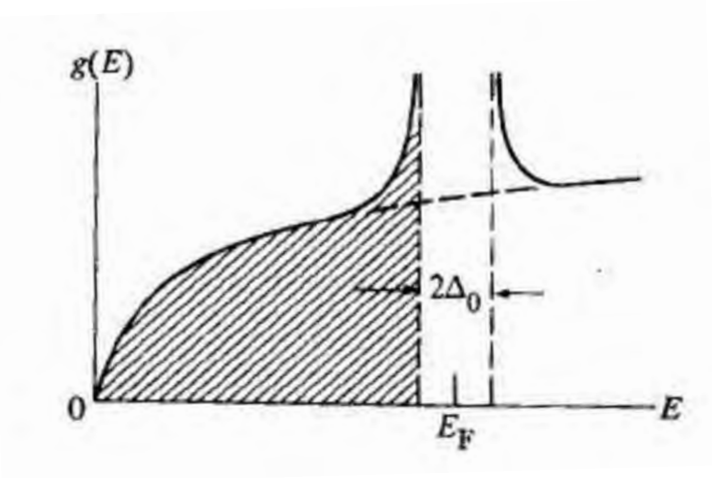
Superconductivity



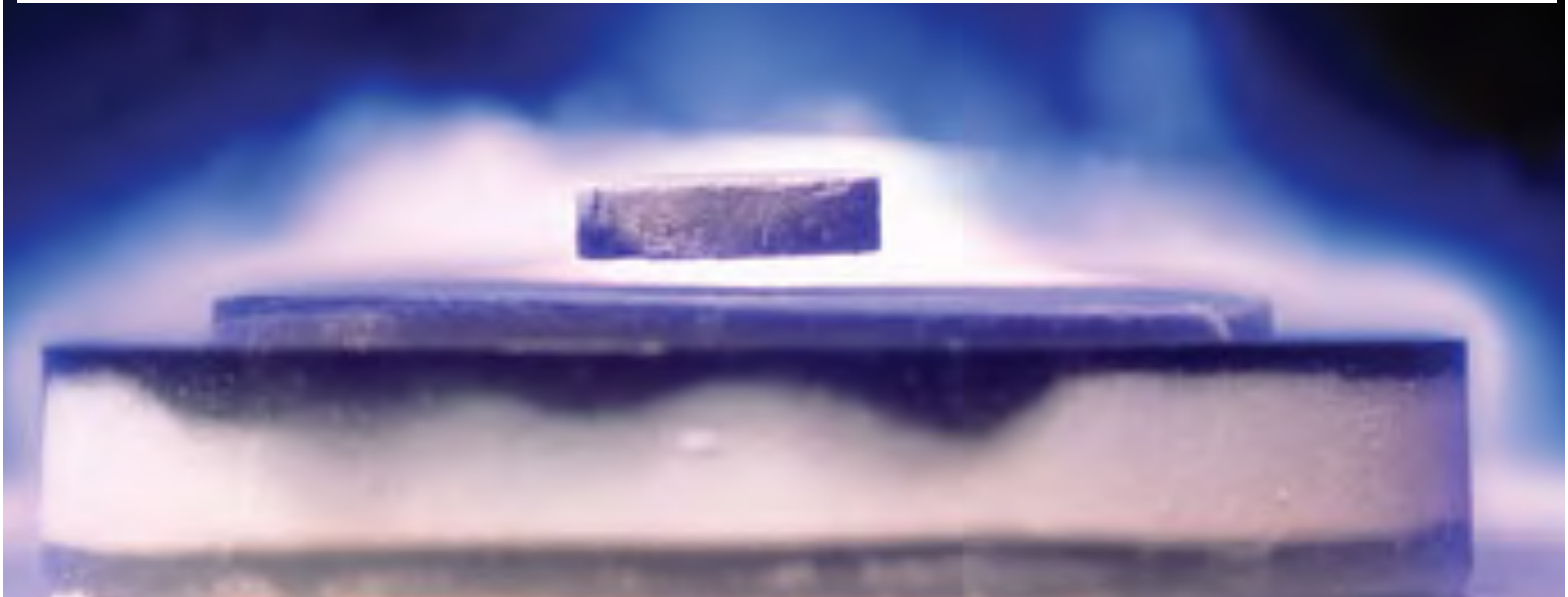
Pairing of electrons



Zero resistance



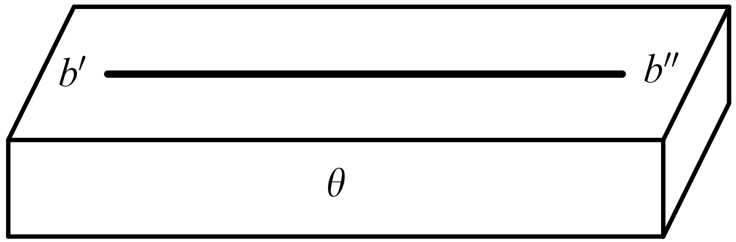
A gap at the Fermi surface



Unpaired Majorana fermions in quantum wires

A Yu Kitaev

Abstract. Certain one-dimensional Fermi systems have an energy gap in the bulk spectrum while boundary states are described by one Majorana operator per boundary point. A finite system of length L possesses two ground states with an energy difference proportional to $\exp(-L/l_0)$ and different fermionic parities. Such systems can be used as qubits since they are intrinsically immune to decoherence. The property of a system to have boundary Majorana fermions is expressed as a condition on the bulk electron spectrum. The condition is satisfied in the presence of an arbitrary small energy gap induced by proximity of a three-dimensional p-wave superconductor, provided that the normal spectrum has an odd number of Fermi points in each half of the Brillouin zone (each spin component counts separately).



† It appears that only a triplet (p-wave) superconductivity in the three-dimensional substrate can effectively induce the desired pairing between electrons with the same spin direction — at least, this is true in the absence of spin-orbit interaction.

Helical Liquids and Majorana Bound States in Quantum Wires

Yuval Oreg,[1] Gil Refael,[2] and Felix von Oppen[3]
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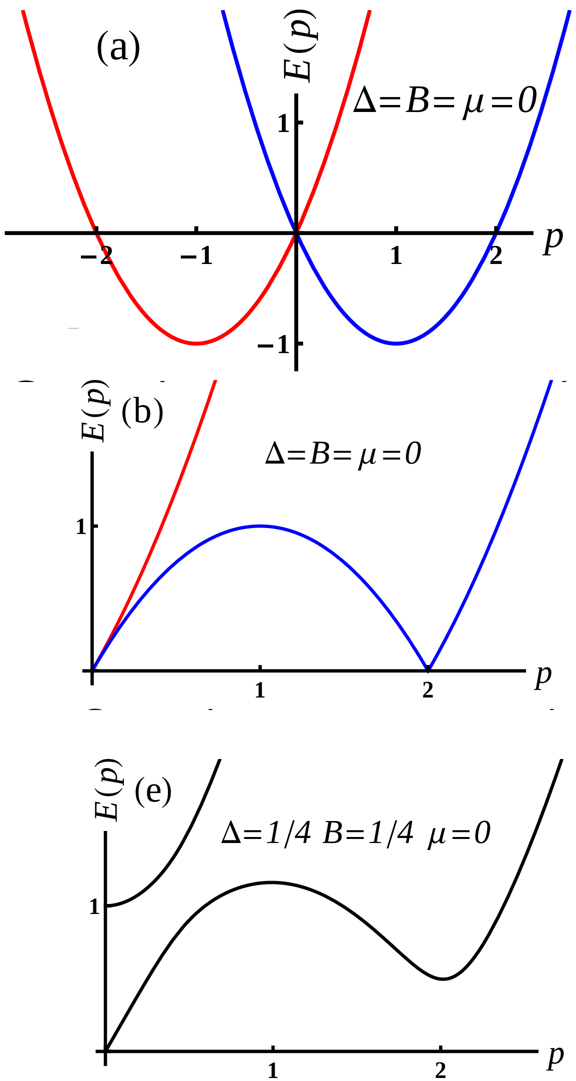
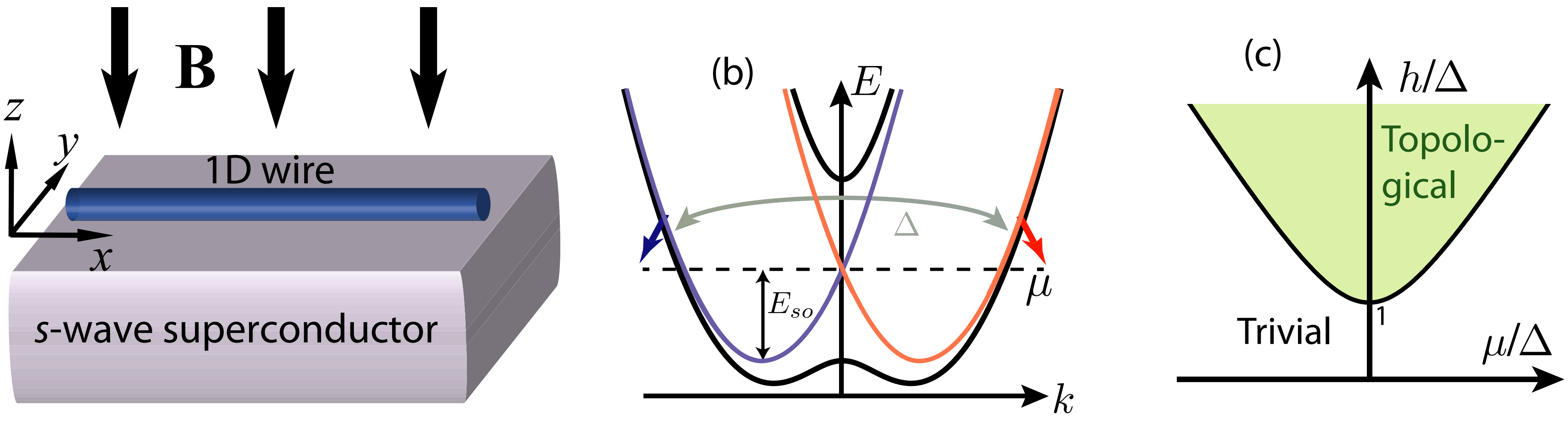
[2]Department of Physics, California Institute of Technology, Pasadena, California 91125, USA
[3]Dahlem Center for Complex Quantum Systems and Fachbereich Physik, Freie Universität Berlin, 14195 Berlin, Germany
(Received 16 March 2010; published 20 October 2010)



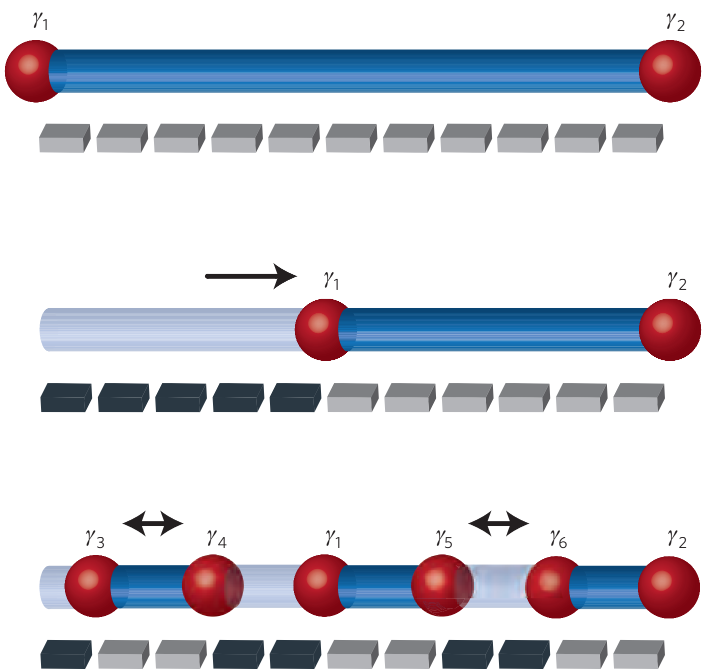
$$E_{\pm}^2 = B^2 + \Delta^2 + \xi_p^2 + (up)^2 \pm 2\sqrt{B^2\Delta^2 + B^2\xi_p^2 + (up)^2\xi_p^2},$$

A more promising candidate is a wire of InAs in the wurtzite structure, known to have strong spin-orbit coupling [17]. The velocity u in the Hamiltonian equation (1) is related to the experimentally measured length scale $\lambda_{S0} = 100$ nm $= mu$ and $\Delta_{SO} = 250\ \mu V = mu^2/2$ via $u \sim \hbar 2\Delta_{SO}\lambda_{SO} \approx 7.6 \times 10^6$ cm/sec and $m = \hbar^2/\lambda_{SO}^2 2\Delta = 0.015 m_e$, with m_e the free electron mass. Similar numbers (with $\Delta = 280\ \mu V$) describe newly fabricated InSb wires, except with a large g factor of $\sim$50, compared to $g \sim 8$ in InAs, requiring only a small, relatively innocuous to the SC, magnetic field [18].

