EPS Grand Challenges

Physics for Society in the Horizon 2050

Online at: https://doi.org/10.1088/978-0-7503-6342-6

EPS Grand Challenges

Physics for Society in the Horizon 2050

Edited by
Carlos Hidalgo
CIEMAT, Laboratorio Nacional de Fusión, Spain

Coordinators
Ralph Assmann
Deutsches Elektronen-Synchrotron (DESY), Germany
and
GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

Felicia Barbato
Gran Sasso Science Institute, Italy

Christian Beck
Queen Mary University of London, London, UK

Giulio Cerullo
Politecnico di Milano, Milan, Italy

Luisa Cifarelli
University of Bologna, Bologna, Italy

Felix Ritort
University of Barcelona, Barcelona, Spain

Christophe Rossel
IBM Research Europe - Zurich, Switzerland

Mairi Sakellariadou
King's College London, London, UK

Kees van Der Beek
Institut Polytechnique de Paris, Paris, France

Luc van Dyck
Euro Argo ERIC, Plouzané, France

Bart van Tiggelen
Laboratoire de Physique et Modélisation des Milieux Condensés,
University Grenoble Alpes/CNRS, Grenoble, France

Claudia-Elisabeth Wulz
Institute of High Energy Physics, Austrian Academy of Sciences, Vienna, Austria

IOP Publishing, Bristol, UK

ISBN 978-0-7503-6342-6 (ebook)
ISBN 978-0-7503-6338-9 (print)
ISBN 978-0-7503-6339-6 (myPrint)
ISBN 978-0-7503-6341-9 (mobi)

DOI 10.1088/978-0-7503-6342-6

Version: 20240301

IOP ebooks

British Library Cataloguing-in-Publication Data: A catalogue record for this book is available from the British Library.

Published by IOP Publishing, wholly owned by The Institute of Physics, London

IOP Publishing, No.2 The Distillery, Glassfields, Avon Street, Bristol, BS2 0GR, UK

US Office: IOP Publishing, Inc., 190 North Independence Mall West, Suite 601, Philadelphia, PA 19106, USA

Contents

Preface

Over the last decades, the European Physical Society (EPS) has raised concerns on some of the main problems humankind faced up to now and examined the role of physics to address them. But what are the urgent societal challenges in the future and what holds the world's physics agenda to solve them? One objective of the *EPS Grand Challenges project* is indeed to explore our ability in imagining and shaping the development of physics at the Horizon 2050.

The scientific committee of this *Grand Challenges* publication chaired by Carlos Hidalgo, includes the following chapter coordinators: Ralph Assmann, Felicia Barbato, Christian Beck, Kees van der Beek, Giulio Cerullo,Luisa Cifarelli, Luc van Dyck, Felix Ritort, Christophe Rossel, Mairi Sakellariadou, Bart van Tiggelen, Claudia-Elisabeth Wulz. They played the leading role in the development of the project that addresses two pillars: *Physics as global human enterprise for understanding nature* and *Physics developments to tackle major issues affecting the lives of citizens*. The essays, written by more than 70 leading scientists, outline the in-depth analysis of the strong links between basic research, its applications and their impact on a sustainable society. The interplay of natural sciences with social and human sciences is also discussed together with the role of open science, education, ethics, and responsible citizens in an interdisciplinarity environment.

The scientific committee would like to express its gratitude to the Editorial Board members[1] for their contribution in defining the structure and the topical content of this project. The constant support of the successive EPS Presidents (Luc Bergé, Petra Rudolf, Rüdiger Voss, Christophe Rossel), the EPS Secretaries General (Anne C Pawsey, David Lee) and the EPS secretariat during the whole process is deeply acknowledged. Finally, the excellent work of the editorial team of *Europhysics News* [EPN] in preparing the special issue on the *EPS Grand Challenges* [1] is also well recognised.

Reference

[1] EUROPHYSICS NEWS 2023 Special issue the EPS Grand Challenges for physics *EUROPHYSICS NEWS* **53** 5

[1] Members Editorial Board: Tariq Ali, Hans-Peter Beck, Els de Wolf, Karl Gradin, Giuseppe Grosso, Eduard Kontar, Eva Kovacevic, Marko Kralj, Douglas Mac Gregor, Eugenio Nappi, JoeNiemela, José Antonio Paixao, Kaido Reivelt, Sylvie Rousset, Petra Rudolf, Enrique Sánchez, Miguel Angel Sanchis, David Sands, Rüdiger Voss, and Victor Zamfir.

Coordinators

Ralph Assmann

Ralph Assmann has obtained his doctorate in physics from the Ludwig-Maximilians-University in Munich. His PhD research was performed at the Max Planck Institute for Physics in Munich and at CERN in the ALEPH experiment on the mass of the Z boson, spin polarized particle beams and precise energy calibration. He then spent almost four years as research associate and staff at Stanford University and SLAC, where he worked on operation, modelling and design of colliders. For the next 15 years he worked at CERN in leading roles on the LEP and LHC colliders. He was LHC machine coordinator in run I of the LHC operation, during which the Higgs boson was discovered in 2012. From 2012 to 2023 he worked as Leading Scientist for Accelerator R&D at DESY, where he researched new, compact accelerators. He was awarded an ERC synergy grant in 2014. Over 10 years, until 2024, Dr Assmann has been the proposer and founding coordinator of the EuPRAXIA ESFRI project, a 569 M€ project on building the world-wide first user facility based on plasma-based accelerators, today supported by more than 50 institutes. He has been the Chair of the Accelerator Group in the European Physical Society from 2020–2023, the leader of several large Helmholtz and European funding grants and the coordinator of the European Network for Novel Accelerators. Presently, Dr Assmann is the Head of Accelerator Operation and Development at GSI in Germany, responsible for GSI's heavy ion beams and the future beam commissioning of the FAIR accelerators.

Felicia Barbato

Felicia Barbato is proposer and principal investigator of the project Crystal Eye: a wide sight to the Universe looking for the electromagnetic counterpart of gravitational waves, a satellite detector for gamma ray astronomy. Thanks to her interest in cosmic rays physics and space experiment she recently joined the HERD and DAMPE collaborations. She is now detector responsible for the Zirè payload of the NUSES space mission.

Her missions as researcher are innovation and education. With these aims in 2015 she joined the Physics and Optics Naples Young Students, a group of students and young researchers dedicated to the diffusion of the scientific culture, and became member of the European Physical Society (EPS) joining the Young Minds Project, giving many contributions for the diffusion of astroparticle physics and technology. This passion for the diffusion of the scientific culture together with the passion for technology, led her to be part of the management board of the EPS Technology and Innovation Group for some years.

Christian Beck

Christian Beck is a Professor at Queen Mary University of London, UK. He is Head of the Dynamical Systems and Statistical Physics Group and a Fellow of the Alan Turing Institute (the UK's national institute for data science and artificial intelligence). Currently he is the Chairman of the EPS Statistical and Nonlinear Physics Division.

Christian Beck got his PhD in Theoretical Physics at RWTH Aachen in Germany and spent some time as a postdoc in Warwick, Copenhagen, Budapest, and Maryland before joining the University of London. He has more than 150 journal publications and is the author of two books. His research interests are in the general area of statistical physics, dynamical systems, data-driven analysis and stochastic modelling of complex systems. Together with E G D Cohen from Rockefeller University, New York, he has developed so-called superstatistical techniques, which have become a well-known method to understand heterogeneous systems in non-equilibrium statistical physics. More recently he has also dealt with the physics of sustainable energy systems, frequency fluctuations in power grid networks, spatio-temporal patterns of air pollution concentrations and other environmental problems where methods from statistical physics can be applied.

Giulio Cerullo

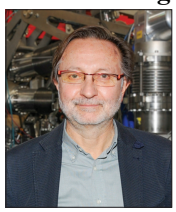
Giulio Cerullo is a Full Professor with the Physics Department, where he leads the Ultrafast Optical Spectroscopy laboratory. He is a Fellow of the Optical Society of America, the European Physical Society, the Accademia dei Lincei and past Chair of the Quantum Electronics and Optics Division of the European Physical Society. He has participated in numerous European projects, including two that received ERC grants. He has co-founded three spin-offs, among which CRI and NIREOS. He is on the Editorial Advisory Board of the journals *Optica*, *Laser & Photonics Reviews*, *Scientific Reports* and *Journal of Raman Spectroscopy*. He has been General Chair of the conferences CLEO/Europe 2017, Ultrafast Phenomena 2018 and International Conference on Raman Spectroscopy 2022.

Luisa Cifarelli

Luisa Cifarelli was until 2022 Full Professor of Experimental Physics at the University of Bologna (Italy) where she is now Emeritus. Her research interests have mostly been in very high energy subnuclear physics in major European laboratories such as CERN, Geneva (Switzerland) and DESY, Hamburg (Germany). She has been a member of the CERN Council, of the INFN Board of Directors (Italy), of the Scientific Council of CNRS (France) and of JINR (Russia). She has been President of the Italian

national research institute Centro Fermi, of the European Physical Society (EPS) and of the Italian Physical Society (SIF). She has been Chair of the Forum on International Physics of the American Physical Society (APS), a member of the APS Committee on International Scientific Affairs and she is now APS International Councillor. She is member of the ALICE Collaboration at the CERN LHC and of the Scientific Advisory Committee of DIPC (Spain). She is a member of the Academia Europaea and of the Accademia delle Scienze dell'Istituto di Bologna. She has been a member of the Governing Board of the Bologna Academy and is currently a member of its Scientific Committee. She is the founder and director of the Joint EPS-SIF International School on Energy, which is held in Varenna (Italy) on a biennial basis.

Carlos Hidalgo



Carlos Hidalgo received his PhD degree from Madrid Complutense University with his work on structural defects in solids and positron annihilation spectroscopy. His next area of research was related to plasma turbulence, transport and plasma diagnostics at CIEMAT where he is currently leading the Spanish National Fusion Laboratory.

Carlos has worked in different international laboratories, initially as a PhD student [Technical University of Denmark, Nuclear Research Centre of Grenoble, Technical University of Helsinki] and later as visiting scientist [Fusion Centre at the University of Austin (US), Oak Ridge National Laboratory (US), Joint European Torus (UK), Max Planck Institute (Germany), National Institute Fusion Studies (Japan), Southwestern Institute of Physics (SWIP, China)].

He has led different research teams in the framework of the International Fusion Programme and participated in European and International Advisory Committees on Fusion Science and Technology. He has chaired the Division of Plasma Physics and the Forum on Physics and Society of the European Physical Society.

Felix Ritort

Felix Ritort is full professor in condensed matter physics. He got his PhD in statistical physics in 1991 under the supervision of G Parisi and M Rubi. Until 2002 he made contributions to the field of disordered and nonequilibrium physics. Afterward, he started an experimental career in single-molecule biophysics to investigate energy processes at the molecular level. Ritort's group is recognized worldwide as a leader in applying the finest methods to extract quantitative information about thermodynamics and kinetics of molecular interactions. He has been awarded several prizes including the ICREA Academia Award 2008, 2013, 2018 and the Bruker Prize 2013 from Spanish Biophysical Society. He chairs the Division of Physics for Life Sciences of the European Physical Society.

His scientific research is highly multidisciplinary at the frontiers of physics, chemistry and biology. His lab is referenced worldwide on merging theory and experiments to investigate the thermodynamics and nonequilibrium behavior of small systems using single-molecule methods. Dr Ritort applies the finest concepts and tools from statistical physics to extract valuable information about a wide range of molecular processes: from the energetics of nucleic acids and proteins to the intermolecular binding kinetics in proteins, peptides and other macromolecular structures. A recurring theme in his research is the understanding of how molecular systems embedded in noisy thermal environments outperform the efficiency of macroscopic systems: being small has advantages that nature has exploited. Recently he has directed his interest to the study of energy and information and the search for principles that govern the emergent complexity of evolutionary ensembles in the molecular and cellular world.

Christophe Rossel

Christophe Rossel is a condensed matter physicist with education and academic professional experience in Switzerland (University of Neuchâtel and Geneva) and in the United States (Temple University, Philadelphia and University of California, San Diego). In 1987 he joined the IBM Research-Zurich Laboratory pursuing a scientific career focused on the physics of superconductors and later on nanoscience and the integration of advanced functional materials for semiconductor technology. As a member of various panels and president of the Swiss (SPS, 2008–12) and European Physical Societies (EPS, 2015–17) he has engaged in science policy issues, representing the community of physicists. A fellow of the EPS and of the Institute of Physics (IOP, UK) he was a member of the Open Science Policy Platform (OSPP, 2016–20) in Brussels and has been an executive board member of the Swiss Academy of Sciences (SCNAT) since 2018. He also chairs the EPS technology and Innovation group (TIG) as well as the working group on Physics and Industry of the International Union of Pure and Applied physics (IUPAP). He is emeritus senior researcher still affiliated with IBM.

Mairi Sakellariadou

Mairi Sakellariadou is a professor of Theoretical Physics at King's College London (University of London). She has studied Mathematics at the National and Kapodistrian University of Athens, Astrophysics at the University of Cambridge and obtained her Doctor of Philosophy in Physics at Tufts University (USA). She has worked at the Universities of Brussels, Tours, Pierre and Marie Curie (Sorbonne University), Zürich, Geneva and the theory division of CERN. She was also professor of General Relativity at the National and Kapodistrian University of Athens. She is a member of the LIGO Scientific Collaboration (LSC), the LISA Consortium, the Einstein Telescope Consortium, as well as the MoEDAL

experiment at LHC (CERN). She chairs the Gravitational Physics Division (GPD) of the European Physical Society (EPS), and is a member of the Executive Committee of EPS and Editor-in-Chief of the International journal 'General Relativity and Gravitation' (Springer Nature). Her research covers various aspects of theoretical physics, early universe cosmology, classical and quantum gravity, particle physics, noncommutative geometry, as well as astrophysics. She has co-authored more than 300 papers published in international specialised journals and has given hundreds of invited talks in international conferences.

Kees van Der Beek

A condensed matter physicist and citizen of the world formerly working for the Centre National de la Recherche Scientifique (CNRS) in Palaiseau, **Kees van der Beek** is now Vice President for Research at the Institut Polytechnique de Paris and Vice-Provost for Research at Ecole polytechnique in Palaiseau, near Paris in France. His scientific interests cover superconductivity and its mechanisms, the ensemble of quantized flux vortices in type II superconductors, the physics of elastic manifolds in a random potential and other soft matter systems and more generally materials science. He has worked on irradiation damage on materials, and used large-scale equipment such as particle accelerators and synchrotrons. More recently, he has been interested in magnetic systems and in semiconductor physics, mainly in the light of topological insulators.

Before moving to France, he completed his secondary education in Singapore as well as in the Netherlands. He obtained his PhD from Leiden university in the Netherlands, graduating on the exotic properties of the vortex lattice in the then recently discovered cuprate high-temperature superconductors, after which he held post-doctoral fellowships at Argonne National Laboratory in the United States and at EPFL in Switzerland. He continued work on superconductivity at the Laboratory of Irradiated Solids of the Ecole polytechnique in France, of which he later became the head. Kees has had a long-term engagement in the French and European Physical Societies, and had the pleasure of successively chairing the condensed matter divisions of both. He was the head of the Physics of Light and matter department of the Paris Saclay University south of Paris, and one of the architects of the new Graduate School of Physics at Paris-Saclay. He is currently scientific delegate at the National Institute of Physics at CNRS.

Luc van Dyck

Luc van Dyck holds a degree in biochemical engineering and a PhD in the life sciences. After twelve years of research in Belgium and Germany, he moved to the private sector where he managed public–private collaborations and public funding in the research department of a global animal health company. From 2001 to 2011 he worked at the European Molecular Biology Laboratory (EMBL), where he served as executive coordinator of a platform of scientific organizations and learned societies, the Initiative for

Science in Europe (ISE), involved in policy and advocacy at the European level. ISE is widely recognized for having been instrumental in the creation of the European Research Council (ERC). As a free-lance consultant, he worked for various organizations such as the OECD/Global Science Forum, EuroScience, the European Physical Society (EPS) and the AXA Research Fund. He now serves as Senior Advisor for Policy and Partnership Relations at the research infrastructure Euro-Argo ERIC.

Bart Van Tiggelen

Bart van Tiggelen got his master's degree in astronomy at the Leyden University and his PhD degree in physics and astrophysics at the University of Amsterdam. After some postdocs he settled in at Grenoble as a full research professor with CNRS and studied the propagation of all kinds of waves (seismic waves, acoustic and elastic waves, electromagnetic and matter waves) and is presently interested in magneto-optics and QED. He has been the scientific coordinator of many interdisciplinary programs in France, especially on the interface of physics and mathematics or biology. He is an engaged member of the French Physical Society and was the former Editor-in-Chief of EPL. Today he defends the new challenges in Open Science, especially towards younger generations.

