

# QUANTUM POINT CONTACTS

The quantization of ballistic electron transport through a constriction demonstrates that conduction is transmission.

Published in abbreviated form in *PHYSICS TODAY*, July 1996, page 22.

*Henk van Houten & Carlo Beenakker*

Punctuated equilibrium, the notion that evolution in nature is stepwise rather than continuous, sometimes applies to evolution in science as well. It happens that the seed of a scientific breakthrough slumbers for a decade or even longer, without generating much interest. The seed can be a theoretical concept without clear predictions to test experimentally, or an intriguing but confusing experiment without a lucid interpretation. When the seed finally germinates, an entire field of science can reach maturity in a few years.

In hindsight, this is what happened ten years ago, when the authors (newly hired PhD's at Philips Research in Eindhoven) ventured into the field of quantum ballistic transport. Together with Bart van Wees, then a graduate student at Delft University of Technology, we were confronted with some pretty vague challenges. On the experimental side, there was the search for a quantum-size effect on the conductance, which would reveal in a clear-cut way the one-dimensional density of states of electrons confined to a narrow wire. Experiments on narrow silicon transistors (at Yale University and AT&T Bell Labs., Holmdel) had come close, but suffered from irregularities due to disorder. (These irregularities would become known as "universal conductance fluctuations", see *PHYSICS TODAY*, December 1988, page 36.) We anticipated that the electron motion should be ballistic, i.e. without scattering by impurities. Moty Heiblum (IBM, Yorktown Heights) had demonstrated ballistic transport of hot electrons, high above the Fermi level. For a quantum-size effect one needs ballistic motion at the Fermi energy. Our colleague Thomas Foxon from Philips Research in Redhill (UK) could provide us with heterojunctions of GaAs and AlGaAs, containing at the interface a thin layer of highly mobile electrons. Such a "two-dimensional electron gas" seemed an ideal system for ballistic transport.

On the theoretical side, there was the debate whether a wire without impurities could have any resistance at all.<sup>1</sup> Ultimately, the question was: "What is measured

when you measure a resistance?" The conventional point of view (held in the classical Drude-Sommerfeld or the quantum mechanical Kubo theories) is that conduction is the flow of current in response to an electric field. An alternative point of view was put forward in 1957 by Rolf Landauer (IBM, Yorktown Heights), who proposed that "conduction is transmission".<sup>2</sup> Landauer's formula, a relationship between conductance and transmission probability, had evolved into two versions. One gave infinite conductance (= zero resistance) in the absence of impurity scattering, while the other gave a finite answer. Although the origin of the difference between the two versions was understood by at least one of the theorists involved in the debate,<sup>3</sup> the experimental implications remained unclear.

Looking back ten years later, we find that the seed planted by Landauer in the fifties has developed into a sophisticated theory, at the basis of the entire field of quantum ballistic transport. The breakthrough can be traced back to experiments on an elementary conductor: a point contact. In this article we present a brief account of these developments. For a more comprehensive and detailed discussion, we direct the reader to the reviews in the bibliography.

## Quantized conductance

The history of ballistic transport goes back to 1965, when Yuri Sharvin (Moscow) used a pair of point contacts to inject and detect a beam of electrons in a single-crystalline metal.<sup>4</sup> In such experiments the quantum mechanical wave character of the electrons does not play an essential role, because the Fermi wave length ( $\lambda_F \approx 0.5$  nm) is much smaller than the opening of the point contact. The two-dimensional (2D) electron gas in a GaAs-AlGaAs heterojunction has a Fermi wave length which is a hundred times larger than in a metal. This makes it possible to study a constriction with an opening comparable to the wave length (and much smaller than the mean free path for impurity scattering). Such a constriction is called a quantum point contact.

In a metal a point contact is fabricated simply by pressing two wedge- or needle-shaped pieces of material together. A quantum point contact requires a more complicated strategy, since the 2D electron gas is confined at the GaAs-AlGaAs interface in the interior of the het-

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# Introduction To Quantum Information Cond Mat

**Kathleen Armour**



## **Introduction To Quantum Information Cond Mat:**

**Introduction to Quantum Information Processing** Eduardo Mucciolo, 2025-09-02 This book introduces quantum computing and quantum communications at the undergraduate level for students in the physical sciences engineering and mathematics assuming no prior knowledge of quantum mechanics It is a self contained guide assuming only that the reader is familiar with physics at the college level calculus up to and including ordinary differential equations and some matrix algebra and complex numbers The book brings the reader up to speed with fundamental concepts in quantum information processing and builds a working knowledge of basic quantum algorithms quantum error correction and quantum communication protocols It covers various models of quantum computation and some of the most common physical realizations of qubits There is a good number of practice problems and exercises that rely on computer programming with the Qiskit language The book can be used to prepare students of physics mathematics electrical and computer engineering computer science optics and photonics and mathematics for internships and research experiences in quantum information processing both during and after their undergraduate studies It also helps those who plan to apply to graduate school and do research in this area Key Features Self contained coverage of quantum computing and quantum communications from the motivations to the fundamentals and applications including key concepts and contemporary topics Contains practice problems and exercises including some that require programming in Qiskit the python based high level language for programming quantum computers adopted by nearly all quantum hardware providers and completely open source Very light background knowledge assumed making this book accessible to a variety of majors in the natural sciences engineering and mathematics