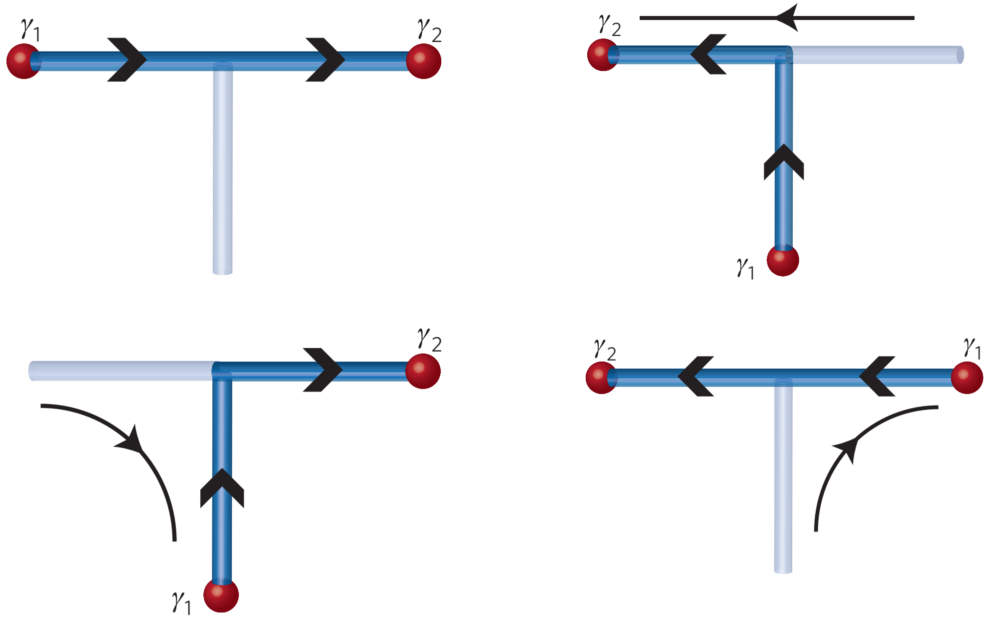
Making Spinless 1D superconductors



creation and movement

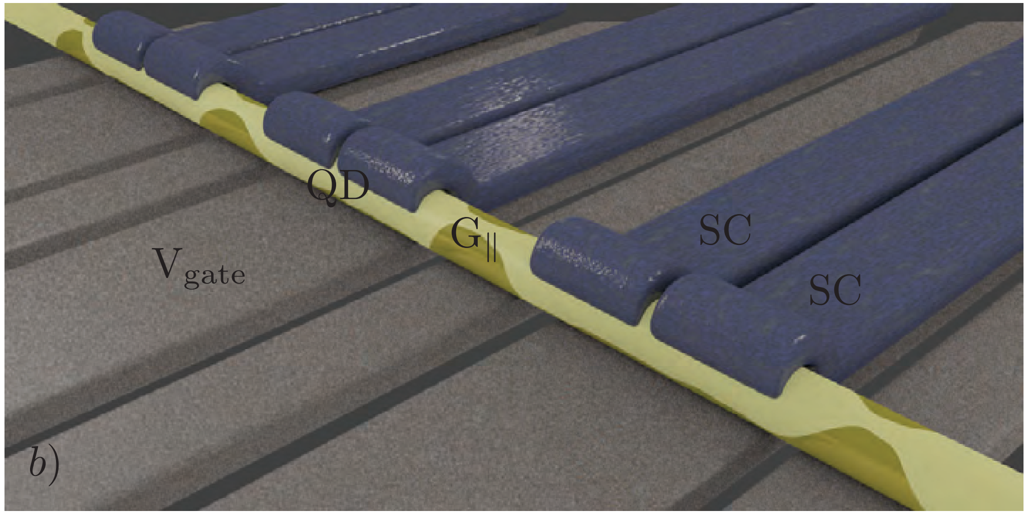


braiding

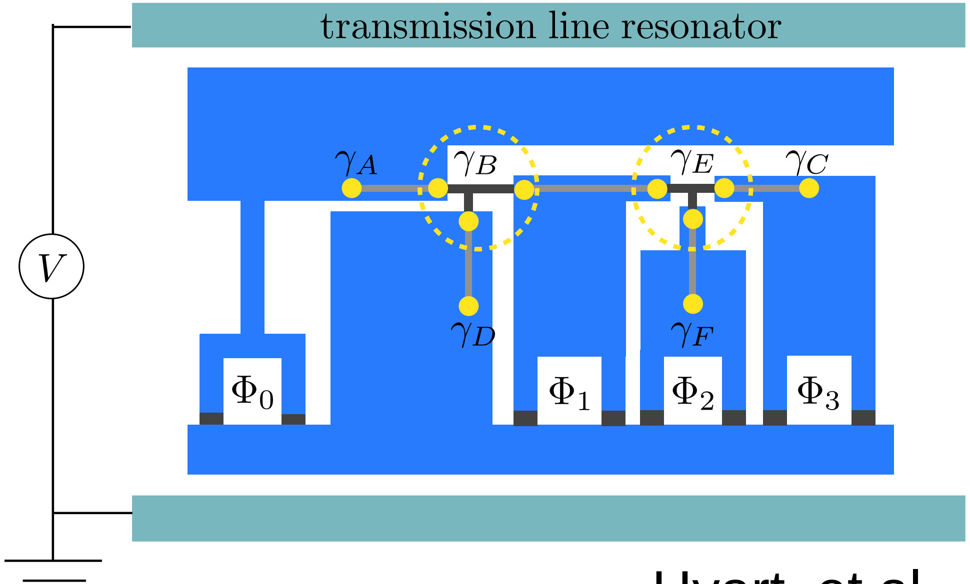


J. Alicea, *Rep. Prog. Phys.* **75**, 076501 (2012).

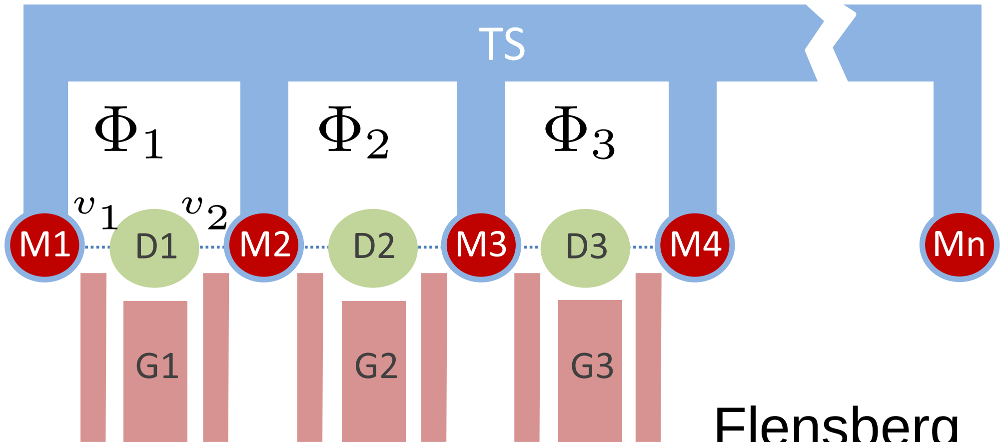
A zoo of theoretical proposals



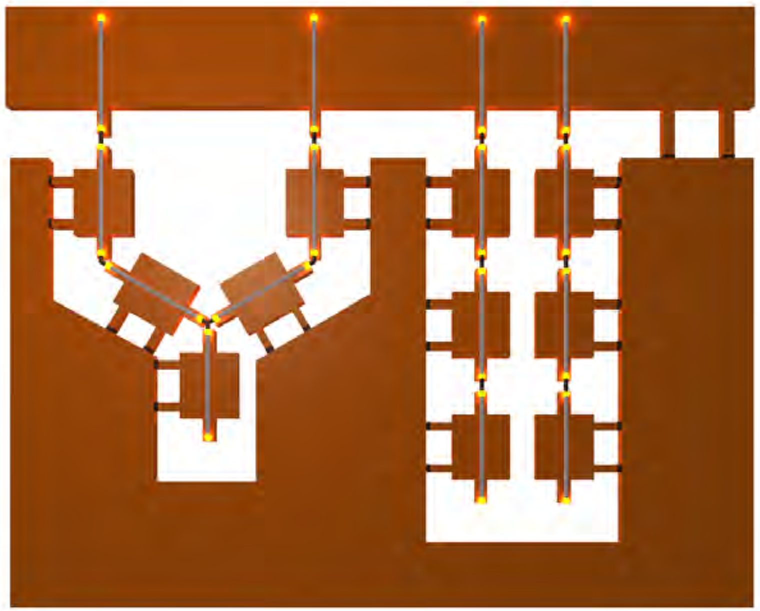
Fulga, et al.



Hyart, et al.



Flensberg



van Heck, et al.