Claudia-Elisabeth Wulz

Claudia-Elisabeth Wulz studied Technical Physics at TU Vienna, where she obtained her PhD 'sub auspiciis', a special form of graduation under the auspices of the Federal President, who awards this highest possible distinction for academic achievements for a doctoral degree in Austria. During her studies she took up research at CERN, the world's largest laboratory for particle physics in Geneva. First as a summer student, and later also as a fellow, she worked in the group of Carlo Rubbia at the UA1 experiment, where she took part in the discovery of the W and Z bosons. As a member of the Institute of High Energy Physics of the Austrian Academy of Sciences she then became a founding member of the CMS experiment, one of the two large multi-purpose detectors at the Large Hadron Collider where the Higgs boson was discovered in 2012. She has held several leading roles, including the Chair of the CMS Collaboration Board, the highest decision-making body of the experiment. She was a member of the High-Energy and Particle Physics Board of the European Physical Society. She is also a member of the Board of Trustees, the Scientific Advisory Board, at Carinthia University of Applied Sciences and an adjunct professor at TU Vienna, lecturing on particle and astro-particle physics.

List of contributors

Ankit Agarwal
Potsdam Institute for Climate Impact Research, Potsdam, Germany
and
Indian Institute of Technology Roorkee, Roorkee, India

Janos K Asboth
Wigner Research Centre for Physics, Budapest, Hungary

Ralph Assmann
Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany
and
GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

Philippe Azais
Université Grenoble-Alpes, CEA, DPE, Grenoble, France

Marco Baldovin
Université Paris-Saclay, Orsay, France
and
CNR - Instute for Complex Systems, Rome, Italy

Felicia Barbato
Gran Sasso Science Institute, Italy

Marc Barthelemy
Université Paris Saclay, Gif-sur-Yvette, France

Patricia Bassereau
Institut Curie, Paris, France

Christian Beck
Queen Mary University of London, London, UK

Tobias Beuchert
German Aerospace Center (DLR), Earth Observation Center (IMF-DAS), Oberpfaffenhofen, Weßling, Germany

Jacob D Biamonte
NASA Ames Research Center, California, United State

Freya Blekman
Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany
and
Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany

Angela Bracco
University of Milano, Milano, Italy

Antoine Browaeys
Institut d'Optique, Université Paris-Saclay, France

Darwin Caldwell
Instituto Italiano di Tecnologia, Genoa, Italy

Angelo Cangelosi
University of Manchester, Manchester, UK

Alan Cayless
School of Physical Sciences, The Open University, Milton Keynes, UK

Jitka Čejková
University of Chemistry and Technology, Prague, Czechia

Giulio Cerullo
Politecnico di Milano, Milan, Italy

Henry Chapman
Center for Free-Electron Laser Science (CFEL), Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany
and
Department of Physics, Universität Hamburg, Hamburg, Germany
and
Centre for Ultrafast Imaging, Hamburg, Germany

Nelson Christensen
Observatoire de la Côte d'Azur, Nice, France

Dana Cialla-May
Leibniz Institute of Photonic Technology, Germany

Luisa Cifarelli
University of Bologna, Bologna, Italy

J Ignacio Cirac
Max Planck Institute of Quantum Optics, Garching, Germany

Frédéric Darbellay
Université de Genève, Geneva, Switzerland

Richard Darwin
Stockholm University, Stockholm, Sweden

Seamus Davis
Oxford University, Oxford, UK

Richard Dawid
Stockholm University, Stockholm, Sweden

Jacob de Boer
Free University of Amsterdam, Amsterdam, Netherlands

José Maria de Teresa
Universidad de Zaragoza, Zaragoza, Spain

Emmanuel Dormy
Ecole Normale Supérieure, Paris, France

Claudia Draxl
Humboldt-Universität zu Berlin, Berlin, Germany

Frédéric Druon
Laboratoire Charles Fabry, France

Marco Durante
GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

Patrick Eggenberger
University of Geneva, Geneva, Switzerland

Deniz Eroglu
Kadir Has University, Istanbul, Turkey

Angeles Faus-Golfe
IN2P3-CNRS—Université Paris-Saclay, Orsay, France

Luigi Fortuna
University of Catania, Catania, Italy

María José García Borge
CSIC, Madrid, Spain

Gérard Gebel
Université Grenoble-Alpes, CEA, Liten, Grenoble, France

Carlos Gershenson
Universidad Autónoma de México, Mexico City, Mexico

Raymond Goldstein
University of Cambridge, Cambridge, UK

Giacomo Gradenigo
Gran Sasso Science Institute, L'Aquila, Italy

Hayit Greenspan
Tel Aviv University, Tel Aviv, Israel

Jean-Jacques Greffet
Institut d'Optique, Université Paris-Saclay, France

Bengt Gustaffson
Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden
and
Nordita, Hannes Alfvéns väg 12, S-10691, Stockholm, Sweden

Susanne Hellwage
Leibniz Institute of Photonic Technology, Germany

Jens Hellwage
Leibniz Institute of Photonic Technology, Germany

Carlos Hidalgo
CIEMAT, Laboratorio Nacional de Fusión, Spain

Didier Jamet
Université Grenoble-Alpes, CEA, Liten, Grenoble, France

Sally Jordan
School of Physical Sciences, The Open University, Milton Keynes, UK

Clause Keifer
CSIC, Madrid, Spain

Christoph Krafft
Leibniz Institute of Photonic Technology, Germany

Jürgen Kurths
Humboldt-Universität zu Berlin, Berlin, Germany and Potsdam Institute for Climate Impact Research, Potsdam, Germany

Florence Lefebvre-Joud
Université Grenoble-Alpes, CEA, Liten, Grenoble, France

Franck Lépine
CNRS-ILM-Lyon, Lyon, France

Søren Linderoth
Technical University of Denmark, Lyngby, Denmark

Alberto Loarte
ITER Organization, Saint-Paul-lez-Durance, France

Jan Lüning
Helmholtz Institute, Berlin, Germany

Philip Macnaghten
Knowledge, Technology and Innovation group, Department of Social Science, Wageningen University, Wageningen, Netherlands

Daniel Malz
Department of Mathematical Sciences, University of Copenhagen, Copenhagen, Denmark

Timo Mappes
Friedrich Schiller University Jena, Jena, Germany

Antigone Marino
Institute of Applied Sciences and Intelligent Systems, National Research Council (CNR), Naples, Italy

Zita Martins
Centro de Química Estrutural, Institute of Molecular Sciences and Department of Chemical Engineering, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal

Norbert Marwan
Potsdam Institute for Climate Impact Research, Potsdam, Germany
and
University of Potsdam, Potsdam, Germany

Sarah Matthews
University College London, London, UK
and
ETH Zürich, Zürich, Switzerland

Thonas G Mayerhöfer
Leibniz Institute of Photonic Technology, Jena, Germany

Eilish McLoughlin
Dublin City University, Dublin, Ireland

Natalio Mingo
Université Grenoble-Alpes, CEA, Liten, Grenoble, France

Thierry Mora
Ecole Normale Supérieure, Paris, France

Ugur Ozturk
University of Potsdam, Potsdam, Germany

Simon Perraud
Université Grenoble-Alpes, CEA, Liten, Grenoble, France

Anreas Peters
HIT GmbH at University Hospital Heidelberg, Heidelberg, Germany

Robert Pitz-Paal
German Aerospace Center (DLR), Cologne, Germany

Stefaan Poedts
KU Leuven, Leuven, Belgium

Chiara Poletto
INSERM and Sorbonne Université, Paris, France

Juergen Popp
Friedrich Schiller University Jena, Jena, Germany

Thierry Priem
Université Grenoble-Alpes, CEA, DPE, Grenoble, France

Bernd Rech
Institut für Silizium-Photovoltaik, Berlin, Germany

Lucia Reining
Laboratoire des Solides Irradiés, CNRS, École Polytechnique, Palaiseau, France

Marco Ripani
National Institute for Nuclear Physics, Genova, Italy

Felix Ritort
University of Barcelona, Barcelona, Spain

Petra Rösch
Friedrich Schiller University Jena, Jena, Germany

Christophe Rossel
IBM Research Europe - Zurich, Switzerland

Lucio Rossi
Università degli Studi di Milano, Milano, Italy

Pedro Russo
Department of Science Communication & Society and Leiden Observatory, Leiden University, Leiden, Netherlands
and
Ciência Viva, National Agency for Scientific and Tecnological Culture, Portugal

Mairi Sakellaridadou
King's College London, London, UK

Marta Sales
Universitat Rovira I Virgili, Tarragona, Spain

Pascal Salières
Université Paris-Saclay, CEA, LIDYL, Gif-sur-Yvette, France

Manos Saridakis
University of Athens, Athens, Greece

Eirini Sarigiannidou
LMGP Grenoble INP, Grenoble, France

Iwan Schie
Leibniz Institute of Photonic Technology, Germany

Jochen Schieck
Institut für Hochenergiephysik der Österreichischen Akademie der Wissenschaften, Wien, Austria
and
Technische Universität Wien, Austria

Michael Schmitt
Friedrich Schiller University Jena, Germany

Sara Seager
Massachusetts Institute of Technology, Cambridge, MA, USA

Pierre Seneor
Université Paris-Saclay, France

Shubham Sharma
Helmholtz Centre Potsdam–GFZ German Research Centre for Geosciences, Potsdam, Germany

Luis Silva
Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal

Friedrich Simmel
Technische Universität München, Garching, Germany

Thomas Tchentscher
European XFEL GmbH, Hamburg, Germany

Daniela Thrän
Deutsches Biomasseforschungszentrum—DBFZ, Leipzig, Germany

Tuan Quoc Tran
Université Grenoble-Alpes, CEA, Liten, INES campus, Le Bourget du Lac, France

Kees van Der Beek
Institut Polytechnique de Paris, Paris, France

Luc van Dyck
Euro Argo ERIC, Plouzané, France

Bart Van Tiggelen
Laboratoire de Physique et de Modélisation des Milieux Condensés, University Grenoble Alpes/CNRS, Grenoble, France

Javier Ventura-Traveset
European Space Agency, Madrid, Spain

David Vernon
Carnegie Mellon University Africa, Kigali, Rwanda

Antje Vollmer
Helmholtz Institute, Berlin, Germany

Ernst Ulrich von Weizsäcker
Professor, Freiburg, Germany

Angelo Vulpiani
Università 'Sapienza', Rome, Italy

Hermann-Josef Wagner
Ruhr-University Bochum, Bochum, Germany

Aleksandra Walczak
Ecole Normale Supérieure, Paris, France

François Weiss
LMGP Grenoble INP, Grenoble, France

Frances Westall
CNRS Orleans Campus, Orleans, France

Claudia-Elisabeth Wulz
Institute of High Energy Physics, Austrian Academy of Sciences, Vienna, Austria

IOP Publishing

EPS Grand Challenges

Physics for Society in the Horizon 2050

Mairi Sakellariadou, Claudia-Elisabeth Wulz, Kees van Der Beek, Felix Ritort, Bart van Tiggelen, Ralph Assmann, Giulio Cerullo, Luisa Cifarelli, Carlos Hidalgo, Felicia Barbato, Christian Beck, Christophe Rossel and Luc van Dyck

Chapter 1

Introduction

Science begins when someone raises a general question and sets about answering it by methodical investigation, including and combining experimentation and logical argumentation. Such scientific action spawns understanding of our world in its broadest sense and therefore the power of predicting and describing the behaviour of different bodies and objects. The corollaries are significant practical advantages—ranging from agriculture to medical applications. The dawn of science is therefore as old as the dawn of man as we know it—the mastery of fire, tools, agriculture and, later, the isolation of alloys and pure metals were, as such, great scientific advances. These were to be followed by the inevitable questions, borne out of sole curiosity, regarding consciousness, the place of man in the Universe and the workings of the cosmos. Thus, one of the first problems to be tackled truly scientifically by ancient historical cultures was to conceive explanations of the seasons and of how heavenly bodies move. Without this initial curiosity, on which our scientific and technological knowledge are based, humanity would be radically different. The build-up of knowledge concerning the workings of the distant Universe and the world at hand on one side, and the properties and behaviour of materials on the other have led, in the second half of the 18th century, to the advent of the industrial revolution. The harnessing of electromagnetism and its phenomenal stream of applications followed during the 19th century. The huge social impact of both events is unrivalled—it is difficult to think of any political, religious or economical doctrine that has brought about such radical and robust changes in society.

Creativity plays a vital role in the development of science, insofar as one of its main objectives is to imagine and shape the future. Scientific knowledge, innovation, progress and even new paradigmes arise mostly from curiosity-driven research but also often from serendipitous discovery. Moreover, one should not overlook the cultural impact of scientific research, education and training. It is the principal

doi:10.1088/978-0-7503-6342-6ch1

method by which citizens can mature to critical, rational and independent thinking. A modern developed society must therefore nurture a strong scientific sector, both in education and research, in order to address its technological and societal challenges.

Although the quest for knowledge is not necessarily susceptible to ethical evaluation, science abandons its ethical neutrality when it crititically checks how knowledge is generated, and how its technological applications impact individuals' lives and society. This is particularly clear in health research, where commercial or financial interests should never prevail over individual liberties and well-being. The opposite is true in research for sustainable development. The desires of individuals should not prevail over the common benefits for society and humanity—a topic worth scientific analysis and debate. Furthermore, the recent progress in artificial intelligence will lead us through a fascinating landscape of novel applications linked to ethical considerations. In fact, science as a whole is not always ethically neutral, i.e., impartial and fair . Quoting Berthold Brecht in his play 'Life of Galileo Galilei', *should people dedicated to science develop something like a Hippocratic Oath with the promise of using Science solely for the benefit of mankind?* Science should aim to raise global life standards, requiring long-term perspectives on international cooperation with investment and cooperation in research, education and sustained development in global challenges such as energy management or climate change.

One of the most dazzling realizations of physics is that of scale and the place of mankind in the Universe. From its smallest constituent parts to its largest structures, the description of the Universe spans an improbable 45 orders of magnitude in length scale[1]. It describes the most fascinating of journeys, from the smallest things that we have ever explored—quark particles that are less than 10^{-18} m across—to the scale of the nucleus of an atom made up of protons and neutrons—10^{-15} m—or to the atoms dreamed by the ancient Greeks, with diameters of about 10^{-10} m. The journey continues in the living world from the size of a living cell that is about 10^{-5} m, to the human scale of 1 m in our natural environment, up to the Earth's diameter of 10^{7} m. Stepping into space one evaluates the size of the Solar System to some 10^{11} m, the distance to the nearest stars outside the Solar System to 10^{16} m, the diameter of our Galaxy to 10^{21} m, until reaching the largest things we have ever measured, the greater breadth of the Universe with 10^{27} m.

What is also remarkable is the amazing effectiveness of mathematics in describing the most fundamental laws of physics. The list of achievements is impressive, ranging from Maxwell electrodynamics that holds at the scale of particles to that of distant galaxies, to Einstein's relativity theory that describes classical newtonian mechanisms as well as quantum mechanisms dealing with the interaction of matter and radiation on the atomic and subatomic scales. In particular, quantum

[1] Scientific notation is a way of writing very large or very small numbers. A number is written in scientific notation when a number between 1 and 10 is multiplied by a power of 10. For example, the Universe is about 10^{27} m across, that is, 1 followed by 27 zeros: 1 000 000 000 000 000 000 000 000 000 m.

electrodynamics, which combines quantum mechanics with Einstein special relativity, is known to be accurate in about one part in 10^{11}.[2]

We have to appreciate that one challenge is to know the laws of Nature, which are few and amazingly accurate, but another one is to predict the outcomes of these laws, which are numerous and quite often complex. In a complex system it is not so much the size of the components that is of primary importance, but the number of interconnections between them. This separation of the scientific perspective into laws and outcomes would help to understand why some disciplines of physics are so different in outlook.

Although important progress has been made and is further expected in specific areas of knowledge, the interlinking between separate areas or topics of science is crucial to addressing some of the grand scientific and societal challenges such as climate change or understanding life. Interdisciplinary allows interconnections to be made between many fields like physics, mathematics, biology, or chemistry in such a way that the whole body of connected individual ideas merge and expand into a successful global output.

There are many different images of science and of the activities of scientists in the public. Some people imply that science may eventually reach the limits of knowledge while others believe in endless horizons. Some think that science has or will provide the answers to key open questions, while others mistrust its development. The COVID-19 epidemic spreading has been more than a health and economic crisis. It illustrates our vulnerability but also the importance of interdisciplinary and multilateral science in addressing such a global challenge that affects societies at their core. Numerous multidisciplinary actions have been developed to tackle the spread of coronavirus and react against other desease outbreaks.[3]

In this book, we look at all these remarkable aspects, going from elementary particles, atoms, living cells, to stars, galaxies, and asking about our place in the Universe. We explore also what makes us, human beings, really unique in nature: our self-consciousness and our ability to imagine the world around us and shape the future by making use of the scientific method.

The book is an EPS enterprise designed to address the social dimension of science and the grand challenges in physics. Hopefully it will succeed to convince the reader that science and physics might help bringing positive changes and solutions to our societies, raising standards of living worldwide and providing further fundamental comprehension of Nature and the Universe on the Horizon 2050.

[2] This is equivalent to measuring the distance from Madrid to Berlin with an accuracy better than the width of a human hair.