**Computer Networks** Andrzej Kwiecien, Piotr Gaj, Piotr Stera, 2012-06-06 This book constitutes the refereed proceedings of the 19th International Conference on Computer Networks CN 2012 held in Szczyrk Poland in June 2012 The 48 revised full papers presented were carefully reviewed and selected for inclusion in the book The papers address subjects such as new and emerging technologies related to networking fields fundamentals of computer networks internet and internetworking security and safety issues industrial computer networks wireless systems and sensor networks the theory of queues and queuing networks applications and computer networks usage

Proceedings of the 7th International Symposium on Foundations of Quantum Mechanics in the Light of New Technology Yoshimasa A. Ono, 2002 This book discusses fundamental problems in quantum physics with emphasis on quantum coherence and decoherence Papers covering the wide range of quantum physics are included atom optics quantum optics quantum computing quantum information cryptography macroscopic quantum phenomena mesoscopic physics physics of precise measurements and fundamental problems in quantum physics The book will serve not only as a good introduction to quantum coherence and decoherence for newcomers in this field but also as a reference for experts

**An Introduction to Condensed Matter Physics for the Nanosciences** Arthur McGurn, 2023-04-13 The book provides an accessible introduction to the principles of condensed

matter physics with a focus on the nanosciences and device technologies The basics of electronic phononic photonic superconducting optics quantum optics and magnetic properties are explored and nanoscience and device materials are incorporated throughout the chapters Many examples of the fundamental principles of condensed matter physics are taken directly from nanoscience and device applications This book requires a background in electrodynamics quantum mechanics and statistical mechanics at the undergraduate level It will be a valuable reference for advanced undergraduates and graduate students of physics engineering and applied mathematics Features Contains discussions of the basic principles of quantum optics and its importance to lasers quantum information and quantum computation Provides references and a further reading list to additional scientific literature so that readers can use the book as a starting point to then follow up with a more advanced treatment of the topics covered Requires only a basic background in undergraduate electrodynamics quantum mechanics and statistical mechanics

**New Frontiers In Fields And Strings (Tasi 2015) - Proceedings Of The 2015 Theoretical Advanced Study Institute In Elementary Particle Physics** Joseph Polchinski, Pedro Vieira, Oliver Dewolfe, 2016-11-28 This volume is a compilation of lectures delivered at the TASI 2015 summer school New Frontiers in Fields and Strings held at the University of Colorado Boulder in June 2015 The school focused on topics in theoretical physics of interest to contemporary researchers in quantum field theory and string theory The lectures are accessible to graduate students in the initial stages of their research careers

**Demystifying Computation: A Hands-on Introduction** Apostolos Syropoulos, 2017-04-19 Problem solving in computing is referred to as computational thinking The theory behind this concept is challenging in its technicalities yet simple in its ideas This book introduces the theory of computation from its inception to current form of complexity from explanations of how the field of computer science was formed using classical ideas in mathematics by G del to conceptualization of the Turing Machine to its more recent innovations in quantum computation hypercomputation vague computing and natural computing It describes the impact of these in relation to academia business and wider society providing a sound theoretical basis for its practical application Written for accessibility Demystifying Computation provides the basic knowledge needed for non experts in the field undergraduate computer scientists and students of information and communication technology and software development

**Fundamentals and Frontiers of the Josephson Effect** Francesco Tafuri, 2019-09-17 This book provides a comprehensive and up to date description of the Josephson effect a topic of never ending interest in both fundamental and applied physics In this volume world renowned experts present the unique aspects of the physics of the Josephson effect resulting from the use of new materials of hybrid architectures and from the possibility of realizing nanoscale junctions These new experimental capabilities lead to systems where novel coherent phenomena and transport processes emerge All this is of great relevance and impact especially when combined with the didactic approach of the book The reader will benefit from a general and modern view of coherent phenomena in weakly coupled superconductors on a macroscopic scale Topics that have been only

recently discussed in specialized papers and in short reviews are described here for the first time and organized in a general framework. An important section of the book is also devoted to applications with focus on long term future applications. In addition to a significant number of illustrations the book includes numerous tables for comparative studies on technical aspects.