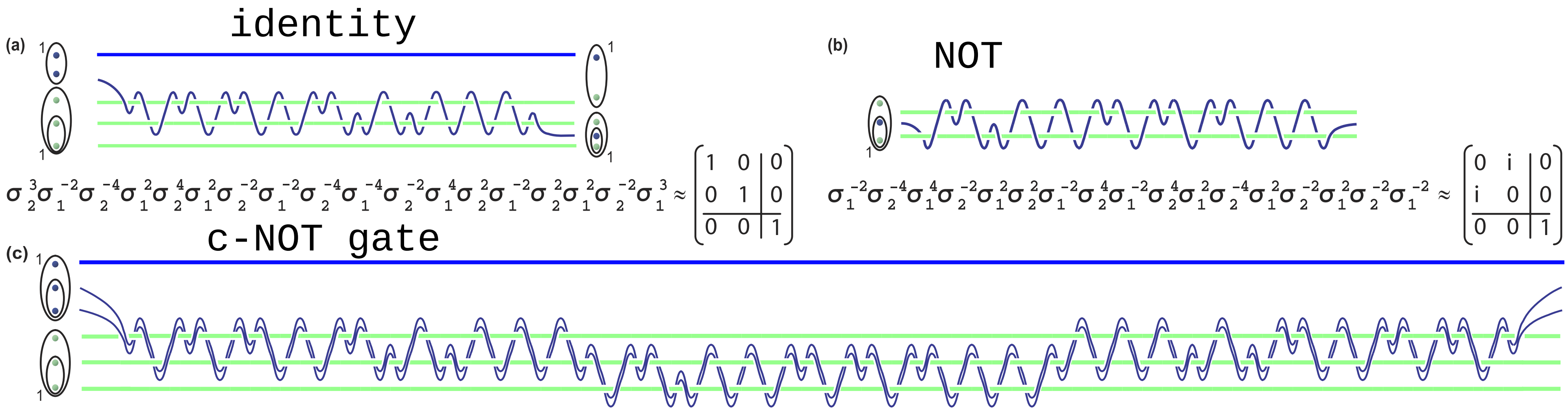
Braid Topologies for Quantum Computation

N. E. Bonesteel, L. Hormozi, and G. Zikos
Department of Physics and National High Magnetic Field Laboratory, Florida State University, Tallahassee, Florida 32310, USA

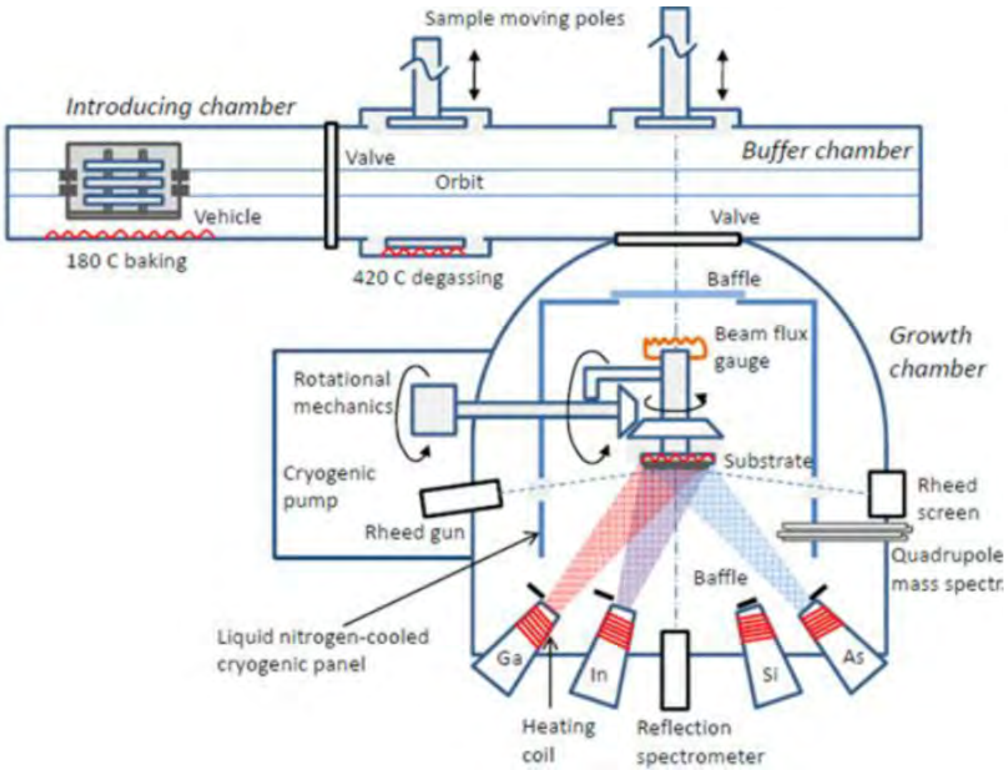
S. H. Simon
Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07974, USA

(Received 23 May 2005; published 29 September 2005)

In topological quantum computation, quantum information is stored in states which are intrinsically protected from decoherence, and quantum gates are carried out by dragging particlelike excitations (quasiparticles) around one another in two space dimensions. The resulting quasiparticle trajectories define world lines in three-dimensional space-time, and the corresponding quantum gates depend only on the topology of the braids formed by these world lines. We show how to find braids that yield a universal set of quantum gates for qubits encoded using a specific kind of quasiparticle which is particularly promising for experimental realization.

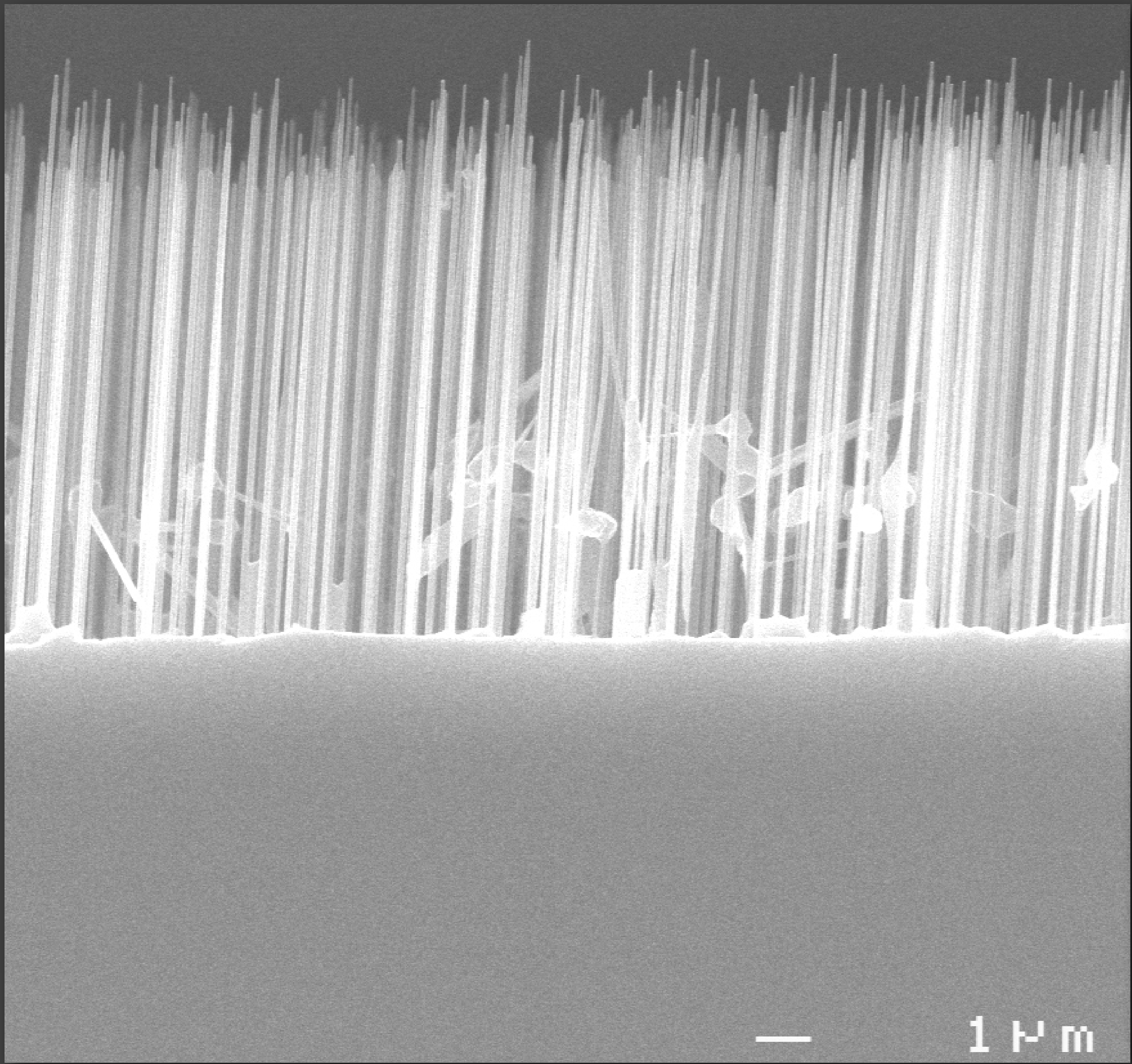


Growing Nanowires



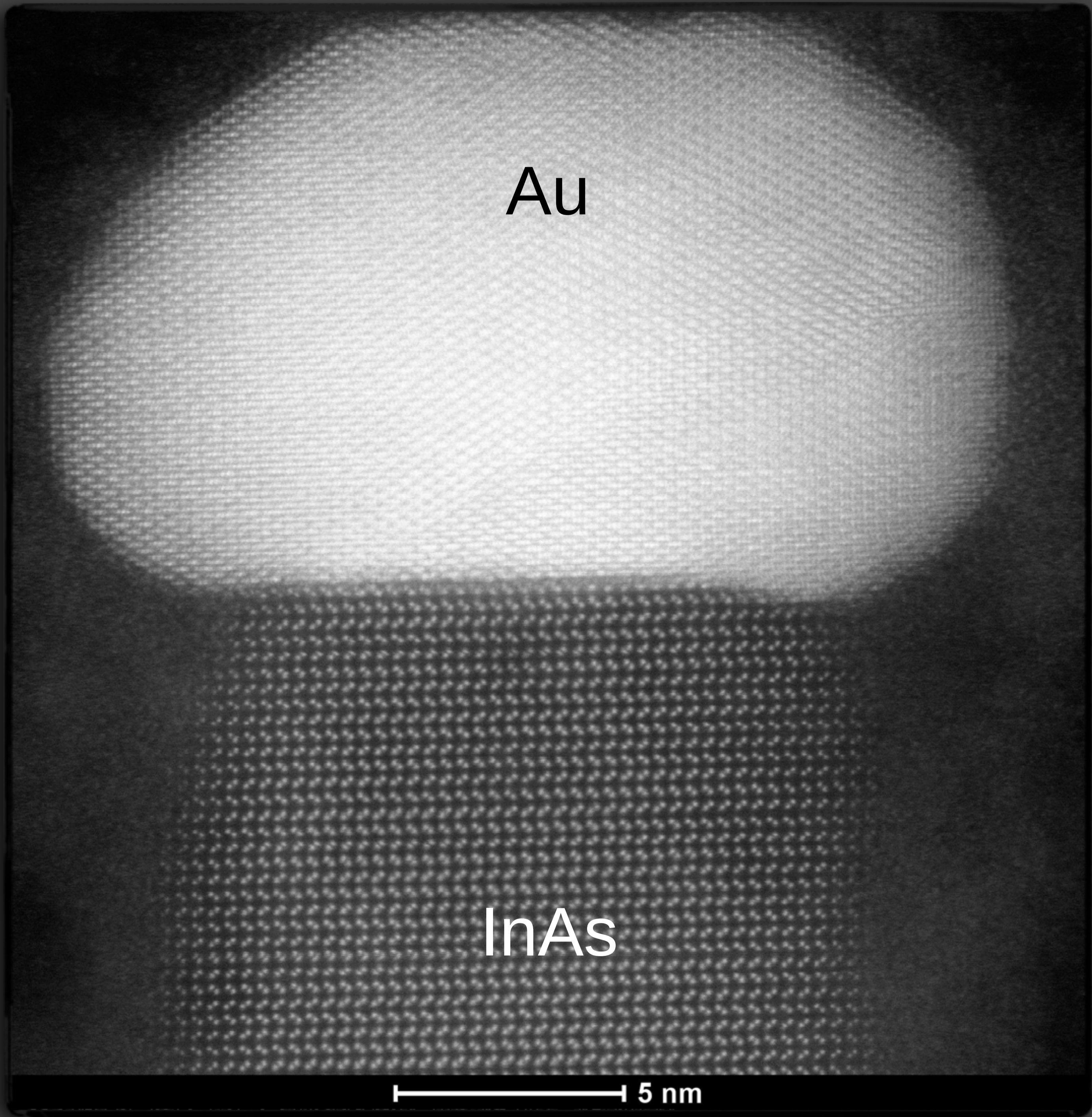
Molecular Beam Epitaxy

Growing Nanowires



M.H. Madsen, P. Krogstrup, J. Nygård, Univ. of Copenhagen

Growing Nanowires



PHYSICAL REVIEW B **84**, 144522 (2011)