[3] https://ec.europa.eu/info/research-and-innovation/research-area/health-research-and-innovation/coronavirus-research_en

Full list of references

Prelims

[1] EUROPHYSICS NEWS 2023 Special issue the EPS Grand Challenges for physics *EUROPHYSICS NEWS* **53** 5

Chapter 2

[1] Director: Mark Levinson 2013 Particle Fever (Documentary) (http://particlefever.com/)
[2] Kajita T and McDonald A B 2015 The Nobel Prize in physics was awarded for the discovery of neutrino oscillations, which shows that neutrinos have mass [online]
[3] Bednyakov A V, Kniehl B A, Pikelner A F and Veretin O L 2015 Stability of the electroweak vacuum: gauge independence and advanced precision *Phys. Rev. Lett.* **115** 201802
[4] Grange J *et al* 2015 Muon (G-2) technical design report 1 arXiv:1501.06858
[5] Rizzo T 2012 The BSM Zoo *Technical Report* (https://www-conf.slac.stanford.edu/ssi/2012/lectures.asp).
[6] Alimena J *et al* 2020 Searching for long-lived particles beyond the standard model at the large hadron collider *J. Phys. G: Nucl. Part. Phys.* **47** 090501
[7] *LHCb Trigger and Online Upgrade Technical Design Report* 5 2014
[8] Data Parking and Data Scouting at the CMS Experiment 9 2012
[9] Yoo J H 2019 The milliQan experiment: search for milli-charged particles at the LHC *PoS* ICHEP2018:520
[10] Lubatti H *et al* 2020 Explore the lifetime frontier with MATHUSLA *JINST* **15** C06026
[11] Ariga A *et al* 2019 FASER: ForwArd Search ExpeRiment at the LHC. 1 arXiv:1901.04468
[12] The LHCf CollaborationAdriani O *et al* 2008 The LHCf detector at the CERN Large Hadron Collider *J. Instrum.* **3** S08006–6
[13] The TOTEM CollaborationAnelli G *et al* 2008 The TOTEM experiment at the CERN large hadron collider *J. Instrum.* **3** S08007–7
[14] Pinfold J *et al* 2009 Technical design report of the MoEDAL experiment. 6
[15] Akerib D S *et al* 2015 LUX-ZEPLIN (LZ) conceptual design report. 9 arXiv:1509.02910
[16] Aprile E *et al* 2005 The XENON dark matter search experiment *New Astron. Rev.* **49** 289–95
[17] European Strategy Group 2020 Update of the European strategy for particle physics *Technical Report, Geneva* 2020 (https://cds.cern.ch/record/2720129)
[18] *The NuPECC Long Range Plan 2017* (http://nupecc.org/pub/lrp17/lrp2017.pdf)
[19] *The NuPECC Long Range Plan Brochure* (https://nupecc.org/pub/lrp17/nupecc_lrp_brochure_2017.pdf)
[20] *The 2015 Long Range Plan for Nuclear Science* (https://science.osti.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf)
[21] Durante M *et al* 2019 All the fun of the FAIR: fundamental physics at the facility for antiproton and ion research *Phys. Scr.* **94** 033001
[22] *JINR Long-Term Development Strategy up to 2030 and Beyond* (http://jinr.ru/posts/jinr-long-term-development-strategy-up-to-2030-and-beyond/)
[23] Gales S *et al* 2018 The extreme light infrastructure—nuclear physics (ELI-NP) facility: new horizons in physics with 10 PW ultra-intense lasers and 20 MeV brilliant gamma beams *Rep. Prog. Phys.* **81** 094301

[24] Savalle A *et al* 2018 SPIRAL2: une sonde de nouvelle génération pour explorer la matière nucléaire *Reflets Phys.* **59** 11
[25] Jokinen A 2014 The Jyväskylä Accelerator Laboratory *Nucl. Phys. News* **24** 4
[26] De Angelis G *et al* 2016 The SPES radioactive ion beam project of LNL: status and perspectives *EPJ Web Conf.* **107** 01001
[27] Calabretta L *et al* 2017 Overview of the future upgrade of the INFN-LNS superconducting cyclotron *Mod. Phys. Lett.* A **32** 1740009 (Special issue on cyclotrons and their applications)
[28] Colonna N *et al* 2018 Neutron physics with accelerators *Prog. Part. Nucl. Phys.* **101** 177
[29] Ashford M *et al* 2020 Exploratory study for the production of Sc beams at the ISOL facility of MYRRHA preliminary thermal investigations *Nucl. Instrum. Methods Phys. Res.* B **463** 244
[30] Warren S *et al* 2020 Offline 2, ISOLDE's target, laser and beams development facility *Nucl. Instrum. Methods Phys. Res.* B **463** 115
[31] Kuchi V *et al* 2020 High efficiency ISOL system to produce neutron deficient short-lived alkali RIBs on GANIL/SPIRAL 1 facility *Nucl. Instrum. Methods Phys. Res.* B **463** 163
[32] Minaya E *et al* 2020 New program for measuring masses of silver isotopes near the $N = 82$ shell closure with MLLTRAP at ALTO *Nucl. Instrum. Methods Phys. Res.* B **463** 315
[33] Kaminki G *et al* 2020 Status of the new fragment separator ACCULINA-2 and first experiments *Nucl. Instrum. Methods Phys. Res.* B **463** 504
[34] Berger N *et al* 2021 The MESA experimental program: a laboratory for precision physics with electron scattering at low energy *Nucl. Phys. News* **31** 5
[35] Facility for Rare Isotope Beams 2021 Rare isotopes aplenty at FRIB *CERN Cour.* https://frib.msu.edu/
[36] Shimizu Y *et al* 2020 Database of radioactive isotope beams produced at the BigRIPS separator *Nucl. Instrum. Methods Phys. Res.* B **463** 158
[37] Marchetto M *et al* 2020 Status of the CANREB high-resolution separator at TRIUMF *Nucl. Instrum. Methods Phys. Res.* B **463** 227
[38] Kim Y J 2020 Current status of experimental facilities at RAON *Nucl. Instrum. Methods Phys. Res.* B **463** 408
[39] Burkert V D 2018 Jefferson Lab at 12 GeV: the science program *Annu. Rev. Nucl. Part. Sci.* **68** 405–28
[40] Ohnishi H *et al* 2020 Hadron Physics at J-Park *Prog. Part. Nucl. Phys.* **113** 103773
[41] Drischl C *et al* 2021 Towards grounding nuclear physics in QCD *Prog. Part. Nucl. Phys.* **121** 103888
[42] Arbuzova A *et al* 2020 On the physics potential to study the gluon content of proton and deuteron at NICA SPD *Prog. Part. Nucl. Phys.* **113** 103858
[43] Peset C 2021 The proton radius (puzzle?) and its relatives *Prog. Part. Nucl. Phys.* **121** 103901
[44] Ireland D G *et al* 2020 Photoproduction reactions and non-strange baryon spectroscopy *Prog. Part. Nucl. Phys.* **111** 103752
[45] Constantinou M *et al* 2021 Parton distributions and lattice-QCD calculations: toward 3D structure *Prog. Part. Nucl. Phys.* **121** 103908
[46] Bartmann W *et al* 2018 The ELENA facility *Philos. Trans. A: Math. Phys. Eng. Sci.* **376** 20170266

[47] Tino G M *et al* 2020 Precision gravity tests and the Einstein equivalence principle *Prog. Part. Nucl. Phys.* **112** 103762
[48] Dong X and Greco V 2019 Heavy quark production and properties of Quark–Gluon plasma *Prog. Part. Nucl. Phys.* **104** 97 and the ALICE Publications https://alice-publications.web.cern.ch/publications
[49] ALICE Collaboration 2020 Unveiling the strong interaction among hadrons at the LHC *Nature* **588** 232–8
[50] Chapon E *et al* 2022 Prospects for quarkonium studies at the high-luminosity LHC *Prog. Part. Nucl. Phys.* **122** 103906
[51] Oganessian Y T *et al* 2017 Superheavy nuclei: from predictions to discovery *Phys. Scr.* **92** 023003
[52] Wilson J N *et al* 2021 Angular momentum generation in nuclear fission *Nature* **590** 566–70
[53] Giovinazzo J *et al* 2021 4D-imaging of drip-line radioactivity by detecting proton emission from Ni pictured with ACTAR TPC *Nat. Commun.* **12** 4805
[54] Mougeot M *et al* 2021 Mass measurements of 99–101In challenge *ab initio* nuclear theory of the nuclide 100Sn *Nat. Phys.* **17** 1099
[55] Leimbach D *et al* 2020 The electron affinity of astatine *Nat. Commun.* **11** 3824
[56] Burgio G F *et al* 2021 Neutron stars and the nuclear equation of state**120** 103879
[57] Arnould M and Goriely S 2020 Astronuclear physics: a tale of the atomic nuclei in the skies *Prog. Part. Nucl. Phys.* **112** 103766
[58] Mossa V *et al* 2020 The baryon density of the Universe from an improved rate of deuterium burning *Nature* **587** 210–3
[59] The Borexino Collaboration 2020 Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun *Nature* **587** 577–82
[60] Korten W *et al* 2020 Physics opportunities with the advanced gamma tracking array: AGATA *Eur. Phys. J.* A **56** 137
[61] Bracco A *et al* 2021 Gamma spectroscopy with AGATA in its first phases: new insights in nuclear excitations along the nuclear chart *Prog. Part. Nucl. Phys.* **121** 103887 and AGATA Publication list: https://agata.org/
[62] Fallon P *et al* 2016 GRETINA and its early science *Rev. Nucl. Part. Sci.* **66** 321 and GRETINA Publication list; http://gretina.lbl.gov/publications
[63] Milner R G 2021 The electron ion collider: the 21st-century electron microscope for the study of the fundamental structure of matter *MIT Physics Annual 2020 and Nuclear Physics News*
[64] EicC working group 2021 EicC white paper *Front. Phys.* **16** 64701
[65] Kiefer C 2012 *Quantum Gravity* (Oxford: Oxford University Press) 3rd edn
[66] Schlosshauer M 2007 *Decoherence and the Quantum-to-Classical Transition* (Berlin: Springer)
[67] Joos E, Zeh H D, Kiefer C, Giulini D, Kupsch J and Stamatescu I-O 2003 *Decoherence and the Appearance of a Classical World in Quantum Theory* 2nd edn (Berlin: Springer)
[68] DeWitt C 1957 *Proc. of the Conf. on the Role of Gravitation in Physics (University of North Carolina, Chapel Hill, January 18–23, 1957)* WADC Technical Report 57–216 (unpublished). These proceedings have recently been edited inD Rickles and C M DeWitt Edition Open Sources, http://www.edition-open-sources.org/sources/5/
[69] Bose S, Mazumdar A, Morley G W, Ulricht H and Toroš M 2017 Spin entanglement witness for quantum gravity *Phys. Rev. Lett.* **119** 240401 6

[70] Marletto C and Vedral V 2017 Witness gravity's quantum side in the lab *Nature* **547** 156–8 see also the Correspondence in *Nature* 549
[71] Albers M, Kiefer C and Reginatto M 2008 Measurement analysis and quantum gravity *Phys. Rev.* D **78** 064051 17
[72] Hehl F W and Lämmerzahl C 2019 Physical dimensions/units and universal constants: their invariance in special and general relativity *Ann. Phys. (Berlin)* **531** 1800407 10
[73] Carlip S 2001 Quantum gravity: a progress report *Rep. Prog. Phys.* **64** 885–942
[74] Woodard R P 2009 How far are we from the quantum theory of gravity? *Rep. Prog. Phys.* **72** 126002 42
[75] Kiefer C 2013 Conceptual problems in quantum gravity and quantum cosmology *ISRN Math. Phys.* **2013** 509316
[76] Zeh H D 2007 *The Physical Basis of the Direction of Time* 5th edn (Berlin: Springer)
[77] Oriti D (ed) 2009 *Approaches to Quantum Gravity* (Cambridge: Cambridge University Press)
[78] Carr B (ed) 2007 *Universe or Multiverse?* (Cambridge: Cambridge University Press)
[79] Penrose R 2007 *The Road to Reality: A Complete Guide to the Laws of the Universe* (New York: Vintage)
[80] Page D N 2013 Time dependence of Hawking radiation entropy *J. Cosmol. Astropart. Phys.* **9** 28 28
[81] Feynman R 1990 *The Character of Physical Law* (Cambridge, MA: MIT Press)
[82] Carlip S 2019 *General Relativity: A Concise Introduction* (Oxford: Oxford University Press)
[83] Bertone G and Hooper D 2018 History of dark matter *Rev. Mod. Phys.* **90** 045002
[84] Zyla P A *et al* 2020 Review of particle physics *Prog. Theor. Exp. Phys.* **2020** 083C01
[85] Zwicky F 1933 Die Rotverschiebung von extragalaktischen Nebeln *Helv. Phys. Acta* **6** 110 127
[86] Milgrom M 1983 A modification of the Newtonian dynamics as a possible alternative to the hidden mass hypothesis *Astrophys. J.* **270** 365 370
[87] Einstein A 1916 The foundation of the general theory of relativity *Ann. Phys.* **49** 769–822
[88] Gaillard M K, Grannis P D and Sciulli F J 1999 The standard model of particle physics *Rev. Mod. Phys.* **71** S96–S111
[89] Blumenthal G R, Faber S M, Primack J R and Rees M J 1984 Formation of galaxies and large scale structure with cold dark matter *Nature* **311** 517–25
[90] Audren B, Lesgourgues J, Mangano G, Serpico P D and Tram T 2014 Strongest model-independent bound on the lifetime of dark matter *J. Cosmol. Astropart. Phys.* **12** 028
[91] Rubin V C and Ford W K 1970 Rotation of the Andromeda nebula from a spectroscopic survey of emission regions *Astrophys. J.* **159** 379–403
[92] White M J, Scott D and Silk J 1994 Anisotropies in the cosmic microwave background *Ann. Rev. Astron. Astrophys.* **32** 319–70
[93] Wayne Hu and Dodelson S 2002 Cosmic microwave background anisotropies *Ann. Rev. Astron. Astrophys.* **40** 171–216
[94] Ade P A R *et al* 2016 Planck 2015 results. XIII. Cosmological parameters *Astron. Astrophys.* **594** A13
[95] Lifshitz E 1946 Republication of: on the gravitational stability of the expanding universe *J. Phys. (USSR)* **10** 116
[96] Vogelsberger M, Marinacci F, Torrey P and Puchwein E 2020 Cosmological simulations of galaxy formation *Nature Rev. Phys.* **2** 42–66

[97] Alpher R A, Follin J W and Herman R C 1953 Physical conditions in the initial stages of the expanding universe *Phys. Rev.* **92** 1347–61
[98] Wagoner R V, Fowler W A and Hoyle F 1967 On the synthesis of elements at very high temperatures *Astrophys. J.* **148** 3–49
[99] Cerdeno D G and Green. A M 2010 Direct detection of WIMPs arXiv:1002.1912 [astro-ph. CO] 2
[100] Bullock J S and Boylan-Kolchin M 2017 Small-scale challenges to the Λ CDM paradigm *Ann. Rev. Astron. Astrophys.* **55** 343–87
[101] Baer H, Choi K-Y, Kim J E and Roszkowski L 2015 Dark matter production in the early Universe: beyond the thermal WIMP paradigm *Phys. Rept.* **555** 1 60
[102] Steigman G and Turner M S 1985 Cosmological constraints on the properties of weakly interacting massive particles *Nucl. Phys.* B **253** 375–86
[103] Hu W, Rennan B and Gruzinov A 2000 Cold and fuzzy dark matter *Phys. Rev. Lett.* **85** 1158–61
[104] Hooper D, Leane R K, Tsai Y-D, Wegsman S and Witte. S J 2020 A systematic study of hidden sector dark matter:application to the gamma-ray and antiproton excesses *J. High Energy Phys.* **07** 163
[105] Griest K 1991 Galactic microlensing as a method of detecting massive compact halo objects *Astrophys. J.* **366** 412–21
[106] Villanueva-Domingo P, Mena O and Palomares-Ruiz S 2021 A brief review on primordial black holes as dark matter *Front. Astron. Space Sci.* **8** 87
[107] Carr B, Kohri K, Sendouda Y and Yokoyama J 2021 Constraints on primordial black holes *Rept. Prog. Phys.* **84** 116902
[108] Bekenstein J D 2005 Modified gravity vs dark matter: relativistic theory for MOND *PoS* JHW2004:012
[109] McGaugh S S 2015 A tale of two paradigms: the mutual incommensurability of Λ CDM and MOND *Can. J. Phys.* **93** 250–9
[110] Gaskins J M 2016 A review of indirect searches for particle dark matter *Contemp. Phys.* **57** 496–525
[111] Kahlhoefer F 2017 Review of LHC dark matter searches *Int. J. Mod. Phys.* A **32** 1730006
[112] Teresa Marrodán UndagoitiaRauch L 2016 Dark matter direct-detection experiments *J. Phys.* G Nucl. Phys. **43** 013001
[113] Silk J *et al* 2010 *Particle Dark Matter: Observations, Models and Searches* (Cambridge: Cambridge University Press)
[114] Lewin J D and Smith P F 1996 Review of mathematics, numerical factors, and corrections for dark matter experiments based on elastic nuclear recoil *Astropart. Phys.* **6** 87 112
[115] Agrawal P *et al* 2021 Feebly-interacting particles: FIPs 2020 workshop report *Eur. Phys. J.* C **81** 1015
[116] Marsh D J E 2016 Axion cosmology *Phys. Rept.* **643** 1 79
[117] Abbott B P *et al* 2016 Observation of gravitational waves from a binary black hole merger *Phys. Rev. Lett.* **116** 061102
[118] Bertone G *et al* 202 Gravitational wave probes of dark matter: challenges and opportunities *SciPost Phys. Core* **3** 007
[119] Arbey A and Mahmoudi F 2021 Dark matter and the early Universe: a review *Prog. Part. Nucl. Phys.* **119** 103865