**Quantum Information & Computation**, 2005 *Quantum Information* Masahito Hayashi, 2006-09-02. Recently quantum information theory has been developing through a fusion of results from various research fields. This requires that understanding of basic results on diverse topics and derived from different disciplinary perspectives is required for appreciating the overall picture. Intended to merge key topics from both the information theoretic and quantum mechanical viewpoints this graduate level textbook provides a unified viewpoint of quantum information theory and lucid explanations of those basic results so that the reader fundamentally grasps advances and challenges. For example advanced topics in quantum communication such as quantum teleportation superdense coding quantum state transmission quantum error correction and quantum encryption especially benefit from this unified approach. Unlike earlier treatments the text requires knowledge of only linear algebra probability theory and quantum mechanics while it treats the topics of quantum hypothesis testing and the discrimination of quantum states and quantum channel coding message transmission with the minimal amount of math needed to convey their essence. Solving the more than 240 exercises provides readers with practice that not only enriches their knowledge of quantum information theory but also can equip them with the techniques necessary for pursuing their own research in this field.

**High-level Quantum Programming with Quantum Walks** Héctor J. García, 2007 *Journal of Experimental and Theoretical Physics*, 2007

**Condensed Matter Theories** F. B. Malik, 2005 **A Short Introduction to Quantum Information and Quantum Computation** Michel Le Bellac, 2006-06-15. Quantum information and computation is a rapidly expanding and cross disciplinary subject. This book first published in 2006 gives a self contained introduction to the field for physicists mathematicians and computer scientists who want to know more about this exciting subject. After a step by step introduction to the quantum bit qubit and its main properties the author presents the necessary background in quantum mechanics. The core of the subject quantum computation is illustrated by a detailed treatment of three quantum algorithms Deutsch Grover and Shor. The final chapters are devoted to the physical implementation of quantum computers including the most recent aspects such as superconducting qubits and quantum dots and to a short account of quantum information. Written at a level suitable for undergraduates in physical sciences no previous knowledge of quantum mechanics is assumed and only elementary notions of physics are required. The book includes many short exercises with solutions available to instructors through solutions.cambridge.org.

**Condensed Matter Theories, Volume 20** John W. Clark, Robert M. Panoff, Haochen Li, 2006. This volume focuses on the many roles played by ab initio theory modelling and high performance computing in condensed matter and materials science.

**Quantum Computing and Communications** Michael Brooks, 1999-05-21. The first handbook to provide a comprehensive inter disciplinary

overview of QCC It includes peer reviewed definitions of key terms such as Quantum Logic Gates Error Correction Quantum Dots Nuclear Magnetic Resonance Quantum Holography and Quantum Cryptography There are also reports on major application areas principles of QCC and targets benchmarks and challenges making this an invaluable buy for any university department with this exciting new topic in its curriculum It equally provides a unique overview of a fast moving and multidisciplinary topic for researchers students lecturers and even the interested amateur Condensed Matter Theories

Araceli N. Proto, Jorge Luis Aliaga, Araceli Noemi Proto, 1992 Proceedings of the Fifteenth International Workshop on Condensed Matter Theories held July 1991 in Mar del Plata Argentina attended by scientists from the diverse areas of condensed matter such as classical and quantum fluids atoms and molecules high Tc superconductivity and particle and nuclear physics 32nd International Workshop on Condensed Matter Theories, 2009 Condensed Matter Theories J Da Providencia and

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Encyclopedia of Mathematical Physics Jean-Pierre Francoise, Gregory L. Naber, Tsou Sheung Tsun, 2006-06-20 The Encyclopedia of Mathematical Physics provides a complete resource for researchers students and lecturers with an interest in mathematical physics It enables readers to access basic information on topics peripheral to their own areas to provide a repository of the core information in the area that can be used to refresh the researcher's own memory banks and aid teachers in directing students to entries relevant to their course work The Encyclopedia does contain information that has been distilled organised and presented as a complete reference tool to the user and a landmark to the body of knowledge that has accumulated in this domain It also is a stimulus for new researchers working in mathematical physics or in areas using the methods originating from work in mathematical physics by providing them with focused high quality background information Editorial Board Jean Pierre Francoise Universit Pierre et Marie Curie Paris France Gregory L Naber Drexel University Philadelphia PA USA Tsou Sheung Tsun University of Oxford UK Also available online via ScienceDirect 2006 featuring extensive browsing searching and internal cross referencing between articles in the work plus dynamic linking to journal articles and abstract databases making navigation flexible and easy For more information pricing options and availability visit [www.info.sciencedirect.com](http://www.info.sciencedirect.com) First comprehensive interdisciplinary coverage Mathematical Physics explained to stimulate new developments and foster new applications of its methods to other fields Written by an international group of experts Contains several undergraduate level introductory articles to facilitate acquisition of new expertise Thematic index and extensive cross referencing to provide easy access and quick search functionality Also available online with active linking

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