Majorana fermions in semiconductor nanowires

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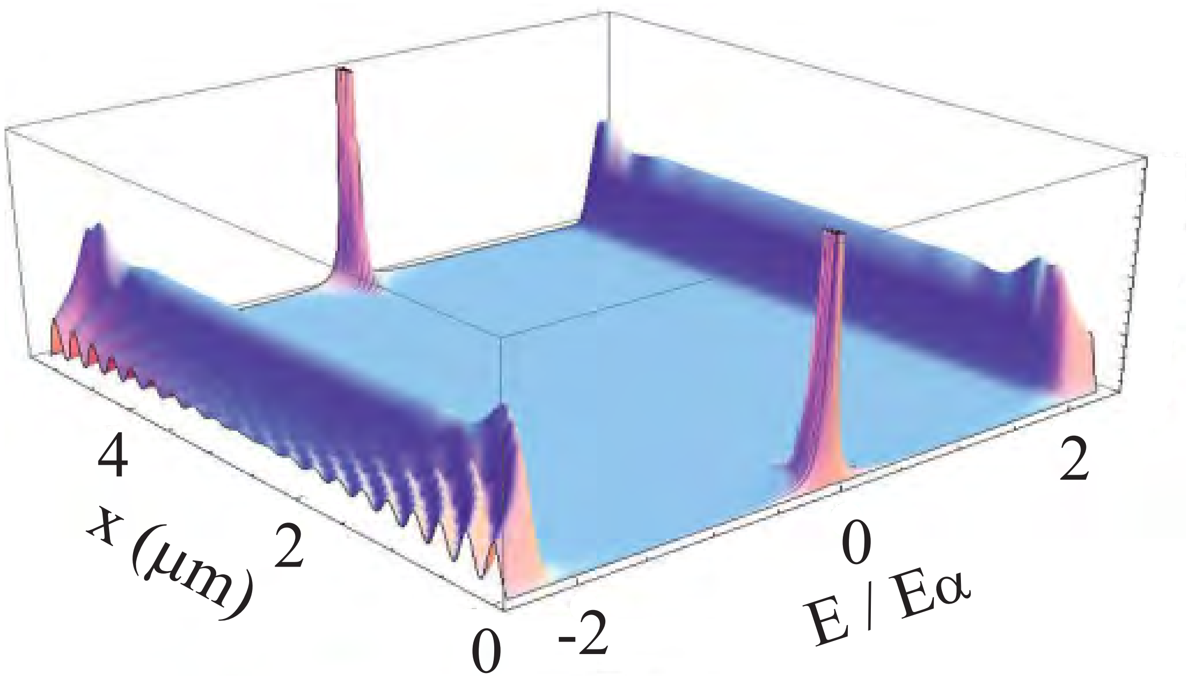
(Received 27 July 2011; revised manuscript received 27 September 2011; published 28 October 2011)

Zero-energy end states as signature of topological superconductor



PHYSICAL REVIEW B **84**, 144522 (2011)

Majorana fermions in semiconductor nanowires

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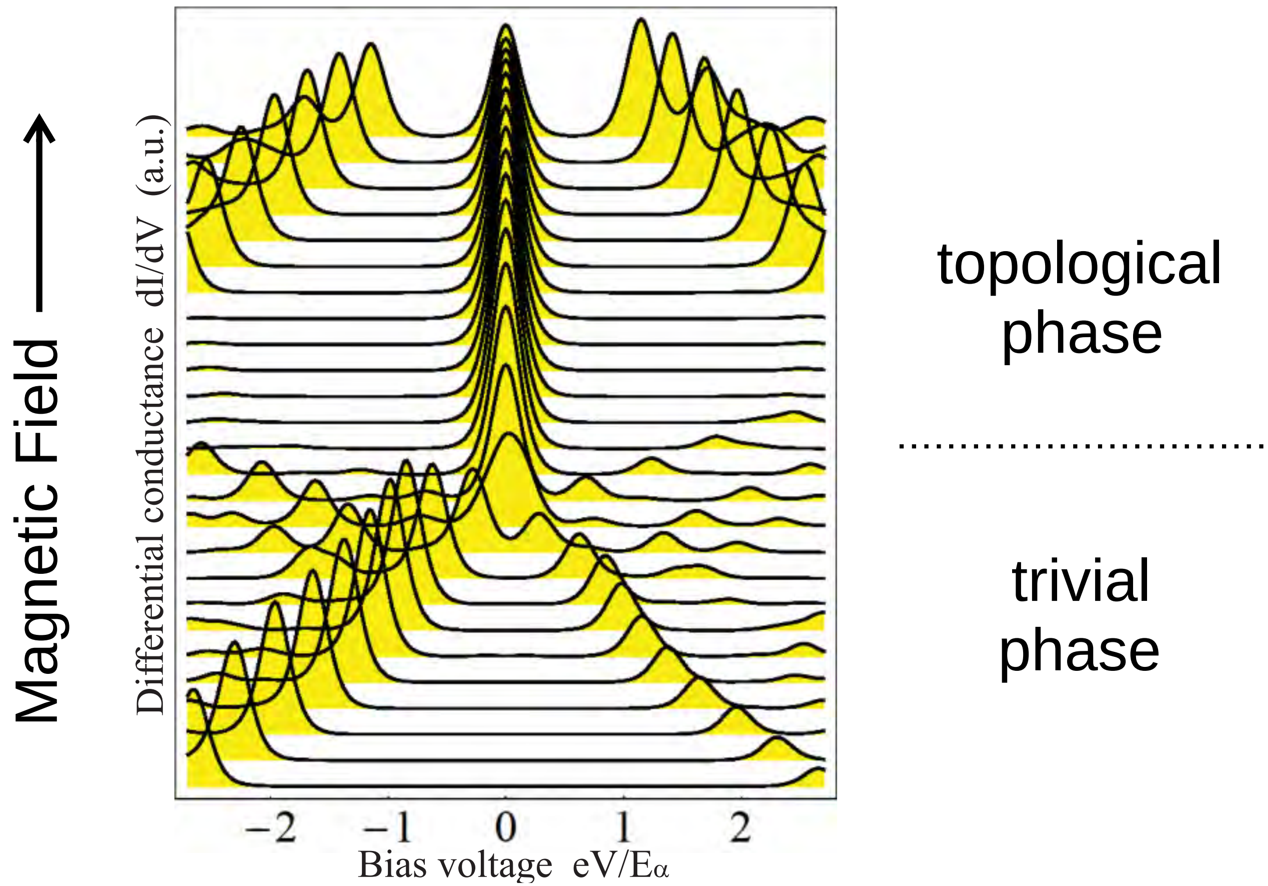
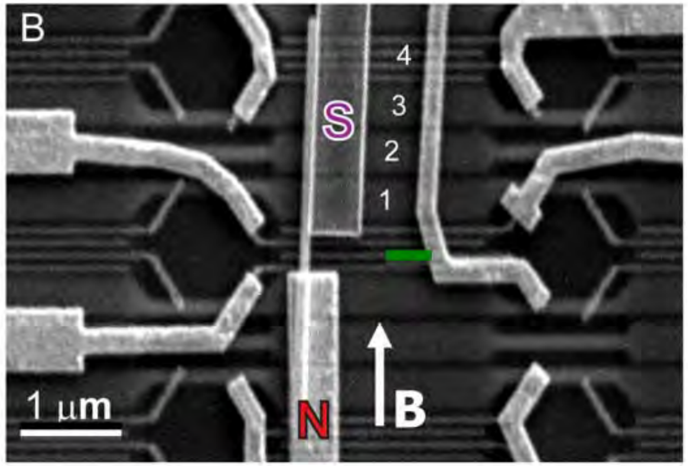
(Received 27 July 2011; revised manuscript received 27 September 2011; published 28 October 2011)