[120] Carney D *et al* 2021 Mechanical quantum sensing in the search for dark matter *Quantum Sci. Technol.* **6** 024002
[121] Donzelli M and Carpineti M 2017 The underground laboratories global research infrastructures *Case Studies Report, GSO—Group of Senior Officials on Global Research Infrastructures, August, 2017. Presented to the G7 Science Ministers' Meeting (Turin, 27–28 September)*
[122] Angloher G *et al* 2019 Exploring with NUCLEUS at the Chooz nuclear power plant *Eur. Phys. J.* C **79** 1018
[123] Bowen M and Huber P 2020 Reactor neutrino applications and coherent elastic neutrino nucleus scattering *Phys. Rev.* D **102** 053008
[124] Dodelson S and Schmidt F 2020 *Modern Cosmology* (London: Academic)
[125] van Albada T S, Bahcall J N, Begeman K and Sancisi R 1985 The Distribution of dark matter in the spiral galaxy NGC-3198 *Astrophys. J.* **295** 305 313
[126] Springel V, White S D M, Frenk C S, Navarro J F, Jenkins A, Vogelsberger M, Wang J, Ludlow A and Helmi A 2008 A blueprint for detecting supersymmetric dark matter in the Galactic halo arXiv:0809.0894 [astro-ph] 9
[127] Einstein A 1916 Die Grundlage der allgemeinen Relativitätstheorie *Ann. Phys. (Berlin)* **49** 769
[128] Einstein A 1916 Sitzungsber *Preuss. Akad. Wiss. Berlin* **1** 688
[129] Einstein A 1918 Sitzungsberichte *Preuss. Akad. Wiss. Berlin* **1** 154
[130] Abbott B P *et al* (LIGO Scientific Collaboration and Virgo Collaboration) 2016 *Phys. Rev. Lett.* **116** 061102
[131] Abbott R *et al* 2020 (LIGO Scientific, Virgo) (*Preprint*)
[132] Aasi J *et al* 2015 Characterization of the LIGO detectors during their sixth science run *Class. Quantum Grav.* **32** 074001
[133] Acernese F *et al* 2015 Advanced Virgo: a second-generation interferometric gravitational wave detector *Class. Quantum Grav.* **32** 024001
[134] Abbott B P *et al* 2020 Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA *Living Rev. Rel.* **23** 3 (KAGRA, LIGO Scientific, Virgo)
[135] Affeldt C *et al* 2014 Advanced techniques in GEO 600 *Class. Quantum Grav.* **31** 224002
[136] Somiya K 2012 Detector configuration of KAGRA—the Japanese cryogenic gravitational-wave detector *Class. Quantum Grav.* **29** 124007
[137] Unnikrishnan C S 2013 IndIGO and LIGO-India: scope and plans for gravitational wave research and precision metrology in India *Int. J. Mod. Phys.* D **22** 1341010
[138] Punturo M *et al* 2010 The Einstein Telescope: a third-generation gravitational wave observatory *Class. Quantum Grav.* **27** 194002
[139] Reitze D *et al* 2019 Cosmic explorer: the U.S. contribution to gravitational-wave astronomy beyond LIGO *Bull. Am. Astron. Soc.* **51** 141 (*Preprint*)
[140] Amaro-Seoane P *et al* 2017 Laser interferometer space antenna arXiv:1702.00786 [astro-ph. IM] *ArXiv e-prints* (*Preprint*)
[141] Arzoumanian Z *et al* 2020 The NANOGrav 12.5 yr data set: search for an isotropic stochastic gravitational-wave background *Astrophys. J. Lett.* **905** L34 (*Preprint*)
[142] Smits R, Kramer M, Stappers B, Lorimer D, Cordes J and Faulkner A 2009 Pulsar searches and timing with the square kilometre array *Astron. Astrophys.* **493** 1161–70

[143] Lazio T 2013 The Square Kilometre Array pulsar timing array *Class. Quantum Grav.* **30** 4011
[144] Stappers B W, Keane E F, Kramer M, Possenti A and Stairs I H 2018 The prospects of pulsar timing with new-generation radio telescopes and the Square Kilometre Array *Phil. Trans. R. Soc.* A **376** 20170293
[145] Taylor J and Weisberg J 1989 Further experimental tests of relativistic gravity using the binary pulsar PSR 1913+16 *Astrophys. J.* **345** 434
[146] Abbott B P *et al* 2016 GW150914: the advanced LIGO detectors in the era of first discoveries *Phys. Rev. Lett.* **116** 131103 (LIGO Scientific, Virgo) (*Preprint*)
[147] Huterer D and Shafer D L 2018 Dark energy two decades after: observables, probes, consistency tests *Rept. Prog. Phys.* **81** 016901 [arXiv:1709.01091 [astro-ph.CO]]
[148] Zhao G B *et al* 2017 Dynamical dark energy in light of the latest observations *Nat. Astron* **1** 627–32 [arXiv:1701.08165 [astro-ph.CO]]
[149] Saridakis E N *et al* [CANTATA] Modified gravity and cosmology: an update by the CANTATA network [arXiv:2105.12582 [gr-qc]]
[150] Fender R and Belloni T 2012 Stellar-mass black holes and ultraluminous X-ray sources *Science* **337** 540 (*Preprint*)
[151] Abbott B P *et al* 2019 GWTC-1: a gravitational-wave transient catalog of compact binary mergers observed by LIGO and Virgo during the first and second observing runs *Phys. Rev.* **X9** 031040 (LIGO Scientific, Virgo)(*Preprint*)
[152] Abbott R *et al* 2020 GW190521: a binary black hole merger with a total mass of 150 $M_{\odot}$ *Phys. Rev. Lett.* **125** 101102 (LIGO Scientific, Virgo)(*Preprint*)
[153] Abbott R *et al* 2020 Properties and astrophysical implications of the 150 $M_{\odot}$ binary black hole merger GW190521 *Astrophys. J. Lett.* **900** L13 (LIGO Scientific, Virgo)(*Preprint*)
[154] Ghez A M *et al* 2008 Measuring distance and properties of the Milky Way's central supermassive black hole with stellar orbits *Astrophys. J.* **689** 1044–62 (*Preprint*)
[155] Genzel R, Eisenhauer F and Gillessen S 2010 The Galactic Center massive black hole and nuclear star cluster *Rev. Mod. Phys.* **82** 3121–95 (*Preprint*)
[156] Akiyama K *et al* 2019 First M87 event horizon telescope results. I. The shadow of the supermassive black hole *Astrophys. J.* **875** L1 (Event Horizon Telescope)(*Preprint*)
[157] Schwarzschild K 1916 On the gravitational field of a mass point according to Einstein's theory *Sitzungsber. Preuss. Akad. Wiss. Berlin (Berlin)* **189** 96
[158] Penrose R 1965 Gravitational collapse and space-time singularities *Phys. Rev. Lett.* **14** 57–9
[159] Penrose R 1969 Gravitational collapse: the role of general relativity *Riv. Nuovo Cim.* **1** 252
[160] Wald R M 1999 *Gravitational Collapse and Cosmic Censorship* (Dordrecht: Springer) pp 69–86
[161] Israel W 1967 Event horizons in static vacuum space-times *Phys. Rev.* **164** 1776–9
[162] Carter B 1971 Axisymmetric black hole has only two degrees of freedom *Phys. Rev. Lett.* **26** 331–3
[163] Bekenstein J D 1972 Black holes and the second law *Lett. Nuovo Cim.* **4** 737–40
[164] Hawking S W 1974 Black hole explosions? *Nature* **248** 30–1
[165] Abbott B PLIGO Scientific Collaboration and Virgo Collaboration *et al* 2016 GW151226: observation of gravitational waves from a 22-solar-mass binary black hole coalescence *Phys. Rev. Lett.* **116** 241103
[166] Abbott B PLIGO Scientific Collaboration and Virgo Collaboration *et al* 2016 Binary black hole mergers in the first advanced LIGO observing run *Phys. Rev.* X **6** 041015

[167] Abbott B PLIGO Scientific Collaboration and Virgo Collaboration *et al* 2017 GW170814: a three-detector observation of gravitational waves from a binary black hole coalescence *Phys. Rev. Lett.* **119** 141101
[168] Abbott B PLIGO Scientific Collaboration and Virgo Collaboration *et al* 2017 GW170817: observation of gravitational waves from a binary neutron star inspiral *Phys. Rev. Lett.* **119** 161101
[169] Abbott B PVirgo, Fermi-GBM, INTEGRAL, LIGO Scientific *et al* 2017 Gravitational waves and gamma-rays from a binary neutron star merger: GW170817 and GRB 170817A *Astrophys. J.* **848** L13
[170] Goldstein A *et al* 2017 An ordinary short gamma-ray burst with extraordinary implications: *Fermi*-GBM detection of GRB 170817A *Astrophys. J.* **848** L14 (*Preprint*)
[171] Abbott B P *et al* 2017 Multi-messenger observations of a binary neutron star merger *Astrophys. J.* **848** L12
[172] Christensen N and Meyer R 1998 Markov chain Monte Carlo methods for Bayesian gravitational radiation data analysis *Phys. Rev.* D **58** 082001
[173] Veitch J *et al* 2015 Parameter estimation for compact binaries with ground-based gravitational-wave observations using the LALInference software library *Phys. Rev.* D **91** 042003 (*Preprint*)
[174] Abbott RLIGO Scientific, Virgo *et al* 2020 Population properties of compact objects from the second LIGO-Virgo gravitational-wave transient catalog arXiv:2010.14533 [astro-ph. HE] (*Preprint*)
[175] Belczynski K *et al* 2020 Evolutionary roads leading to low effective spins, high black hole masses, and O1/O2 rates for LIGO/Virgo binary black holes *Astron. Astrophys.* **636** A104 (*Preprint*)
[176] Ivanova N *et al* 2013 Common envelope evolution: where we stand and how we can move forward *Astron. Astrophys. Rev.* **21** 59 (*Preprint*)
[177] Spera M and Mapelli M 2017 Very massive stars, pair-instability supernovae and intermediate-mass black holes with the SEVN code *Mon. Not. Roy. Astron. Soc.* **470** 4739–49 (*Preprint*)
[178] Farmer R, Renzo M, de Mink S E, Marchant P and Justham S 2019 Mind the gap: the location of the lower edge of the pair-instability supernova black hole mass gap *Astrophys. J.* **887** 53
[179] Rodriguez C L, Zevin M, Pankow C, Kalogera V and Rasio F A 2016 Illuminating black hole binary formation channels with spins in advanced LIGO *Astrophys. J. Lett.* **832** L2 (*Preprint*)
[180] Vitale S, Lynch R, Sturani R and Graff P 2017 Use of gravitational waves to probe the formation channels of compact binaries *Class. Quant. Grav.* **34** 03LT01 (*Preprint*)
[181] Carr B J and Hawking S W 1974 Black holes in the early Universe *Mon. Not. R. Astron. Soc.* **168** 399–415 (*Preprint*)
[182] Carr B, Kühnel F and Sandstad M 2016 Primordial black holes as dark matter *Phys. Rev.* D **94** 083504
[183] Bird S, Cholis I, Muñoz J B, Ali-Hamoud Y, Kamionkowski M, Kovetz E D, Raccanelli A and Riess A G 2016 Did LIGO detect dark matter? *Phys. Rev. Lett.* **116** 201301 (*Preprint*)
[184] Sasaki M, Suyama T, Tanaka T and Yokoyama S 2016 Primordial black hole scenario for the gravitational-wave event GW150914 *Phys. Rev. Lett.* **117** 061101

Erratum 2018 Primordial black hole scenario for the gravitational-wave event GW150914 *Phys. Rev. Lett.* **121** 059901 (*Preprint*)

[185] Jenkins A C and Sakellariadou M 2020 Primordial black holes from cusp collapse on cosmic strings arXiv:2006.16249 [astro-ph.CO] (*Preprint*)

[186] Boehm C, Kobakhidze A, O'Hare C A J, Picker Z S C and Sakellariadou M 2020 Eliminating the LIGO bounds on primordial black hole dark matter arXiv:2008.10743 [astro-ph.CO] (*Preprint*)

[187] Fernandez N and Profumo S 2019 Unraveling the origin of black holes from effective spin measurements with LIGO-Virgo *J. Cosmol. Astropart. Phys.* **08** 022 (*Preprint*)

[188] Abbott B PLIGO Scientific, Virgo *et al* 2019 Search for subsolar mass ultracompact binaries in advanced LIGO's second observing run *Phys. Rev. Lett.* **123** 161102 (*Preprint*)

[189] Knox L, Christensen N and Skordis C 2001 The age of the Universe and the cosmological constant determined from cosmic microwave background anisotropy measurements *Astrophys. J. Lett.* **563** L95–8 (*Preprint*)

[190] Kulier A, Ostriker J P, Natarajan P, Lackner C N and Cen R 2015 Understanding black hole mass assembly via accretion and mergers at late times in cosmological simulations *Astrophys. J.* **799** 178 (*Preprint*)

[191] Begelman M C, Volonteri M and Rees M J 2006 Formation of supermassive black holes by direct collapse in pre-galactic haloes *Mon. Not. Roy. Astron. Soc.* **370** 289–98 (*Preprint*)

[192] Banados E *et al* 2018 An 800-million-solar-mass black hole in a significantly neutral Universe at a redshift of 7.5 *Nature* **553** 473–6 (*Preprint*)

[193] Wang F *et al* 2021 A luminous quasar at redshift 7.642 *Astrophys. J. Lett.* **907** L1 (*Preprint*)

[194] Greene J E, Strader J and Ho L C 2020 Intermediate-mass black holes *Annu. Rev. Astron. Astrophys.* **58** 257–312 (*Preprint*)

[195] Abbott B PLIGO Scientific, Virgo *et al* 2020 A guide to LIGO–Virgo detector noise and extraction of transient gravitational-wave signals *Class. Quant. Grav.* **37** 055002

[196] Abbott B PLIGO Scientific Collaboration, Virgo Collaboration *et al* 2017 GW170104: observation of a 50-solar-mass binary black hole coalescence at redshift 0.2 *Phys. Rev. Lett.* **118** 221101

[197] Unnikrishnan C S 2013 IndIGO and LIGO-India: scope and plans for gravitational wave research and precision metrology in India *Int. J. Mod. Phys.* D **22** 1341010 (*Preprint*)

[198] Abbott B PLIGO Scientific Collaboration, Virgo Collaboration *et al* 2017 GW170817: observation of gravitational waves from a binary neutron star inspiral *Phys. Rev. Lett.* **119** 161101 (*Preprint*)

[199] Abbott B PLIGO Scientific Collaboration, Virgo Collaboration, Fermi-GBM, INTEGRAL *et al* 2017 Gravitational waves and gamma-rays from a binary neutron star merger: GW170817 and GRB 170817A *Astrophys. J.* **848** L13 (*Preprint*)

[200] Savchenko V *et al* 2017 *INTEGRAL* detection of the first prompt gamma-ray signal coincident with the gravitational-wave event GW170817 *Astrophys. J.* **848** L15 (*Preprint*)

[201] Goldstein A *et al* 2017 An ordinary short gamma-ray burst with extraordinary implications: *Fermi*-GBM detection of GRB 170817A *Astrophys. J. Lett.* **848** L14 (*Preprint*)

[202] Abbott B PLIGO Scientific Collaboration, Virgo Collaboration *et al* 2019 Tests of general relativity with the binary black hole signals from the LIGO-Virgo catalog GWTC-1 *Phys. Rev.* **D100** 104036 (*Preprint*)

[203] Bekenstein J D and Mukhanov V F 1995 Spectroscopy of the quantum black hole *Phys. Lett.* B **360** 7–12 (*Preprint*)