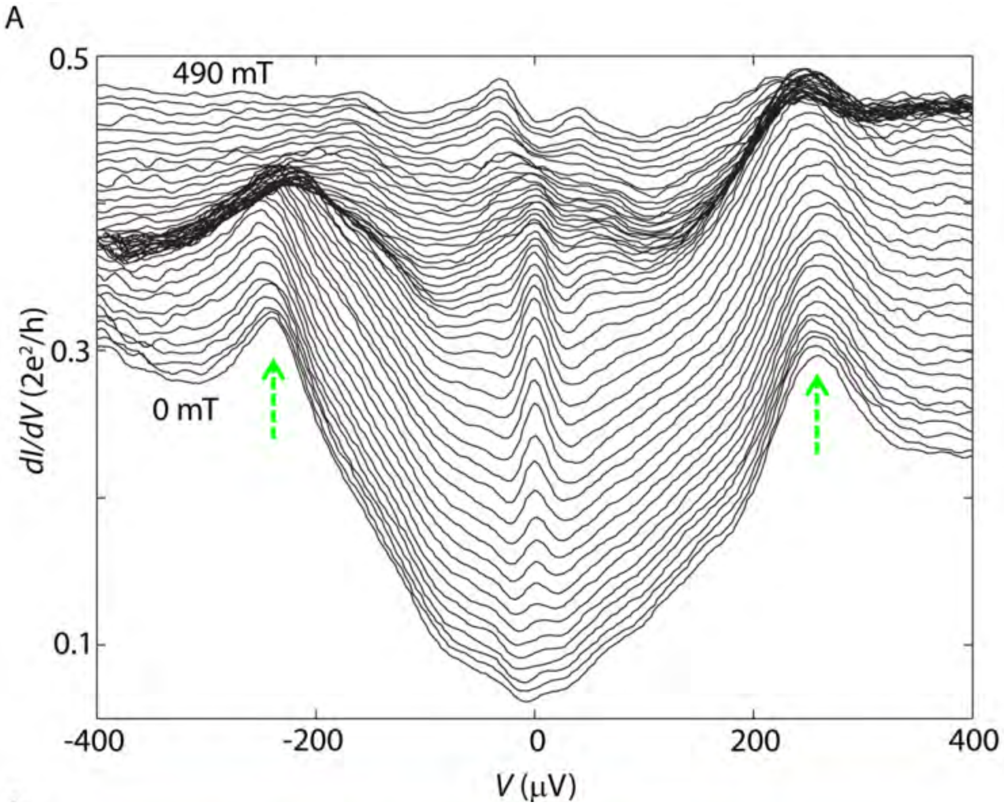


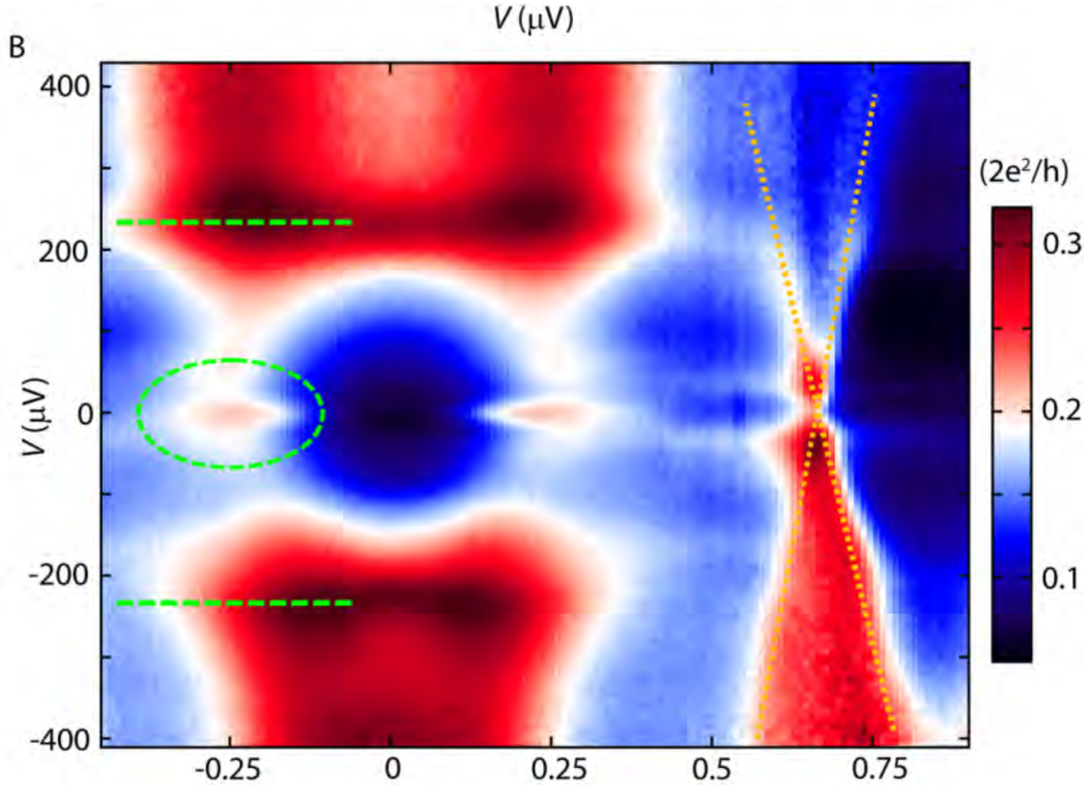
Zero-bias Peak as Majorana Signature

Signatures of Majorana Fermions in Hybrid Superconductor-Semiconductor Nanowire Devices

V. Mourik,[1]* K. Zuo,[1]* S. M. Frolov,[1] S. R. Plissard,[2] E. P. A. M. Bakkers,[1,2] L. P. Kouwenhoven[1]†





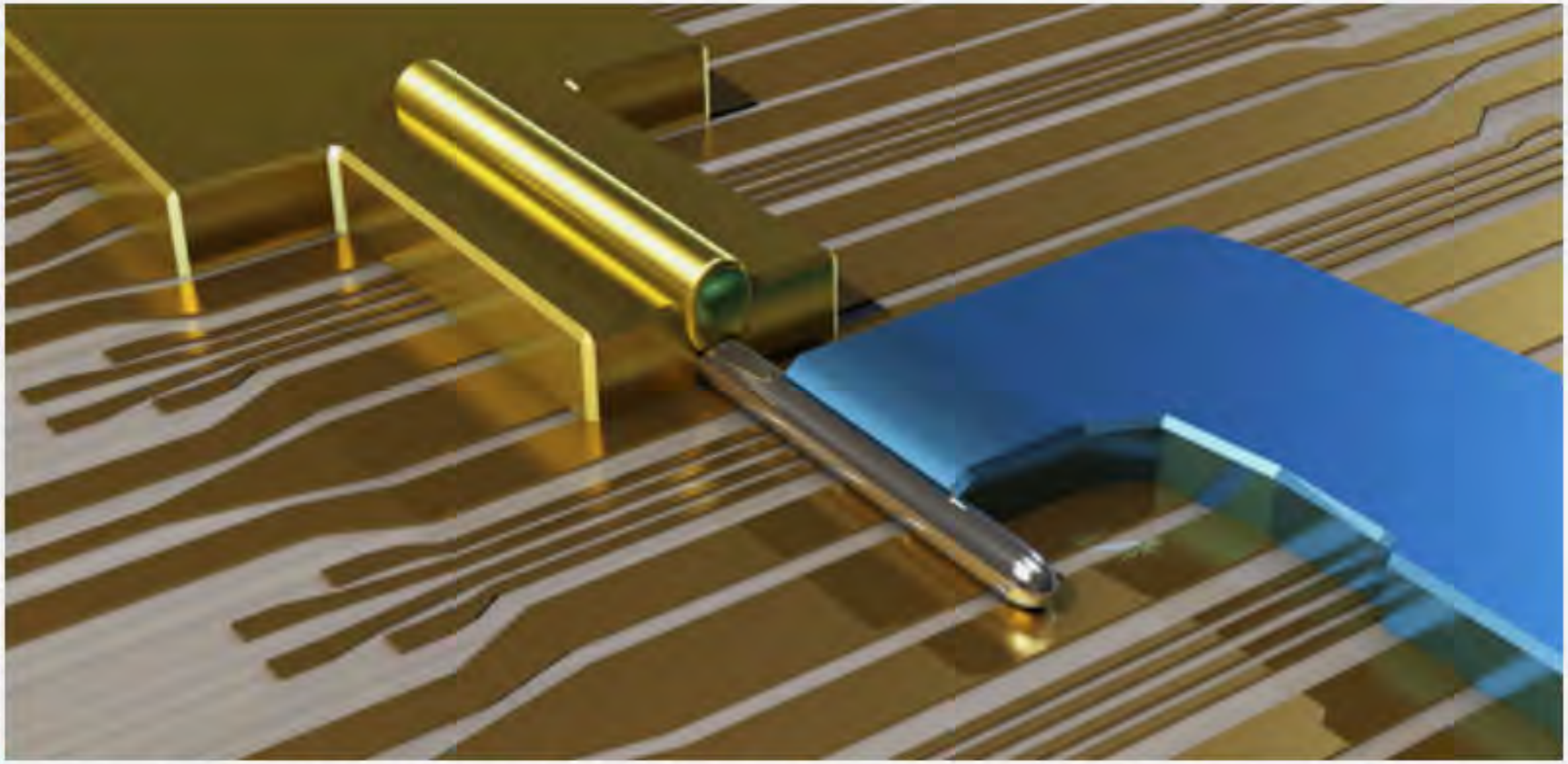


SCIENTIFIC METHOD —

Elusive Majorana fermions may be lurking in a cold nanowire

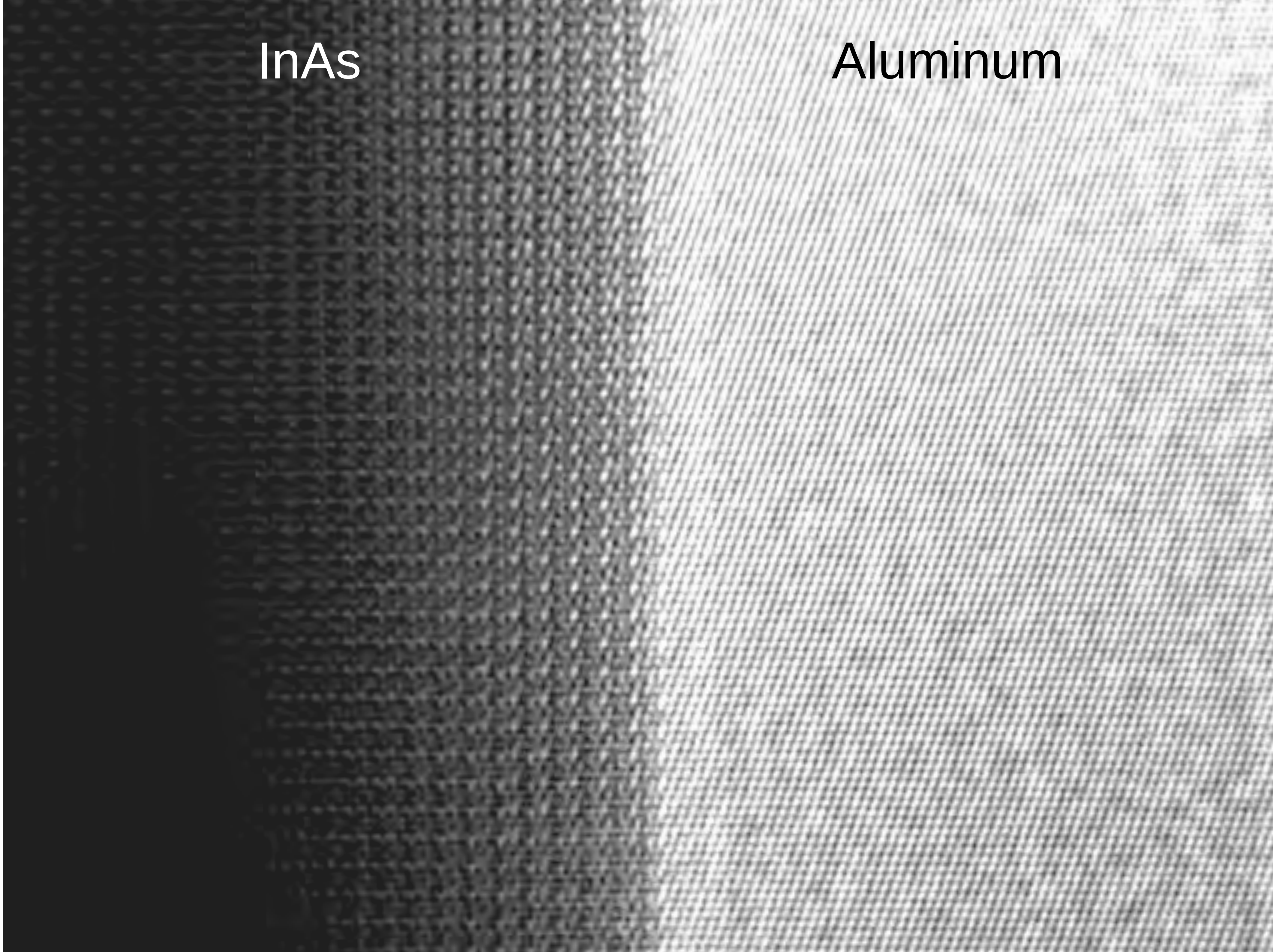
Majorana fermions are particles that act as their own antiparticles: if two of ...

MATTHEW FRANCIS - 4/12/2012, 8:00 PM



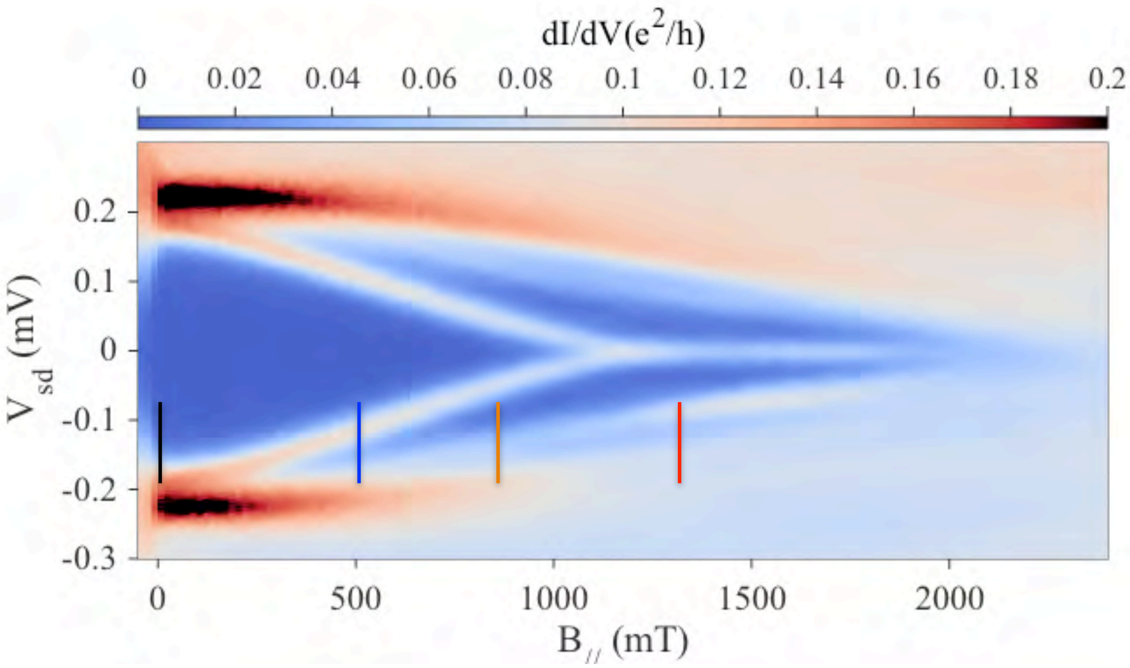
Photograph by kouwenhovenlab.tudelft.nl

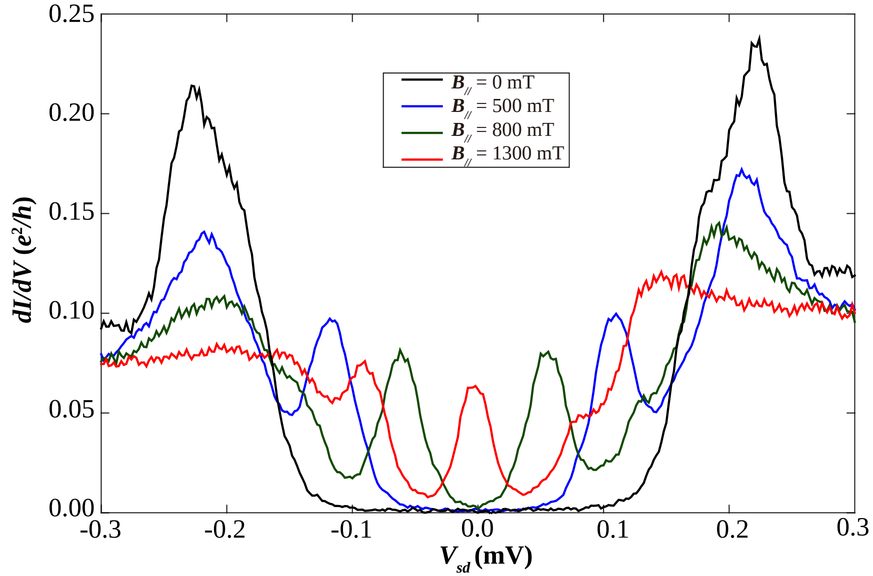
A nanowire (silver color) is attached to a gold electrode and rests against a superconductor (blue). The combination produces quasiparticles that may be Majorana fermions.