[204] Cardoso V, Foit V F and Kleban M 2019 Gravitational wave echoes from black hole area quantization *J. Cosmol. Astropart. Phys.* **2019** 6
[205] Abbott B PLIGO Scientific, Virgo *et al* 2016 Observation of gravitational waves from a binary black hole merger *Phys. Rev. Lett.* **116** 061102 (*Preprint*)
[206] Abedi J, Dykaar H and Afshordi N 2017 Echoes from the abyss: tentative evidence for Planck-scale structure at black hole horizons *Phys. Rev.* D **96** 082004 (*Preprint*)
[207] Westerweck J, Nielsen A B, Fischer-Birnholtz O, Cabero M, Capano C, Dent T, Krishnan B, Meadors G and Nitz A H 2018 Low significance of evidence for black hole echoes in gravitational wave data *Phys. Rev.* D **97** 124037
[208] Schutz B F 1986 Determining the Hubble constant from gravitational wave observations *Nature* **323** 310–1
[209] Nissanke S, Holz D E, Hughes S A, Dalal N and Sievers J L 2010 Exploring short gamma-ray bursts as gravitational-wave standard sirens *Astrophys. J.* **725** 496–514 (*Preprint*)
[210] Christensen N, Meyer R, Knox L and Luey B 2001 Bayesian methods for cosmological parameter estimation from cosmic microwave background measurements *Class. Quantum Grav.* **18** 2677–88
[211] Riess A G *et al* 2016 A 2.4% determination of the local value of the Hubble constant *Astrophys. J.* **826** 56 (*Preprint*)
[212] Abbott B PLIGO Scientific, Virgo, 1M2H, Dark Energy Camera GW-E, DES, DLT40, Las Cumbres Observatory, VINROUGE, MASTER *et al* 2017 Hungary rewards highly cited scientists with bonus grants *Nature* **551** 425–6 (*Preprint*)
[213] Ade P A R *et al* 2016 *Planck* 2015 results *Astron. Astrophys.* **594** A13 (*Preprint*)
[214] Abbott B PKAGRA, LIGO Scientific Collaboration and Virgo Collaboration *et al* 2019 Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA *Living Rev. Relativ.* **23** 3 (*Preprint*)
[215] https://gw-openscience.org
[216] Armano M *et al* 2016 Sub-femto-*g* free fall for space-based gravitational wave observatories: LISA pathfinder results *Phys. Rev. Lett.* **116** 231101
[217] Armano M *et al* 2018 Beyond the required LISA free-fall performance: new LISA pathfinder results down to 20 μHz *Phys. Rev. Lett.* **120** 061101
[218] Kamionkowski M and Kovetz E D 2016 The quest for B modes from inflationary gravitational waves *Annu. Rev. Astron. Astrophys.* **54** 227–69 (*Preprint*)
[219] Maggiore M *et al* 2020 Science case for the Einstein telescope *J. Cosmol. Astropart. Phys.* **03** 050 (*Preprint*)
[220] Christensen N 2019 Stochastic gravitational wave backgrounds *Rep. Prog. Phys.* **82** 016903
[221] Biscoveanu S, Talbot C, Thrane E and Smith R 2020 Measuring the primordial gravitational-wave background in the presence of astrophysical foregrounds *Phys. Rev. Lett.* **125** 241101
[222] Martinovic K, Meyers P M, Sakellariadou M and Christensen N 2021 Simultaneous estimation of astrophysical and cosmological stochastic gravitational-wave backgrounds with terrestrial detectors *Phys. Rev.* D **103** 043023
[223] Regimbau T, Evans M, Christensen N, Katsavounidis E, Sathyaprakash B and Vitale S 2017 Digging deeper: observing primordial gravitational waves below the binary-black-hole-produced stochastic background *Phys. Rev. Lett.* **118** 151105
[224] Sachdev S, Regimbau T and Sathyaprakash B 2020 Subtracting compact binary foreground sources to reveal primordial gravitational-wave backgrounds *Phys. Rev.* D **102** 024051 (*Preprint*)

[225] Sesana A 2016 Prospects for multiband gravitational-wave astronomy after GW150914 *Phys. Rev. Lett.* **116** 231102 (*Preprint*)
[226] Adams M R and Cornish N J 2014 Detecting a stochastic gravitational wave background in the presence of a galactic foreground and instrument noise *Phys. Rev.* D **89** 022001 (*Preprint*)
[227] Boileau G, Christensen N, Meyer R and Cornish N J 2020 Spectral separation of the stochastic gravitational-wave background for LISA: observing both cosmological and astrophysical backgrounds arXiv:2011.05055 (*Preprint*) arXiv e-prints
[228] Mingarelli C M F 2019 Improving binary millisecond pulsar distances with Gaia arXiv:1812.06262 [astro-ph.IM] (*Preprint*)
[229] Buldgen G, Salmon S and Noels A 2019 Progress in global helioseismology: a new light on the solar modelling problem and its implications for solar-like stars *Front. Astron. Space Sci.* **6** 42
[230] Christensen-Dalsgaard J 2021 Solar structure and evolution *Living Rev. Sol. Phys.* **18** 2
[231] Basu S and Antia H M 1997 Seismic measurement of the depth of the solar convection zone *Mon. Not. R. Astron. Soc.* **287** 189–98
[232] Basu S and Antia H M 1995 Helium abundance in the solar envelope *Mon. Not. R. Astron. Soc.* **276** 1402–8
[233] Vorontsov S V, Baturin V A, Ayukov S V and Gryaznov V K 2013 Helioseismic calibration of the equation of state and chemical composition in the solar convective envelope *Mon. Not. R. Astron. Soc.* **430** 1636–52
[234] Vorontsov S V, Baturin V A and Pamiatnykh A A 1991 Seismological measurement of solar helium abundance *Nature* **349** 49–51
[235] Grevesse N and Noels A 1992 Cosmic abundances of the elements *Origin and Evolution of the Elements: Proceedings of a Symposium in Honour of H. Reeves held in Paris, June 22–25, 1993* ed N Prantzos, E Vangioni-Flam, M Casse, N Prantzos, E Vangioni-Flam and M Casse (Cambridge: Cambridge University Press) p 14
[236] Christensen-Dalsgaard J *et al* 1996 The current state of solar modeling *Science* **272** 1286
[237] Asplund M, Grevesse N and Sauval A J 2005 The solar chemical composition *Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis, of Astronomical Society of the Pacific Conf. Series* ed III Barnes, G Thomas and F N Bash (San Francisco, CA: Astronomical Society of the Pacific)vol 336 p 25
[238] Asplund M, Grevesse N, Jacques Sauval A and Scott. P 2009 The chemical composition of the Sun *Annu. Rev. Astron. Astrophys.* **47** 481–522
[239] Basu S and Antia H M 2008 Helioseismology and solar abundances *Phys. Rep.* **457** 217–83
[240] Pezzotti C, Eggenberger P, Buldgen G, Meynet G, Bourrier V and Mordasini C 2021 Revisiting Kepler-444. II. Rotational, orbital, and high-energy fluxes evolution of the system *Astron. Astrophys.* **650** A108
[241] Serenelli A M, Basu S, Ferguson J W and Asplund M 2009 New solar composition: the problem with solar models revisited *Astrophys. Lett.* **705** L123–7
[242] Pinsonneault M H, Kawaler S D, Sofia S and Demarque P 1989 Evolutionary models of the rotating sun *Astrophys. J.* **338** 424–52
[243] Charbonneau P and MacGregor K B 1993 Angular momentum transport in magnetized stellar radiative zones. II. The solar spin-down *Astrophys. J.* **417** 762
[244] Gough D O and McIntyre M E 1998 Inevitability of a magnetic field in the Sun's radiative interior *Nature* **394** 755–7

[245] Mestel L 1953 Rotation and stellar evolution *Mon. Not. R. Astron. Soc.* **113** 716
[246] Mestel L and Weiss N O 1987 Magnetic fields and non-uniform rotation in stellar radiative zones *Mon. Not. R. Astron. Soc.* **226** 123–35
[247] Mosser B *et al* 2012 Spin down of the core rotation in red giants *Astron. Astrophys.* **548** A10
[248] Spada F, Lanzafame A C and Lanza A F 2010 A semi-analytic approach to angular momentum transport in stellar radiative interiors *Mon. Not. R. Astron. Soc.* **404** 660
[249] Braithwaite J and Spruit H C 2017 Magnetic fields in non-convective regions of stars *R. Soc. Open Sci.* **4** 160271
[250] Brun A S and Zahn J-P 2006 Magnetic confinement of the solar tachocline *Astron. Astrophys.* **457** 665–74
[251] Tayler R J 1973 The adiabatic stability of stars containing magnetic fields-I. Toroidal fields *Mon. Not. R. Astron. Soc.* **161** 365
[252] Spruit H C 2002 Dynamo action by differential rotation in a stably stratified stellar interior *Astron. Astrophys.* **381** 923–32
[253] Eggenberger P, Maeder A and Meynet G 2005 Stellar evolution with rotation and magnetic fields. IV. The solar rotation profile *Astron. Astrophys.* **440** L9–L12
[254] Eggenberger P, Buldgen G and Salmon S J A J 2019 Rotation rate of the solar core as a key constraint to magnetic angular momentum transport in stellar interiors *Astron. Astrophys.* **626** L1
[255] Salmon S, Buldgen G, Noels A, Eggenberger P, Scuflaire R and Meynet G 2021 Standard solar models: perspective from updated solar neutrino fluxes and gravity-mode period spacing *Astron. Astrophys.* **651** A106
[256] Miglio A *et al* 2013 Galactic archaeology: mapping and dating stellar populations with asteroseismology of red-giant stars *Mon. Not. R. Astron. Soc.* **429** 423–8
[257] Miglio A, Montalbán J, Baudin F, Eggenberger P, Noels A, Hekker S, De Ridder J, Weiss W and Baglin A 2009 Probing populations of red giants in the galactic disk with CoRoT *Astron. Astrophys.* **503** L21–4
[258] Miglio A *et al* 2021 HAYDN *Exp. Astron.* **51** 963–1001
[259] Arnett W D, Meakin C, Viallet M, Campbell S W, Lattanzio J C and Mocák M 2015 Beyond mixing-length theory: a step toward 321D *Astrophys. J.* **809** 30
[260] Aerts C 2021 Probing the interior physics of stars through asteroseismology *Rev. Mod. Phys.* **93** 015001
[261] Beck P G *et al* 2012 Fast core rotation in red-giant stars as revealed by gravity-dominated mixed modes *Nature* **481** 55–7
[262] Deheuvels S *et al* 2012 Seismic evidence for a rapidly rotating core in a lower-giant-branch star observed with kepler *Astrophys. J.* **756** 19
[263] Gehan C, Mosser B, Michel E, Samadi R and Kallinger T 2018 Core rotation braking on the red giant branch for various mass ranges *Astron. Astrophys.* **616** A24
[264] Ceillier T, Eggenberger P, Garca R A and Mathis S 2013 Understanding angular momentum transport in red giants: the case of KIC 7341231 *Astron. Astrophys.* **555** A54
[265] Eggenberger P, Montalbán J and Miglio A 2012 Angular momentum transport in stellar interiors constrained by rotational splittings of mixed modes in red giants *Astron. Astrophys.* **544** L4
[266] Marques J P *et al* 2013 Seismic diagnostics for transport of angular momentum in stars. I. Rotational splittings from the pre-main sequence to the red-giant branch *Astron. Astrophys.* **549** A74

[267] Eggenberger P *et al* 2019 Asteroseismology of evolved stars to constrain the internal transport of angular momentum. I. Efficiency of transport during the subgiant phase *Astron. Astrophys.* **621** A66
[268] Eggenberger P *et al* 2017 Constraining the efficiency of angular momentum transport with asteroseismology of red giants: the effect of stellar mass *Astron. Astrophys.* **599** A18
[269] Mayor M and Queloz D 1995 A Jupiter-mass companion to a solar-type star *Nature* **378** 355–9
[270] Ricker G R *et al* 2015 Transiting Exoplanet Survey Satellite (TESS) *J. Astron. Teles., Instrum., Syst.* **1** 014003
[271] Rüdiger G and Kitchatinov L L 1996 The internal solar rotation in its spin-down history *Astrophys. J.* **466** 1078
[272] Privitera G, Meynet G, Eggenberger P, Vidotto A A, Villaver E and Bianda M 2016 Star–planet interactions. I. Stellar rotation and planetary orbits *Astron. Astrophys.* **591** A45
[273] Privitera G, Meynet G, Eggenberger P, Vidotto A A, Villaver E and Bianda M 2016 Star–planet interactions. II. Is planet engulfment the origin of fast rotating red giants? *Astron. Astrophys.* **593** A128
[274] Rao S, Meynet G, Eggenberger P, Haemmerlé L, Privitera G, Georgy C, Ekström S and Mordasini C 2018 Star–planet interactions. V. Dynamical and equilibrium tides in convective zones *Astron. Astrophys.* **618** A18
[275] Lopez E D and Fortney J J 2013 The role of core mass in controlling evaporation: the Kepler radius distribution and the Kepler-36 density dichotomy *Astrophys. J.* **776** 2
[276] Owen J E and Lai D 2018 Photoevaporation and high-eccentricity migration created the sub-Jovian desert *Mon. Not. R. Astron. Soc.* **479** 5012–21
[277] Johnstone C P, Bartel M and Güdel M 2021 The active lives of stars: a complete description of the rotation and XUV evolution of F, G, K, and M dwarfs *Astrophys. J.* **649** A96
[278] Tu L, Johnstone C P, Güdel M and Lammer H 2015 The extreme ultraviolet and X-ray Sun in time: high-energy evolutionary tracks of a solar-like star *Astrophys. J.* **577** L3
[279] Johnstone C P, Güdel M, Stökl A, Lammer H, Tu L, Kislyakova K G, Lüftinger T, Odert P, Erkaev N V and Dorfi E A 2015 The evolution of stellar rotation and the hydrogen atmospheres of habitable-zone terrestrial planets *Astrophys. Lett.* **815** L12
[280] Kubyshkina D *et al* 2019 The Kepler-11 system: evolution of the stellar high-energy emission and initial planetary atmospheric mass fractions *Astron. Astrophys.* **632** A65
[281] Rao S, Pezzotti C, Meynet G, Eggenberger P, Buldgen G, Mordasini C, Bourrier V, Ekström S and Georgy C 2021 Star–planet interactions VI. Tides, stellar activity, and planetary evaporation *Astron. Astrophys.* **651** A50
[282] Turcotte D and Schubert J 2014 *Geodynamics* (London: Cambridge University Press)
[283] Moffatt K and Dormy E 2019 *Self-Exciting Fluid Dynamos* (London: Cambridge University Press)
[284] Braginskii S I 1964 Kinematic models of the Earth's hydromagnetic dynamo *Geomagn. Aeron.* **4** 572–83
[285] Steenbeck M, Krause F and Radler K-H 1966 Berechnung der mittleren Lorentz-Feldstärke für ein elektrisch leitendes Medium in turbulenter, durch Coriolis-Kräfte beeinflusster Bewegung *Z. Naturforsch.* **21a** 369–76 (English translation: Roberts and Stix (1971) pp 29–47)
[286] Glatzmaier G A and Roberts P H 1995 A three-dimensional convective dynamo solution with rotating and finitely conducting inner core and mantle *Phys. Earth Planet. Inter.* **91** 63–75

[287] Pétrélis F, Fauve S, Dormy E and Valet J-P 2009 Simple mechanism for reversals of Earth's magnetic field *Phys. Rev. Lett.* **102** 144503
[288] Dormy E 2006 The origin of the Earth's magnetic field: fundamental or environmental research? *Europhys. News* **37** 2
[289] Kaminski E and Jaupart C 1998 The size distribution of pyroclasts and the fragmentation sequence in explosive volcanic eruptions *J. Geophys. Res.* **103** 29759–79
[290] Michaud-Dubuy A, Carazzo G, Kaminski E and Girault F 2002 A revisit of the role of gas entrapment on the stability conditions of explosive volcanic columns *J. Volcanol. Geotherm. Res.* **357** 349–61
[291] Geshi N, Browning J and Kusumoto S 2020 Magmatic overpressures, volatile exsolution and potential explosivity of fissure eruptions inferred via dike aspect ratios *Sci. Rep.* **10** 9406
[292] D'Incecco P, Filiberto J, López I, Gorinov D and Idunn Mons K G 2021 Evidence for ongoing volcano-tectonic activity and atmospheric implications on Venus *Planet. Sci. J.* **2** 215
[293] Burridge R and Knopoff L 1967 Model and theoretical seismicity *Bull. Seismol. Soc. Am.* **57** 341
[294] Clancy I and Corcoran D 2006 Burridge-Knopoff model: exploration of dynamic phases *Phys. Rev.* E **73** 046115
[295] Pétrélis F, Chanard K, Schubnel A and Hatano T 2023 Earthquake magnitude distribution and aftershocks: A statistical geometry explanation *Phys. Rev.* E **107** 034132
[296] Morell K D, Styron R, Stirlin M, Griffin J, Archuleta R and Onur T 2020 Seismic hazard analyses from geologic and geomorphic data: current and future challenges *Tectonics* **39** e2018TC005365