InAs
Aluminum

From Andreev to Majorana States

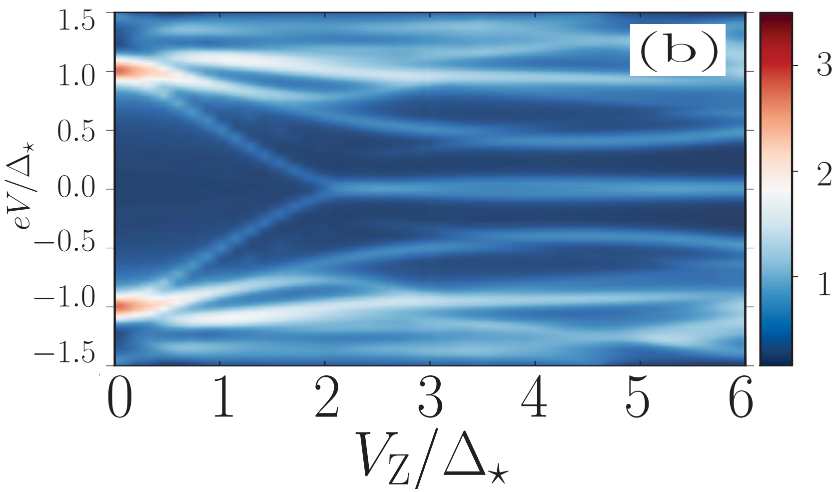
Experiment

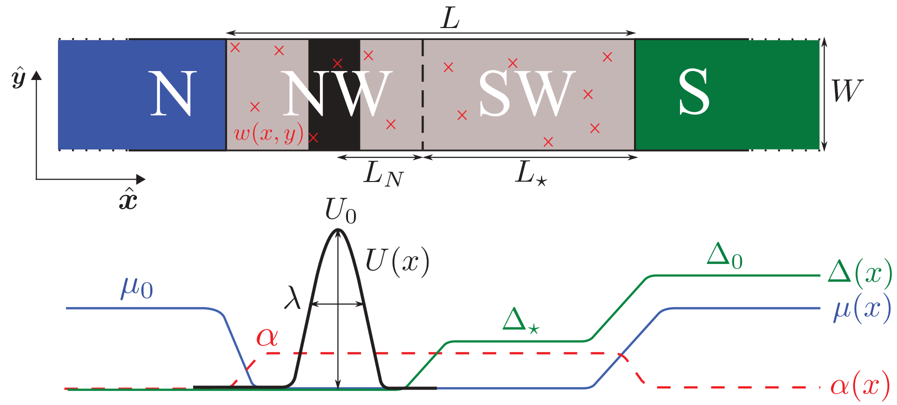




M. T. Deng, *et al.*
QDev

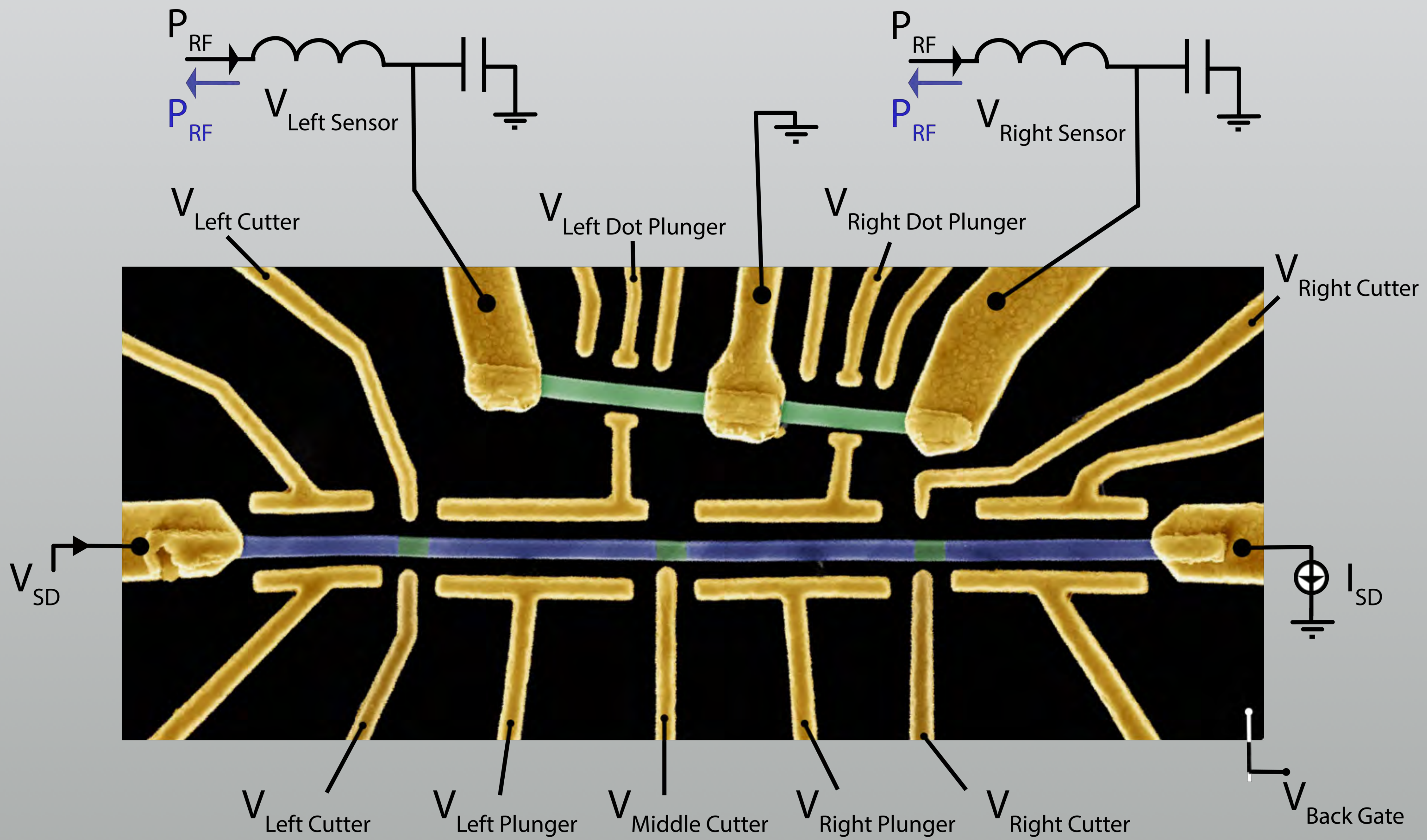
Theory



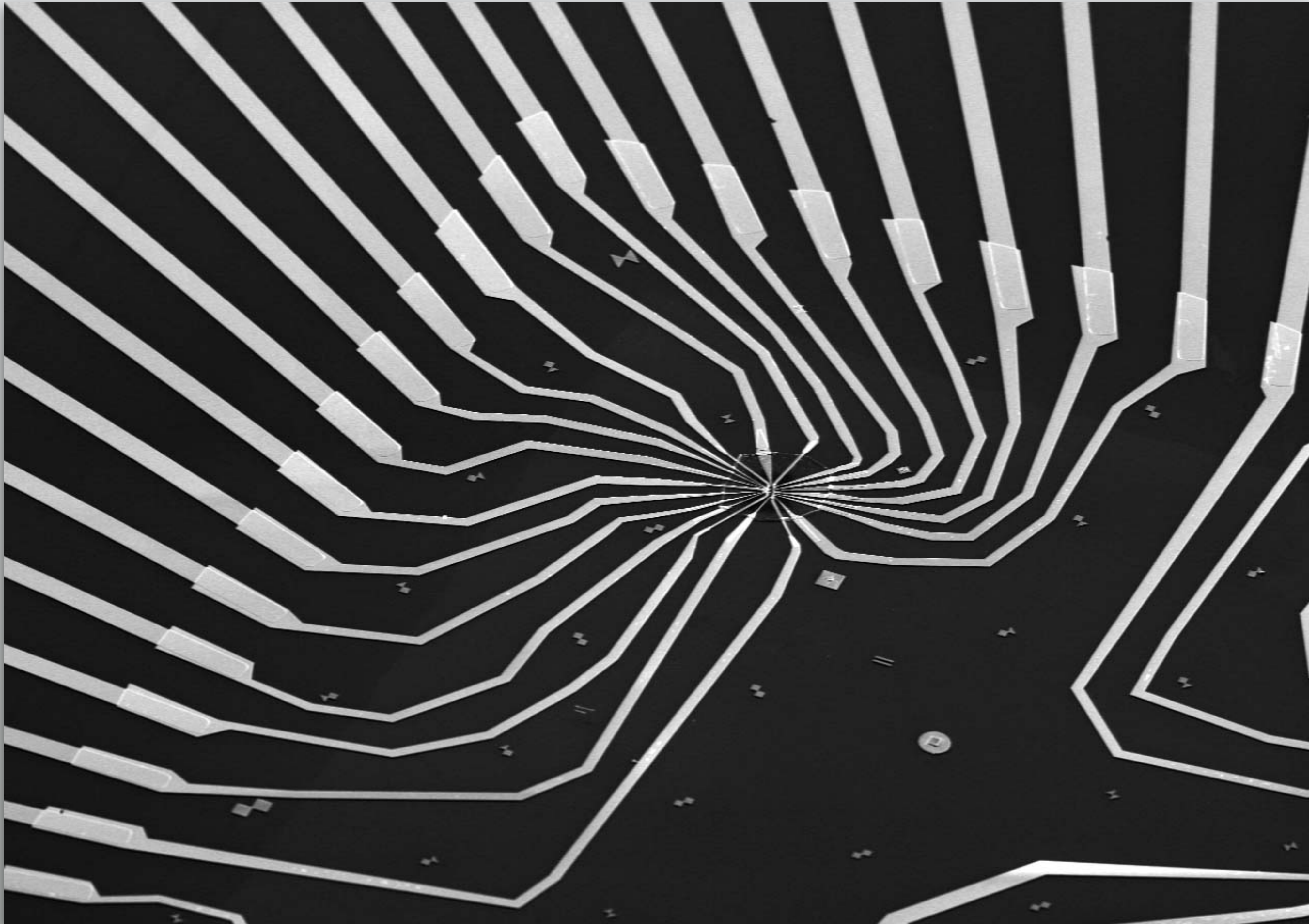


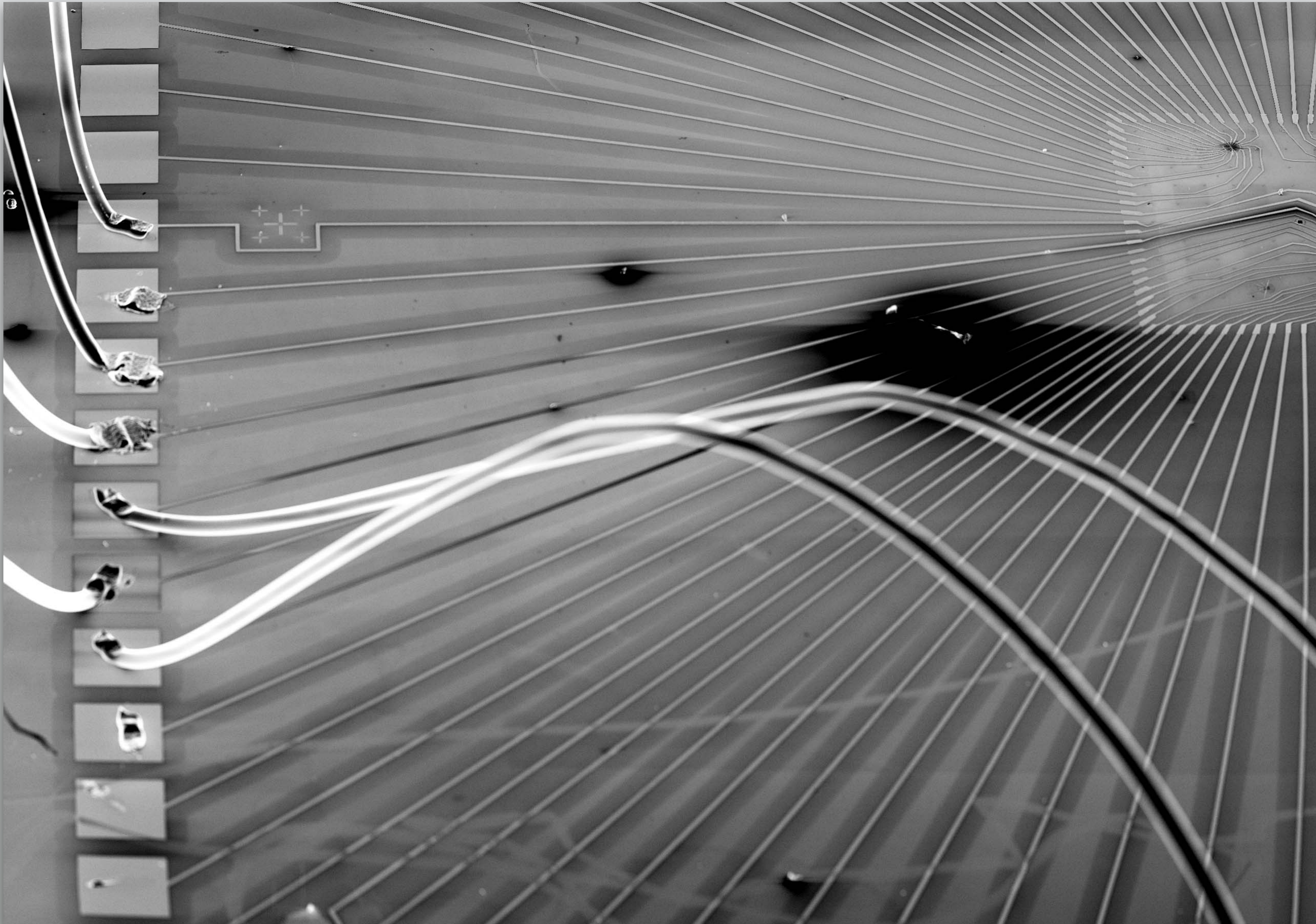
D. Rainis, L. Trifunovic, J. Klinovaja, D. Loss, *Phys Rev. B*. **87**, 024515 (2013).

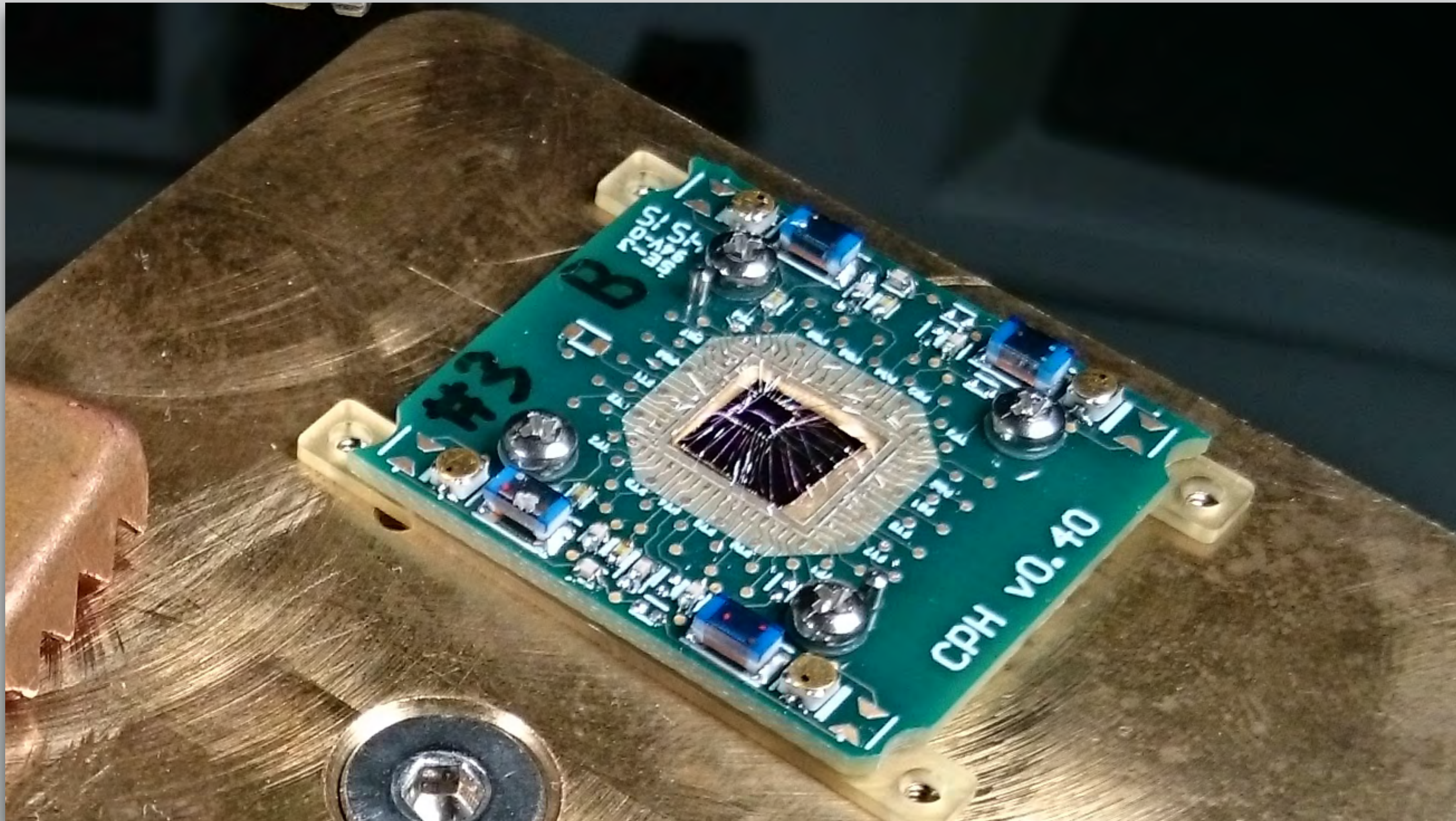
Fusion Rule Device



See Poster by David Sabonis et al.