Chapter 3

[1] Hartree D R 1928 The wave mechanics of an atom with non-Coulombic central field: parts I, II, III *Proc. Cambridge Phil. Soc.* **24** 89,111,426
[2] Tkatchenko A, Rossi M, Blum V, Ireta J and Scheffler M 2011 Unraveling the stability of polypeptide helices: critical role of van der waals interactions *Phys. Rev. Lett.* **106** 118102
[3] Martin R M, Reining L and Ceperley D M 2016 *Interacting Electrons* (Cambridge: Cambridge University Press)
[4] Keimer B and Moore J E 2017 The physics of quantum materials *Nat. Phys.* **13** 1045–55
[5] Hüfner S 2003 *Photoemission Spectroscopy: Principles and Applications* (Berlin: Springer)
[6] Sky Zhou J *et al* 2020 Unraveling intrinsic correlation effects with angle-resolved photoemission spectroscopy *Proc. Natl Acad. Sci.* **117** 28596–602
[7] Fitzgerald R 2000 What really gives a quantum computer its power? *Phys. Today* **53** 20–2
[8] Kohn W 1999 Nobel lecture: electronic structure of matter—wave functions and density functionals *Rev. Mod. Phys.* **71** 1253–66
[9] Martin R M 2020 *Electronic Structure: Basic Theory and Practical Methods* 2nd edn (Cambridge: Cambridge University Press)
[10] Bohm D and Pines D 1953 A collective description of electron interactions. 3. Coulomb interactions in a degenerate electron gas *Phys. Rev.* **92** 609–25
[11] Pines D and Bohm D 1952 A collective description of electron interactions.2. Collective vs individual particle aspects of the interactions *Phys. Rev.* **85** 338–53
[12] Huotari S, Sternemann C, Schülke W, Sturm K, Lustfeld H, Sternemann H, Volmer M, Gusarov A, Müller H and Monaco G 2008 Electron-density dependence of double-plasmon excitations in simple metals *Phys. Rev.* B **77** 195125

[13] Schülke W 2007 Electron dynamics by inelastic x-ray scattering *Oxford Series on Synchrotron Radiation* (Oxford: Oxford University Press)
[14] Egerton R F 2009 Electron energy-loss spectroscopy in the TEM *Rep. Prog. Phys.* **72** 016502
[15] Yu H, Peng Y, Yang Y and Li Z-Y 2019 Plasmon-enhanced light–matter interactions and applications *npj Comput. Mater.* **5** 45
[16] de Seauve V, Languille M-A, Kociak M, Belin S, Ablett J, Andraud C, StÃ©phan O, Rueff J-P, Fonda E and Lavédrine B 2020 Spectroscopies and electron microscopies unravel the origin of the first colour photographs *Angew. Chem. Int. Ed.* **59** 9113–9
[17] Kazimierczuk T, Fröhlich D, Scheel S, Stolz H and Bayer M 2014 Giant Rydberg excitons in the copper oxide Cu_2O *Nature* **514** 343–7
[18] Laughlin R B 2005 *A Different Universe: Reinventing Physics from the Bottom Down* (New York: Basic Books)
[19] Anderson P W 1972 More is different *Science* **177** 393–6
[20] Unkrich L and Stanton A 2003 Finding Nemo (Pixar Animation Studios)
[21] Wigner E 1934 On the interaction of electrons in metals *Phys. Rev.* **46** 1002–11
[22] Novoselov K, Geim A and Morozov S *et al* 2005 Two-dimensional gas of massless dirac fermions in graphene *Nature* **438** 197–200
[23] Pines D 1997 *The Many Body Problem (Advanced Book Classics, originally published in 1961)* (Reading, MA: Addison-Wesley)
[24] David P 2009 Excitonics heats up *Nat. Photonics* **3** 604–4
[25] Kruglyak V V, Demokritov S O and Grundler D 2010 Magnonics *J. Phys.* D **43** 264001
[26] Zhao X-G, Wang Z, Malyi O I and Zunger A 2021 Effect of static local distortions vs. dynamic motions on the stability and band gaps of cubic oxide and halide perovskites *Mater. Today* **49** 107–22
[27] Editorial 2016 The rise of quantum materials *Nat. Phys.* **12** 105
[28] Giustino F *et al* 2020 The 2021 quantum materials roadmap *J. Phys.: Mater.* **3** 042006
[29] Ohtomo A and Hwang H Y 2004 A high-mobility electron gas at the $LaAlO_3/SrTiO_3$ heterointerface *Nature* **427** 423–6
[30] Bistritzer R and MacDonald A H 2011 Moiré bands in twisted double-layer graphene *Proc. Natl. Acad. Sci.* **108** 12233–7
[31] Cao Y *et al* 2018 Correlated insulator behaviour at half-filling in magic-angle graphene superlattices *Nature* **556** 80–4
[32] Cao Y, Fatemi V, Fang S, Watanabe K, Taniguchi T, Kaxiras E and Jarillo-Herrero P 2018 Unconventional superconductivity in magic-angle graphene superlattices *Nature* **556** 43–50
[33] Lopes dos Santos J M B, Peres N M R and Castro Neto A H 2007 Graphene bilayer with a twist: electronic structure *Phys. Rev. Lett.* **99** 256802
[34] Savary L and Balents L 2016 Quantum spin liquids: a review *Rep. Prog. Phys.* **80** 016502
[35] Volkov B A and Pankratov O A 1985 Two-dimensional massless electrons in an inverted contact *JETP Lett.* **42** 178
[36] Wang J and Zhang S-C 2017 Topological states of condensed matter *Nat. Mater.* **16** 1062–7
[37] Qi X-L and Zhang S-C 2011 Topological insulators and superconductors *Rev. Mod. Phys.* **83** 1057–110
[38] Ghiringhelli G *et al* 2012 Long-range incommensurate charge fluctuations in (Y,Nd) $Ba_2Cu_3O_{6+x}$ *Science* **337** 821–5

[39] Arute F *et al* 2019 Quantum supremacy using a programmable superconducting processor *Nature* **574** 505–10
[40] Lejinse M and Flensberg K 2012 Introduction to topological superconductivity and Majorana fermions *Semicond. Sci. Technol.* **27** 124003
[41] Zázvorka J *et al* 2019 Thermal skyrmion diffusion used in a reshuffler device *Nat. Nanotechnol.* **14** 658–61
[42] Song K M *et al* 2020 Skyrmion-based artificial synapses for neuromorphic computing *Nat. Electron.* **3** 148–55
[43] Bukov M, D'Alessio L and Polkovnikov A 2015 Universal high-frequency behavior of periodically driven systems: from dynamical stabilization to floquet engineering *Adv. Phys.* **64** 139–226
[44] Mahmood F, Chan C-K, Alpichshev Z, Gardner D, Lee Y, Lee P A and Gedik N 2016 Selective scattering between Floquet–Bloch and Volkov states in the topological insulator Bi_2Se_3 arXiv:1512.05714 [cond-mat.mes-hall]
[45] Flick J, Ruggenthaler M, Appel H and Rubio A 2017 Atoms and molecules in cavities, from weak to strong coupling in quantum-electrodynamics (QED) chemistry *Proc. Natl Acad. Sci.* **114** 3026–34
[46] Fausti D, Tobey R I, Dean N, Kaiser S, Dienst A, Hoffmann M C, Pyon S, Takayama T, Takagi H and Cavalleri A 2011 Light-induced superconductivity in a stripe-ordered cuprate *Science* **331** 189–91
[47] Mor S, Gosetti V, Molina-Sánchez A, Sangalli D, Achilli S, Agekyan V F, Franceschini P, Giannetti C, Sangaletti L and Pagliara S 2021 Photoinduced modulation of the excitonic resonance via coupling with coherent phonons in a layered semiconductor *Phys. Rev. Res.* **3** 043175
[48] Sachdev S 2003 Colloquium: order and quantum phase transitions in the cuprate superconductors *Rev. Mod. Phys.* **75** 913–32
[49] Sacha K and Zakrzewski J 2017 Time crystals: a review *Rep. Prog. Phys.* **81** 016401
[50] Vergniory M G, Elcoro L, Felser C, Regnault N, Andrei Bernevig B and Wang Z 2019 A complete catalogue of high-quality topological materials *Nature* **566** 480–5
[51] Zhang T, Jiang Y, Song Z, Huang H, He Y, Fang Z, Weng H and Fang C 2019 Catalogue of topological electronic materials *Nature* **566** 475–9
[52] Schmidt J, Marques M R G, Botti S and Marques M A L 2019 Recent advances and applications of machine learning in solid-state materials science *NPJ Comput. Mater.* **5** 83
[53] Schleder G R, Padilha A C M, Acosta C M, Costa M and Fazzio A 2019 From DFT to machine learning: recent approaches to materials science—a review *J. Phys.: Mater.* **2** 032001
[54] Canfield P C and Fisk Z 1992 Growth of single crystals from metallic fluxes *Phil. Mag.* B **65** 117
[55] Kanatzidis M G *et al* 2005 The metal flux: a preparative tool for the exploration of intermetallic compounds *Angew. Chem. Int. Ed.* **44** 6996
[56] Stewart G R 2011 Superconductivity in iron compounds *Rev. Mod. Phys.* **83** 1589
[57] Tong C-J *et al* 2005 Microstructure characterization of Al_xCoCrCuFeNi high-entropy alloy system with multiprincipal elements *Metall. Mater. Trans.* A **36** 881
[58] Ligon S C *et al* 2017 Polymers for 3D printing and customized additive manufacturing *Chem. Rev.* **117** 10212

[59] Parkin S S P *et al* 2004 Giant tunnelling magnetoresistance at room temperature with MgO (100) tunnel barriers *Nat. Mater.* **3** 862
[60] Hoppe H *et al* 2004 Organic solar cells: an overview *J. Mater. Res.* **19** 1924
[61] Priyadarshini P *et al* 2021 Structural and optoelectronic properties change in Bi/In_2Se_3 heterostructure films by thermal annealing and laser irradiation *J. Appl. Phys.* **129** 223101
[62] Strite S and Morkoç H 1992 GaN, AlN, and InN: a review *J. Vac. Sci. Technol.* B **10** 1237
[63] Faist J *et al* 1994 Quantum cascade laser *Science* **264** 553
[64] Zheng H *et al* 2004 Multiferroic $BaTiO_3$–$CoFe_2O_4$ nanostructures *Science* **303** 661
[65] Özgür Ü *et al* 2005 A comprehensive review of ZnO materials and devices *J. Appl. Phys.* **98** 041301
[66] Li X *et al* 2009 Large-area synthesis of high-quality and uniform graphene films on copper foils *Science* **324** 1312
[67] George S M 2010 Atomic layer deposition: an overview *Chem. Rev.* **110** 111
[68] De Teresa J M (ed) 2020 *Nanofabrication: Nanolithography Techniques and Their Applications* (Bristol: IOP Publishing)
[69] Wagner R S and Ellis W C 1964 Vapor–liquid–solid mechanism of single crystal growth *Appl. Phys. Lett.* **4** 89
[70] Law M *et al* 2004 Semiconductor nanowires and nanotubes *Ann. Rev. Mater. Res.* **34** 83
[71] Nietsch K *et al* 2000 Uniform nickel deposition into ordered alumina pores by pulsed electrodeposition *Adv. Mater.* **12** 582
[72] Fert A and Piraux L 1999 Magnetic nanowires *J. Magn. Magn. Mater.* **200** 338
[73] Utke I *et al* 2008 Gas-assisted focused electron beam and ion beam processing and fabrication *J. Vac. Sci. Technol.* B **26** 1197
[74] Córdoba R *et al* 2019 Three-dimensional superconducting nanohelices grown by He^+ -focused-ion-beam direct writing *Nano Lett.* **19** 8597
[75] Laurenti M *et al* 2017 Surface engineering of nanostructured ZnO surfaces *Adv. Mater. Interfaces* **4** 1600758
[76] Novoselov K S *et al* 2004 Electric field effect in atomically thin carbon films *Science* **306** 666
[77] Cao Y *et al* 2018 Unconventional superconductivity in magic-angle graphene superlattices *Nature* **556** 43
[78] Lopes W *et al* 2001 Hierarchical self-assembly of metal nanostructures on diblock copolymer scaffolds *Nature* **414** 735
[79] Lu W and Lieber C 2007 Nanoelectronics from the bottom up *Nature* **6** 841
[80] Pendry J B *et al* 2006 Controlling electromagnetic fields *Science* **312** 1780
[81] Bradlyn B *et al* 2017 Topological quantum chemistry *Nature* **547** 298
[82] Xu S-Y *et al* 2015 Discovery of a Weyl fermion semimetal and topological Fermi arcs *Science* **349** 613
[83] Cui J *et al* 2018 Current progress and future challenges in rare-earth-free permanent magnets *Acta Mater.* **158** 118
[84] Larcher D and Tarascon J M 2015 Towards greener and more sustainable batteries for electrical energy storage *Nat. Chem.* **7** 19
[85] Chen Z-G *et al* 2012 Nanostructured thermoelectric materials: current research and future challenge *Prog. Nat. Sci. Mater. Int* **22** 535
[86] Dresselhaus M S *et al* 2007 New directions for low-dimensional thermoelectric materials *Adv. Mater.* **19** 1043

[87] Bux S K *et al* 2010 Nanostructured materials for thermoelectric applications *Chem. Commun.* **46** 8311
[88] Szczech J R *et al* 2011 Enhancement of the thermoelectric properties in nanoscale and nanostructured materials *J. Mater. Chem.* **21** 4037
[89] Venkatasubramanian R *et al* 2001 Thin-film thermoelectric devices with high room-temperature figures of merit *Nature* **413** 597
[90] Zhao L-D *et al* 2014 Ultralow thermal conductivity and high thermoelectric figure of merit in SnSe crystals *Nature* **508** 373
[91] George E P *et al* 2019 High- entropy alloys *Nat. Rev. Mater.* **4** 515
[92] Bennett C H and DiVincenzo D P 2000 Quantum information and computation *Nature* **404** 247
[93] Arute F 2019 Quantum supremacy using a programmable superconducting processor *Nature* **574** 505
[94] Wendin G 2017 Quantum information processing with superconducting circuits: a review *Rep. Prog. Phys.* **80** 106001
[95] Kuzum D *et al* 2013 Synaptic electronics: materials, devices and applications *Nanotechnology* **24** 382001
[96] Saïghi S *et al* 2015 Plasticity in memristive devices for spiking neural networks *Front. Neurosci.* **9** 51
[97] Torrejón J *et al* 2017 Neuromorphic computing with nanoscale spintronic oscillators *Nature* **547** 428
[98] Clark R *et al* 2018 Perspective: new process technologies required for future devices and scaling *APL Mater.* **6** 058203
[99] Nomura K *et al* 2004 Room-temperature fabrication of transparent flexible thin-film transistors using amorphous oxide semiconductors *Nature* **432** 488
[100] Kim K S *et al* 2009 Large-scale pattern growth of graphene films for stretchable transparent electrodes *Nature* **457** 7230
[101] Garcia-Cortadella R *et al* 2021 Graphene active sensor arrays for long-term and wireless mapping of wide frequency band epicortical brain activity *Nat. Commun.* **12** 211
[102] Baselt D R *et al* 1998 A biosensor based on magnetoresistance technology *Biosens. Bioelectron.* **13** 731
[103] Klauk H *et al* 2007 Ultralow-power organic complementary circuits *Nature* **445** 745
[104] Gibson D and MacGregor C 2013 A novel solid state non-dispersive infrared CO_2 gas sensor compatible with wireless and portable deployment *Sensors* **13** 7079
[105] Yin W-J *et al* 2015 Halide perovskite materials for solar cells: a theoretical review *J. Mater. Chem.* A **3** 8926
[106] Lampert C M 2004 Chromogenic smart materials *Mater. Today* **7** 28
[107] Sootsman J R *et al* 2009 New and old concepts in thermoelectric materials *Angew. Chem., Int. Ed.* **48** 8616
[108] Harb A 2011 Energy harvesting: state-of-the-art *Renew. Energy* **36** 2641
[109] Ehrlich K 2001 Materials research towards a fusion reactor *Fusion Eng. Des.* **56–7** 71
[110] Himanen L *et al* 2019 Data-driven materials science: status, challenges, and perspectives *Adv. Sci.* **6** 1900808
[111] Haastrup S *et al* 2018 The computational 2D materials database: high-throughput modeling and discovery of atomically thin crystals *2D Mater.* **5** 042002

[112] Chung Y G *et al* 2019 Advances, updates, and analytics for the computation-ready, experimental metal–organic framework database: CoRE MOF 2019 *J. Chem. Eng. Data* **64** 5985
[113] Draxl C and Scheffle M 2019 *Handbook of Materials Modeling* ed W Andreoni and S Yip (Cham: Springer)
[114] Kim E *et al* 2017 Materials synthesis insights from scientific literature via text extraction and machine learning *Chem. Mater.* **29** 9436
[115] Wilkinson M D *et al* 2016 The FAIR Guiding Principles for scientific data management and stewardship *Sci. Data* **3** 160018
[116] Lejaeghere K *et al* 2016 Reproducibility in density functional theory calculations of solids *Science* **351** aad3000
[117] Gulans A *et al* 2018 Microhartree precision in density functional theory calculations *Phys. Rev.* B **97** 161105(R)
[118] Jensenet S R *et al* 2020 Polarized Gaussian basis sets from one-electron ions *J. Chem. Phys. Lett.* **152** 134108
[119] Nabok D *et al* 2016 Accurate all-electron G_0W_0 quasiparticle energies employing the full-potential augmented plane-wave method *Phys. Rev.* B **94** 035418
[120] Rangel T *et al* 2020 Reproducibility in G_0W_0 calculations for solids *Comput. Phys. Commun.* **255** 107242
[121] Draxl C and Scheffler M 2018 NOMAD: the FAIR concept for big data-driven materials science *MRS Bull.* **43** 676
[122] Draxl C and Scheffler M 2019 The NOMAD laboratory: from data sharing to artificial intelligence *J. Phys.: Mater.* **2** 036001
[123] Scheffler M *et al* 2022 FAIR data enabling new horizons for materials research *Nature* **604** 635
[124] Greene G *et al* 2019 Building open access to research (OAR) data infrastructure at NIST *CODATA Data Sci. J.* **18** 30
[125] Zambrini R and Rius G 2021 *Digital and Complex Information* (CSIC)
[126] Gray M *et al* 2018 Implantable biosensors and their contribution to the future of precision medicine *Vet. J.* **239** 21
[127] Qi X L 2011 Topological insulators and superconductors *Rev. Mod. Phys.* **83** 1057
[128] Kimble H J 2008 The quantum internet *Nature* **453** 1023
[129] Marchiori E *et al* 2022 Nanoscale magnetic field imaging for 2D materials *Nat. Rev.* **4** 49
[130] Maze J R *et al* 2008 Nanoscale magnetic sensing with an individual electronic spin in diamond *Nature* **455** 644
[131] Wellman S M *et al* 2018 A materials roadmap to functional neural interface design *Adv. Funct. Mater.* **28** 1701269
[132] Goering S *et al* 2021 Recommendations for responsible development and application of neurotechnologies *Neuroethics* **14** 365
[133] Errea I 2022 Superconducting hydrides on a quantum landscape *J. Phys.: Condens. Matter* **34** 231501
[134] Hawryluk R and Zohm H 2019 The challenge and promise of studying burning plasmas *Phys. Today* **72** 34
[135] Andersen C W *et al* 2021 OPTIMADE, an API for exchanging materials data *Sci. Data* **8** 217

[136] Tanaka I, Rajan K and Wolverton C 2018 Data-centric science for materials innovation *MRS Bull.* **43** 659
[137] Botti R S and Marques M 2021 Roadmap on machine learning in electronic structure *Electron. Struct.* **4** 023004 2021
[138] Ghiringhelli L M, Vybiral J, Levchenko S V, Draxl C and Scheffler M 2015 Big data of materials science: critical role of the descriptor *Phys. Rev. Lett.* **114** 105503
[139] Isayev O *et al* 2017 Universal fragment descriptors for predicting properties of inorganic crystals *Nat. Commun.* **8** 15679
[140] Jäckle M, Helmbrecht K, Smits M, Stottmeister D and Groß A 2018 Self-diffusion barriers: possible descriptors for dendrite growth in batteries? *Energy Environ. Sci.* **11** 3400
[141] Ward L, Agrawal A, Choudhary A and Wolverton C 2016 A general-purpose machine learning framework for predicting properties of inorganic materials *npj Comput. Mater.* **2** 16028
[142] Zhou X *et al* 2021 High- temperature superconductivity *Nat. Rev. Phys.* **3** 462
[143] European Commission 2020 Study on the EU's list of critical raw materials *Final Report*
[144] Schrödinger E 1952 Are there quantum jumps? (Part II) *Br. J. Philos. Sci.* **III** 233
[145] Feynman R P 1960 There is plenty of room at the bottom *Eng. Sci.* **XXIII** 22
[146] Eigler D M and Schweizer E K 1990 Positioning single atoms with a scanning tunnelling microscope *Nature* **344** 524
[147] Ash E A and Nicholls G 1972 Super-resolution aperture scanning microscope *Nature* **237** 510
[148] Pohl D W, Denk W and Lanz M 1984 Optical stethoscopy: image recording with resolution l/20 *Appl. Phys. Lett.* **44** 651
[149] Betzig E *Single Molecules, Cells, and Super-Resolution Optics* (Nobel Lectures) https://nobelprize.org/prizes/chemistry/2014/betzig/lecture/
[150] Moerner W E *Single-molecule Spectroscopy, Imaging and Photocontrol: Foundations for Super-Resolution Microscopy* (Nobel Lecture) www.nobelprize.org/prizes/chemistry/2014/moerner/lecture/
[151] Hell S 2014 *Nanoscopy with Focused Light* (Nobel Lectures) www.nobelprize.org/prizes/chemistry/2014/Hell/lecture/
[152] Orrit M and Bernard J 1990 Single pentacene molecules detected by fluorescence excitation in a p-terphenyl crystal *Phys. Rev. Lett.* **65** 2716
[153] Ashkin A 1970 Acceleration and trapping of particles by radiation pressure *Phys. Rev. Lett.* **24** 156
[154] Fert A *The Origin, Development and Future of Spintronics* (Nobel Lectures) www.nobelprize.org/prizes/physics/2007/fert/lecture/
[155] Grünberg P A *From Spinwaves to Giant Magnetoresistance (GMR) and Beyond* (Nobel Lecture) www.nobelprize.org/prizes/physics/2007/grunberg/lecture/
[156] Vellekoop I M and Mosk A P 2007 Focussing coherent light through opaque scattering media *Opt. Lett.* **32** 2309
[157] European Commission 2019 The European Green Deal sets out how to make Europe the first climate-neutral continent by 2050, boosting the economy, improving people's health and quality of life, caring for nature, and leaving no one behind (press release) https://ec.europa.eu/commission/presscorner/detail/en/IP_19_6691
[158] See books such asFan C and Zhao Z 2018 *Synchrotron Radiation Applications, or Synchrotron Radiation in Materials Science: Light Sources, Techniques, and Applications* (Wiley)

[159] Eriksson M 2016 The multi-bend achromat storage rings *AIP Conf. Proc.* **1741** 020001
[160] European Synchrotron Radiation Facility (https://esrf.eu/about/upgrade)
[161] Madey J M J 1971 Stimulated emission of bremsstrahlung in a periodic magnetic field *J. Appl. Phys.* **42** 1906
[162] Pellegrini C, Marinelli A and Reiche S 2016 The physics of x-ray free-electron lasers *Rev. Mod. Phys.* **88** 015006
[163] Kim J G *et al* 2020 Mapping the emergence of molecular vibrations mediating bond formation *Nature* **582** 520
[164] Buzzi M, Först M and Cavalleri A 2019 Measuring non-equilibrium dynamics in complex solids with ultrashort X-ray pulses *Phil. Trans. R. Soc.* A **377** 20170478
[165] Büttner F *et al* 2021 Observation of fluctuation-mediated picosecond nucleation of a topological phase *Nat. Mater.* **20** 30
[166] Cerantola V *et al* 2021 New frontiers in extreme conditions science at synchrotrons and free electron lasers *J. Phys.: Condens. Matter* **33** 274003
[167] Young L *et al* 2018 Roadmap of ultrafast x-ray atomic and molecular physics *J. Phys. B: At. Mol. Opt. Phys.* **51** 032003
[168] Tschentscher Th 2023 Investigating ultrafast structural dynamics using high repetition rate x-ray FEL radiation at European XFEL *Eur. Phys. J. Plus* **138** 274
[169] Huang S *et al* 2017 Generating single-spike hard x-ray pulses with nonlinear bunch compression in free-electron lasers *Phys. Rev. Lett.* **119** 154801
[170] Duris J *et al* 2020 Tunable isolated attosecond x-ray pulses with gigawatt peak power from a free-electron laser *Nat. Photonics* **14** 30–6
[171] Praveen Kumar M *et al* 2020 Attosecond pulse shaping using a seeded free-electron laser *Nature* **578** 386–91
[172] Huang Z and Ruth R R 2006 Fully coherent x-ray pulses from a regenerative-amplifier free-electron laser *Phys. Rev. Lett.* **96** 144801
Kwang-je Kim Y, Shvyd'ko and Reiche S 2008 A proposal for an x-ray free-electron laser oscillator with an energy-recovery linac *Phys. Rev. Lett.* **100** 244802
[173] Rouxel J R *et al* 2021 Hard X-ray transient grating spectroscopy on bismuth germanate *Nat. Photonics* **15** 499
[174] Zewail A H 2000 Femtochemistry: atomic-scale dynamics of the chemical bond *J. Phys. Chem.* A **104** 5660–94
[175] Ferray M, L'Huillier A, Li X F, Lompre L A, Mainfray G and Manus C 1988 Multiple harmonic conversion of 1064 nm radiation in rare gases *J. Phys.* B **21** L31–5
[176] McPherson A, Gibson G, Jara H, Johann U, Luk T S, McIntyre I A, Boyer K and Rhodes C K 1987 Studies of multiphoton production of vacuum-ultraviolet radiation in the rare gases *J. Opt. Soc. Am.* B **4** 595–601
[177] Schafer K J, Yang B, DiMauro L F and Kulander K C 1993 Above threshold ionization beyond the high harmonic cutoff *Phys. Rev. Lett.* **70** 1599–602
[178] Corkum P B 1993 Plasma perspective on strong field multiphoton ionization *Phys. Rev. Lett.* **71** 1994–7
[179] Lewenstein M, Balcou P, Ivanov M Y, L'Huillier A and Corkum P B 1994 Theory of high-harmonic generation by low-frequency laser fields *Phys. Rev.* A **49** 2117–32
[180] Salières P *et al* 2001 Feynman's path-integral approach for intense-laser-atom interactions *Science* **292** 902–5
[181] Krausz F and Ivanov M 2009 Attosecond physics *Rev. Mod. Phys.* **81** 163–234

[182] Paul P M *et al* 2001 Observation of a train of attosecond pulses from high harmonic generation *Science* **292** 1689–92
[183] Chang Z 2016 *Fundamentals of Attosecond Optics* (Boca Raton, FL: CRC Press)
[184] Li J, Lu J, Chew A, Han S, Li J, Wu Y, Wang H, Ghimire S and Chang Z 2020 Attosecond science based on high harmonic generation from gases and solids *Nat. Commun.* **11** 2748
[185] Li J *et al* 2017 53-Attosecond X-ray pulses reach the carbon k-edge *Nat. Commun.* **8** 186
[186] Gaumnitz T, Jain A, Pertot Y, Huppert M, Jordan I, Ardana-Lamas F and Wörner H J 2017 Streaking of 43-attosecond soft-X-ray pulses generated by a passively cep-stable mid-infrared driver *Opt. Express* **25** 27506–18
[187] Johnson A S *et al* 2018 High-flux soft x-ray harmonic generation from ionization-shaped few-cycle laser pulses *Sci. Adv.* **4** eaar3761
[188] Popmintchev T *et al* 2012 Bright coherent ultrahigh harmonics in the kev x-ray regime from mid-infrared femtosecond lasers *Science* **336** 1287–91
[189] Takahashi E J, Lan P, Mücke O D, Nabekawa Y and Midorikawa K 2013 Attosecond nonlinear optics using gigawatt-scale isolated attosecond pulses *Nat. Commun.* **4** 2691
[190] Klas R, Eschen W, Kirsche A, Rothhardt J and Limpert J 2020 Generation of coherent broadband high photon flux continua in the XUV with a subtwo- cycle fiber laser *Opt. Express* **28** 6188–96
[191] Nomura Y *et al* 2009 Attosecond phase locking of harmonics emitted from laser-produced plasmas *Nat. Phys.* **5** 124–8
[192] Wheeler J A, Borot A, Monchocé S, Vincenti H, Ricci A, Malvache A, Lopez-Martens R and Quéré F 2012 Attosecond lighthouses from plasma mirrors *Nat. Photonics* **6** 829–33
[193] Lépine F, Sansone G and Vrakking M J J 2013 Molecular applications of attosecond laser pulses *Chem. Phys. Lett.* **578** 1–14
[194] Drescher M, Hentschel M, Kienberger R, Uiberacker M, Yakovlev V and Scrinzi A 2002 Time-resolved atomic inner-shell spectroscopy *Nature* **419** 803–7
[195] Pazourek R, Nagele S and Burgdörfer J 2015 Attosecond chronoscopy of photoemission *Rev. Mod. Phys.* **87** 765
[196] Kotur M *et al* 2016 Spectral phase measurement of a Fano resonance using tunable attosecond pulses *Nat. Commun.* **7** 10566
[197] Nandi S *et al* 2020 Attosecond timing of electron emission from a molecular shape resonance *Sci. Adv.* **6** eaba7762
[198] Cattaneo L, Pedrelli L, Bello R Y, Palacios A, Keathley P D, Martín F and Keller U 2022 Isolating attosecond electron dynamics in molecules where nuclei move fast *Phys. Rev. Lett.* **128** 063001
[199] You D *et al* 2020 New method for measuring angle-resolved phases in photoemission *Phys. Rev.* X **10** 031070
[200] Seiffert L *et al* 2017 Attosecond chronoscopy of electron scattering in dielectric nanoparticles *Nat. Phys. (N. Y.)* **13** 766–70
[201] Jordan I, Huppert M, Rattenbacher D, Peper M, Jelovina D, Perry C, von Conta A, Schild A and Wörner H J 2020 Attosecond spectroscopy of liquid water *Science* **369** 974–9
[202] Gruson V *et al* 2016 Attosecond dynamics through a Fano resonance: monitoring the birth of a photoelectron *Science* **354** 734–8
[203] Autuori A *et al* 2022 Anisotropic dynamics of two-photon ionization: an attosecond movie of photoemission *Sci. Adv.* **8** eabl7594

[204] Lépine F, Ivanov M Y and Vrakking M J J 2014 Attosecond molecular dynamics: fact or fiction? *Nat. Photonics* **8** 195–204
[205] Sansone G *et al* 2010 Electron localization following attosecond molecular photoionization *Nature* **465** 763–6
[206] Neidel C *et al* 2013 Probing time-dependent molecular dipoles on the attosecond time scale *Phys. Rev. Lett.* **111** 033001
[207] Calegari F *et al* 2014 Ultrafast electron dynamics in phenylalanine initiated by attosecond pulses *Science* **346** 336–9
[208] Barillot T *et al* 2021 Correlation-driven transient hole dynamics resolved in space and time in the isopropanol molecule *Phys. Rev.* X **11** 031048
[209] Hervé M *et al* 2021 Ultrafast dynamics of correlation bands following XUV molecular photoionization *Nat. Phys. (N.Y.)* **17** 327–31
[210] Attar A R, Bhattacherjee A, Pemmaraju C D, Schnorr K, Closser K D, Prendergast D and Leone S R 2017 Femtosecond x-ray spectroscopy of an electrocyclic ring-opening reaction *Science* **356** 54–9
[211] Schultze M *et al* 2013 Controlling dielectrics with the electric field of light *Nature* **493** 75–8
[212] Moulet A, Bertrand J B, Klostermann T, Guggenmos A, Karpowicz N and Goulielmakis E 2017 Soft x-ray excitonics *Science* **357** 1134–8
[213] The Nobel Prize organisation 2018 https://nobelprize.org/prizes/physics/2018/summary/
[214] Danson C *et al* 2019 Petawatt and exawatt class lasers worldwide *High Power Laser Sci. Eng.* **7** E54
[215] Yoon J W, Y G K, Choi I W, Sung J H, Lee H W, Lee S K and Nam C H 2021 Realization of laser intensity over 10^{23}W/cm^2 *Optica* **8** 630–5
[216] Joshi C 2021 New ways to smash particles *Sci. Am.* **55**
[217] Kneip S *et al* 2010 Bright spatially coherent synchrotron X-rays from a table-top source *Nat. Phys.* **6** 980–3
[218] Fiuza F, Swadling G F and Grassi A *et al* 2020 Electron acceleration in laboratory-produced turbulent collisionless shocks *Nat. Phys.* **16** 916–20
[219] Wang W, Feng K and Ke L *et al* 2021 Free-electron lasing at 27 nanometres based on a laser wakefield accelerator *Nature* **595** 516–20
[220] For a popular account see; Silva L O 2017 Boiling the vacuum: in silico plasmas under extreme conditions in the laboratory and in astrophysics *Europhys. News* **48** 34–7
for comprehensive reviews, seeMarklund M and Shukla P K 2006 Nonlinear collective effects in photon-photon and photon-plasma interactions *Rev. Mod. Phys.* **78** 591
Di Piazza A, Müller C, Hatsagortsyan K Z and Keitel C H 2012 Extremely high-intensity laser interactions with fundamental quantum systems *Rev. Mod. Phys.* **84** 1177
Gonoskov A, Blackburn T G, Marklund M and Bulanov S S 2022 Charged particle motion and radiation in strong electromagnetic fields arXiv:2107.02161
[221] Diamond Light Source 2022 https://diamond.ac.uk/Home/About/Vision/Diamond-II.html
[222] Elettra Sincrotrone Trieste 2023 https://elettra.eu/images/Documents/ELETTRA%20Machine/Elettra2/Elettra_2.0_CDR_abridged.pdf
[223] Deutsches Elektronen-Synchrotron DESY 2019 PETRA IV, Upgrade of PETRA III to the Ultimate 3D X-ray Microscope, Conceptual Design Report https://bib-pubdb1.desy.de/record/426140/files/DESY-PETRAIV-Conceptual-Design-Report.pdf
[224] Paul Scherrer Institute 2022 SLS 2.0 https://psi.ch/en/sls2-0