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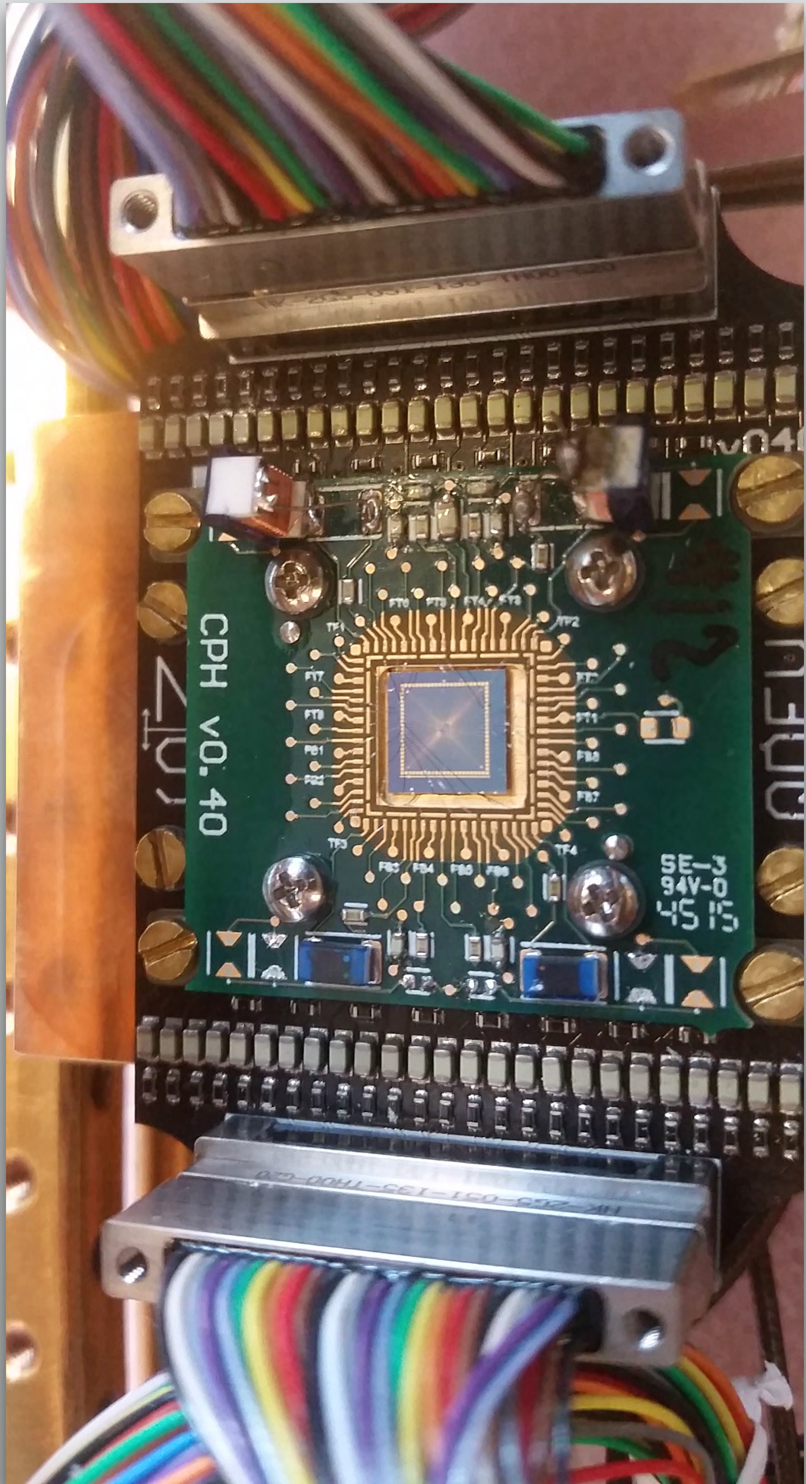
B
CPH v0.40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QDEV
5E-3
94V-0
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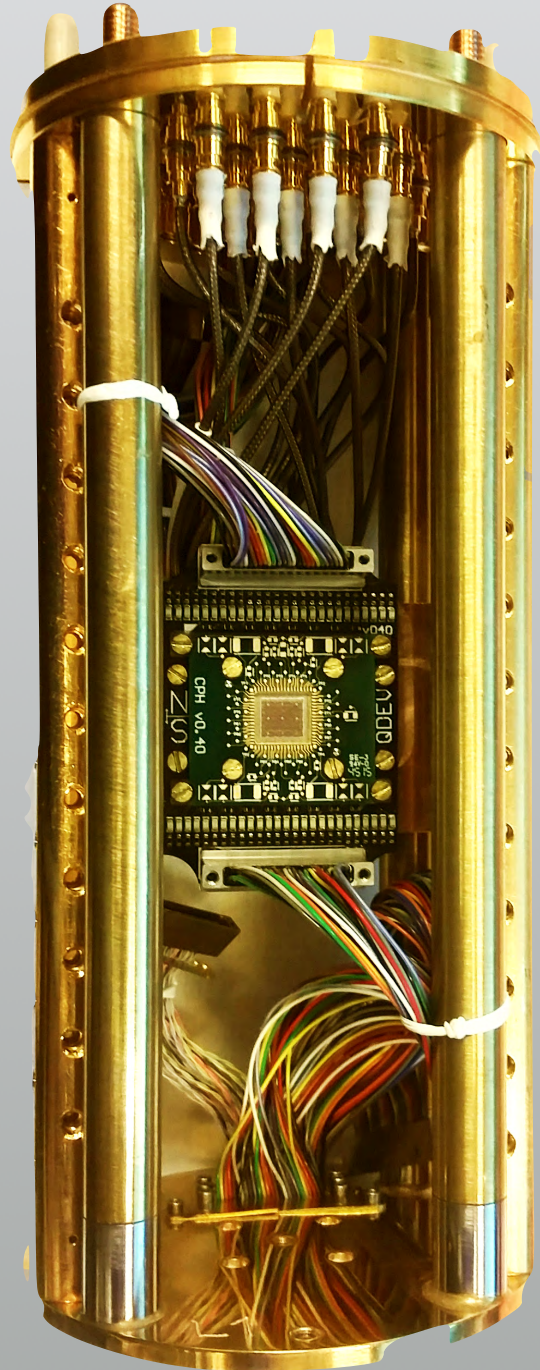
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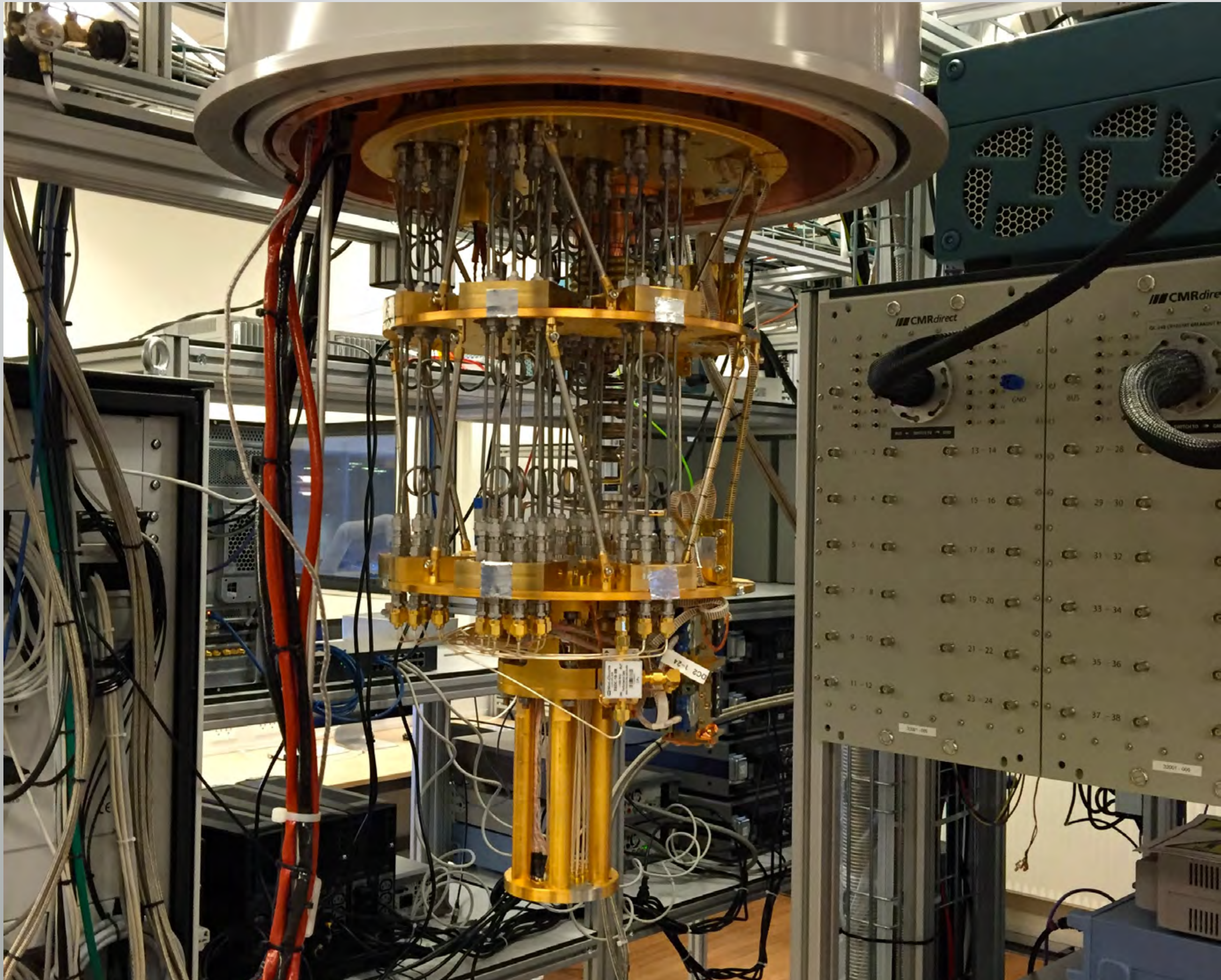
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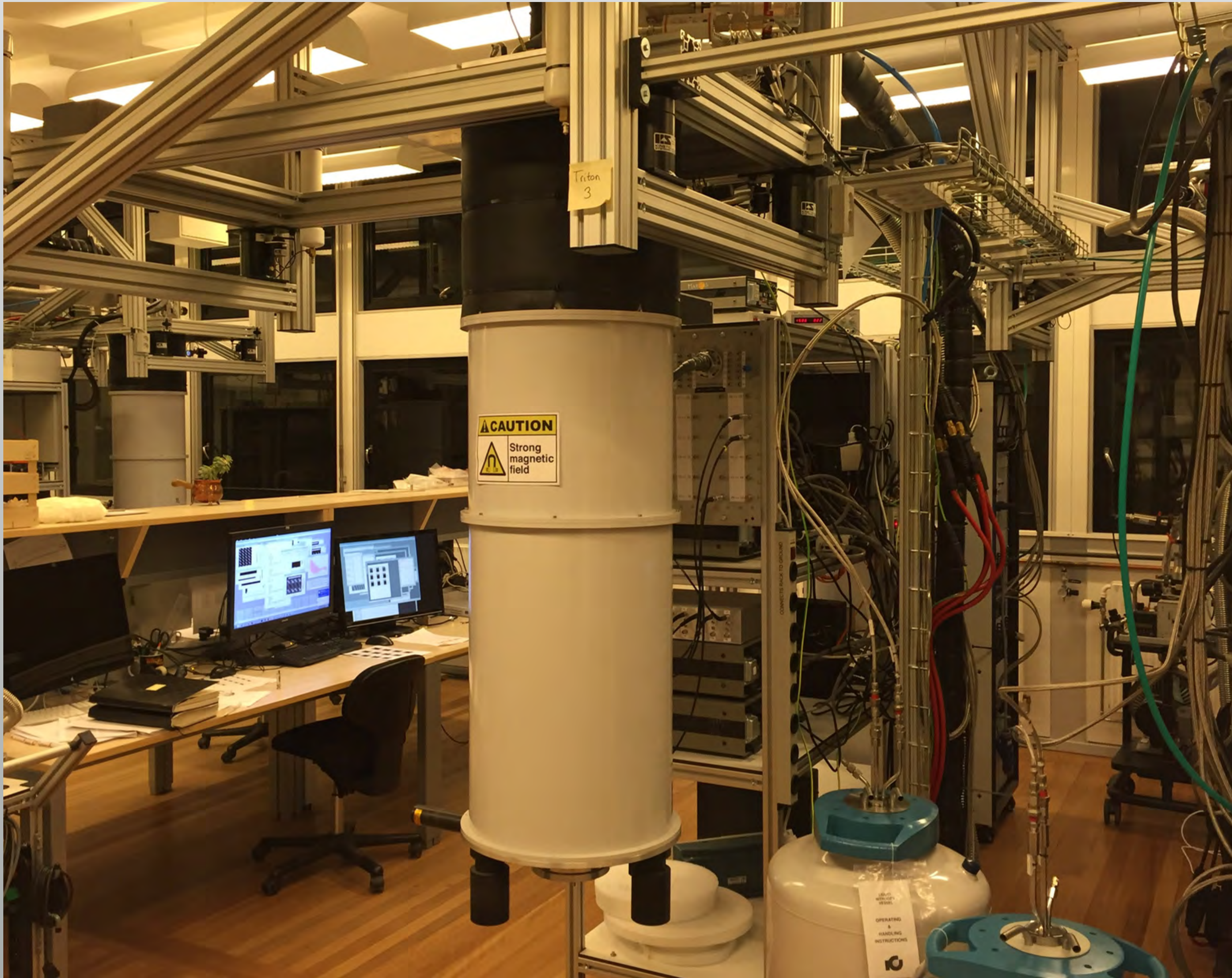
Triton
3
CAUTION
Strong
magnetic
field

The most important part:
the young people who will invent the future