[225] *Source Optimisée de Lumière d'Energie Intermédiaire du LURE* (https://synchrotron-soleil.fr/en/news/conceptual-design-report-soleil-upgrade)
[226] Lee T D 1981 *Particle Physics and Introduction to Field Theory* (New York: Harwood Academic Publishers)
[227] Castiglione P, Falcioni M, Lesne A and Vulpiani A 2008 *Chaos and Coarse Graining in Statistical Mechanics* (Cambridge: Cambridge University Press)
[228] Cencini M, Cecconi F and Vulpiani A 2009 *Chaos: From Simple Models to Complex Systems* (Singapore: World Scientific)
[229] Oono Y 2013 *The Nonlinear World* (Berlin: Springer)
[230] Khinchin A I 1949 *Mathematical Foundations of Statistical Mechanics* (New York: Dover)
[231] Von Neumann J 2010 Proof of the Ergodic theorem and H-theorem in quantum mechanics *Eur. Phys. J.* H **35** 201
[232] Goldstein S, Lebowitz J L, Mastrodonato C, Tumulka R and Zanghì N 2010 Normal typicality and von Neumann's quantum ergodic theorem *Proc. R. Soc.* A **466** 3203–24
[233] Goldstein S, Lebowitz J L, Tumulka R and Zanghí N 2010 Long-time behavior of macroscopic quantum systems *Eur. Phys. J.* H **35** 173
[234] Emch G and Liu C 2002 *The Logic of Thermo-Statistical Physics* (Berlin: Springer)
[235] Gallavotti G (ed) 2008 *The Fermi-Pasta-Ulam Problem: A Status Report* (Berlin: Springer)
[236] Benettin G, Chrisodoulidi H and Ponno A 2013 The Fermi–Pasta–Ulam problem and its underlying integrable dynamics *J. Stat. Phys.* **152** 195–212
[237] Pikovsky A and Politi A 2016 *Lyapunov Exponents, A Tool to Explore Complex Dynamics* (Cambridge: Cambridge University Press)
[238] Kaneko K and Bagley R J 1985 Arnold diffusion, ergodicity and intermittency in a coupled standard mapping *Phys. Lett.* A **110** 435
[239] Falcioni M, Marini Bettolo Marconi U and Vulpiani A 1991 Ergodic properties of high-dimensional symplectic maps *Phys. Rev.* A **44** 2263
[240] Yamagishi J F and Kaneko K 2020 Chaos with a high-dimensional torus *Phys. Rev. Res.* **2** 023044
[241] Hurd L, Grebogi C and Ott E 1994 On the tendency toward ergodicity with increasing number of degrees of freedom in Hamiltonian systems *Hamiltonian Mechanics* ed J Siemenis (New York: Plenum) p 123
[242] Mézard M, Parisi G and Virasoro M-A 1987 *Spin Glass Theory and Beyond* (Singapore: World Scientific)
[243] Kaneko K and Konishi T 1987 Transition, ergodicity and Lyapunov spectra of Hamiltonian dynamical systems *J. Phys. Soc. Japan* **56** 2993
[244] Livi R, Politi A and Ruffo S 1986 Distribution of characteristic exponents in the thermodynamic limit *J. Phys. A: Math. Gen.* **19** 2033
[245] Bunimovich L A and Sinai G 1993 Statistical mechanics of coupled map lattices *Theory and Applications of Coupled Map Lattices* ed K Kaneko (New York: Wiley) p 169
[246] Livi R, Pettini M, Ruffo S and Vulpiani A 1987 Chaotic behavior in nonlinear Hamiltonian systems and equilibrium statistical mechanics *J. Stat. Phys.* **48** 539
[247] Hénon M 1974 Integrals of the Toda lattice *Phys. Rev.* B **9** 1921
[248] Cugliandolo L F and Kurchan J 1995 Weak ergodicity breaking in mean-field spin-glass models *Philos. Mag.* B **71** 501–14
[249] Baldovin M, Vulpiani A and Gradenigo G 2020 Statistical mechanics of an integrable system arXiv:2009.06556

[250] Flaschka H 1974 The Toda lattice. II. Existence of integrals *Phys. Rev.* B **9** 1924–5
[251] Mazur P and van der Linden J 1963 Asymptotic form of the structure function for real systems *J. Math. Phys.* **4** 271
[252] Bohigas O, Giannoni M and Schmit C 1984 Characterization of chaotic quantum spectra and universality of level fluctuations law *Phys. Rev. Lett.* **52** 1
[253] Vulpiani A 1994 Determinismo e Caos *Carocci Editore* (Roma)
[254] Rigol M and Srednicki M 2012 Alternatives to Eigenstate thermalization *Phys. Rev. Lett.* **108** 110601
[255] Heisenberg W 1925 Über quantentheoretische Umdeutung kinematischer undmechanischer Beziehungen *Z. Phys.* **33** 879
[256] Schrödinger E 1926 An ondulatory theory of the mechanics of atoms and molecules *Phys. Rev.* **28** 1049

Chapter 4

[1] Crowe M J 2008 The extraterrestrial life debate *Antiquity to 1915: A Source Book* (Notre Dame, IN: University of Notre Dame Press)
[2] Mifflin M 2009 *The Blue Tattoo: The Life of Olive Oatman* (Lincoln: University of Nebraska Press)
[3] Arcichovsky V M 1912 Auf der Suche nach Chlorophyll auf den Planeten *Ann. Inst. Polytechnique DonCesarevitch Alexis a Novotcherkassk* **1** 195–214
[4] Jeans J 1930 *The Universe Around US* (Cambridge: Cambridge University Press)
[5] Lowell P 1895 Evidence of a twilight arc upon the planet Mars *Nature* **52** 401–5
[6] Lowell P 1906 First photographs of the canals of Mars *Proc. R. Soc.* A **77** 132–5
[7] Sinton W M 1957 Spectroscopic evidence for vegetation on Mars *Astrophys. J.* **126** 231
[8] Sinton W M 1959 Further evidence of vegetation on Mars *Science* **130** 1234–7
[9] Rea D G, O'Leary B T and Sinton W M 1965 Mars: the origin of the 3.58- and 3.69-micron minima in the infrared spectra *Science* **147** 1286–8
[10] McCauley J F, Carr M H, Cutts J A, Hartmann W K, Masursky H, Milton D J, Sharp R P and Wilhelms D E 1972 Preliminary Mariner 9 Report on the geology of Mars (A 4. 3) *Icarus* **17** 289–327
[11] Biemann K *et al* 1976 Search for organic and volatile inorganic compounds in two surface samples from the Chryse Planitia region of Mars *Science* **194** 72–6
[12] Glavin D P, Schubert M, Botta O, Kminek G and Bada J L 2001 Detecting pyrolysis products from bacteria on Mars *Earth Planet. Sci. Lett.* **185** 1–5
[13] dos Santos R, Patel M, Cuadros J and Martins Z 2016 Influence of mineralogy on the preservation of amino acids under simulated Mars conditions *Icarus* **277** 342–53
[14] Fornaro T, Boosman A, Brucato J R, ten Kate I L, Siljeström S, Poggiali G, Steele A and Hazen R M 2018 UV irradiation of biomarkers adsorbed on minerals under Martian-like conditions: hints for life detection on Mars *Icarus* **313** 38–60
[15] Garry J R C, ten Kate I L, Martins Z, Nørnberg P and Ehrenfreund P 2006 Analysis and survival of amino acids in Martian regolith analogs *Meteorit. Planet. Sci.* **41** 391–405
[16] Laurent B, Cousins C R, Pereira M F C and Martins Z 2019 Effects of UV-organic interaction and Martian conditions on the survivability of organics *Icarus* **323** 33–9
[17] Poch O, Noblet A, Stalport F, Correia J J, Grand N, Szopa C and Coll P 2013 Chemical evolution of organic molecules under Mars-like UV radiation conditions simulated in the

laboratory with the 'Mars organic molecule irradiation and evolution' (MOMIE) setup *Planet. Space Sci.* **85** 188–97

[18] Poch O, Kaci S, Stalport F, Szopa C and Coll P 2014 Laboratory insights into the chemical and kinetic evolution of several organic molecules under simulated Mars surface UV radiation conditions *Icarus* **242** 50–63

[19] Poch O, Jaber M, Stalport F, Nowak S, Georgelin T, Lambert J-F, Szopa C and Coll P 2015 Effect of nontronite smectite clay on the chemical evolution of several organic molecules under simulated Martian surface ultraviolet radiation conditions *Astrobiology* **15** 221–37

[20] Stoker C R and Bullock M A 1997 Organic degradation under simulated Martian conditions *J. Geophys. Res.* **102** 10881–8

[21] ten Kate I L, Garry J R C, Peeters Z, Quinn R, Foing B and Ehrenfreund P 2005 Amino acid photostability on the Martian surface *Meteorit. Planet. Sci.* **40** 1185–93

[22] ten Kate I L, Garry J R C, Peeters Z, Foing B and Ehrenfreund P 2006 The effects of Martian near surface conditions on the photochemistry of amino acids *Planet. Space Sci.* **54** 296–302

[23] Crandall P B, Góbi S, Gillis-Davis J and Kaiser R I 2017 Can perchlorates be transformed to hydrogen peroxide (H_2O_2) products by cosmic rays on the Martian surface? *J. Geophys. Res.: Planets* **122** 1880–92

[24] Pavlov A A, Vasilyev G, Ostryakov V M, Pavlov A K and Mahaffy P 2012 Degradation of the organic molecules in the shallow subsurface of Mars due to irradiation by cosmic rays *Geophys. Res. Lett.* **39** L13202

[25] Benner S A, Devine K G, Matveeva L N and Powell D H 2000 The missing organic molecules on Mars *Proc. Natl Acad. Sci.* **97** 2425–30

[26] Hecht M H *et al* 2009 Detection of perchlorate and the soluble chemistry of Martian soil at the phoenix lander site *Science* **325** 64–7

[27] Kounaves S P *et al* 2010 Wet chemistry experiments on the 2007 Phoenix Mars Scout Lander mission: data analysis and results *J. Geophys. Res.* **115** E00E10-1–E00E10-16

[28] Gaudi B S, Seager S, Mennesson B, Kiessling A, Warfield K and Cahoy K *et al* 2020 The habitable exoplanet observatory (HabEx) mission concept study final report *ArXiv E-Prints* arXiv:2001.06683 (https://jpl.nasa.gov/habex/pdf/HabEx-Final-Report-Public-Release.pdf)

[29] National Academies of Science 2018 *Exoplanet Science Strategy* (Washington, DC: National Academies Press)

[30] Haldane J B S 1929 The origin of life *Ration. Ann.* **148** 3–10

[31] Haldane J B S 1954 The origin of life *New Biol.* **16** 12–27

[32] Oparin A I 1924 Proiskhodenie Zhizni. Moscoksky Rabotichii, Moscow translated by ed A S Bernal 1967 *The Origin of Life* In: ed R Carrington *The Origin of Life* (London: Weidenfeld and Nicolson) pp 199–234

[33] Urey H C 1952 *The Planets, Their Origin and Development* (New Haven: Yale University Press)

[34] Miller S L 1953 A production of amino acids under possible primitive Earth conditions *Science* **117** 528–9

[35] Miller S L and Urey H C 1959 Organic compound synthesis on the primitive Earth *Science* **130** 245–51

[36] Kasting J F, Eggler D H and Raeburn S P 1993 Mantle redox evolution and the oxidation state of the Archean atmosphere *J. Geol.* **101** 245–57

[37] Kasting J F and Catling D 2003 Evolution of a habitable planet *Annu. Rev. Astron. Astrophys.* **41** 429–63
[38] Olson J M 2006 Photosynthesis in the Archean era *Photosynth. Res.* **88** 109–17
[39] Walker J C G 1986 Carbon dioxide on the early Earth *Origins Life* **16** 117–27
[40] Zahnle K, Schaefer L and Fegley B 2010 Earth's earliest atmospheres *Cold Spring Harb. Perspect. Biol.* **2** a003467
[41] Cleaves H J, Chalmers J H, Lazcano A, Miller S L and Bada J L 2008 *Orig. Life Evol. Biosph.* **38** 105–15
[42] Plankensteiner K, Reiner H and Schranz B *et al* 2004 Prebiotic formation of amino acids in a neutral atmosphere. by electric discharge *Angew. Chem. Int. Ed. Engl.* **43** 1886–8
[43] Schlesinger G and Miller S L 1983 Prebiotic synthesis in atmospheres containing CH_4, CO and CO_2. II. Hydrogen cyanide, formaldehyde and ammonia. *J. Mol. Evol.* **19** 383–90
[44] Schlesinger G and Miller S L 1983 Prebiotic synthesis in atmospheres containing CH_4, CO, and CO_2. I. Amino acids *J. Mol. Evol.* **19** 376–82
[45] Stribling R and Miller S L 1987 Energy yields for hydrogen cyanide and formaldehyde syntheses: the HCN and amino acid concentrations in the primitive ocean *Orig. Life Evol. Biosph.* **17** 261–73
[46] Furnes H, Banerjee N R, Muehlenbachs K, Staudigel H and de Wit M 2004 Early life recorded in archean pillow lavas *Science* **304** 578–81
[47] Javaux E J, Marshall C P and Bekker A 2010 Organic-walled microfossils in 3.2-billion-year-old shallow-marine siliciclastic deposits *Nature* **463** 934–8
[48] Mojzsis S J, Arrhenius G, McKeegan K D, Harrison T M, Nutman A P and Friend C R L 1996 Evidence for life on Earth before 3,800 million years ago *Nature* **384** 55–9
[49] Rosing M T 1999 ^{13}C-Depleted carbon microparticles in >3700-Ma sea-floor sedimentary rocks from west Greenland *Science* **283** 674–6
[50] Rosing M T and Frei R 2004 U-rich Archaean sea-floor sediments from Greenland—indications of >3700 Ma oxygenic photosynthesis *Earth Planet. Sci. Lett.* **217** 237–44
[51] Schidlowski M 1988 A 3,800-million-year isotopic record of life from carbon in sedimentary rocks *Nature* **333** 313–8
[52] Sugitani K, Grey K and Nagaoka T *et al* 2009 Taxonomy and biogenicity of Archaean spheroidal microfossils (ca. 3.0 Ga) from the Mount Goldsworthy–Mount Grant area in the northeastern Pilbara Craton, Western Australia *Precambrian Res.* **173** 50–9
[53] Wacey D, McLoughlin N and Whitehouse M J *et al* 2010 Two coexisting sulfur metabolisms in a ca. 3400 Ma sandstone *Geology* **38** 1115–8
[54] Westall F *et al* 2006 *Processes on the Early Earth* ed W U Reimold and R L Gibson (Boulder, CO: Geological Society of America) pp 105–31
[55] Westall F *et al* 2011 Implications of in situ calcification for photosynthesis in a ~3.3 Ga-old microbial biofilm from the Barberton greenstone belt, South Africa *Earth Planet. Sci. Lett.* **310** 468–79
[56] Westall F *et al* 2011 Volcaniclastic habitats for early life on Earth and Mars: a case study from ~3.5 Ga-old rocks from the Pilbara, Australia *Planet. Space Sci.* **59** 1093–106
[57] Westall and Matthews, *Grand Challenges 2050* ch 1.3.5
[58] Cleaves H J and Lazcano A 2009 *Chemical Evolution II: From Origins of Life to Modern Society* ed L Zaikowski, J M Friedrich and S R Seidel (New York: Oxford University Press) pp 17–43

[59] Miller S L and Bada J L 1988 Submarine hot springs and the origin of life *Nature* **334** 609–11
[60] Bains W 2004 Many chemistries could be used to build living systems *Astrobiology* **4** 137–67
[61] Morris R V *et al* 2010 Identification of carbonate-rich outcrops on Mars by the Spirit Rover *Science* **329** 421–4
[62] Poulet F, Bibring J-P, Mustard J F, Gendrin A, Mangold N, Langevin Y, Arvidson R E, Gondet B and Gomez C 2005 Phyllosilicates on Mars and implications for early martian climate *Nature* **438** 623–7
[63] Coradini A, Federico C, Forni O and Magni G 1995 Origin and thermal evolution of icy satellites *Surv. Geophys.* **16** 533–91
[64] Néri A, Guyot F, Reynard B and Sotin C 2020 A carbonaceous chondrite and cometary origin for icy moons of Jupiter and Saturn *Earth Planet. Sci. Lett.* **530** 1–10
[65] Roberts J H and Nimmo F 2008 Near-surface heating on Enceladus and the south polar thermal anomaly *Geophys. Res. Lett.* **35** L09201
[66] Sohl F, Choukroun M, Kargel J, Kimura J, Pappalardo R, Vance S and Zolotov M 2010 Subsurface water oceans on icy satellites: chemical composition and exchange processes *Space Sci. Rev.* **153** 485–510
[67] de Marcellus P, Meinert C, Nuevo M, Filippi J J, Danger G, Deboffle D, Nahon L, d'Hendecourt L L S and Meierhenrich U J 2011 Non-racemic amino acid production by ultraviolet irradiation of achiral interstellar ice analogs with circularly polarized light *Astrophys. J. Lett.* **727** L27
[68] Meinert C, Filippi J-J, Marcellus P D, D'Hendecourt L L S and Meierhenrich U J 2012 *N*-(2-aminoethyl)glycine and amino acids from interstellar ice analogues *ChemPlusChem* **77** 186–91
[69] Modica P, Meinert C, Marcellus P D, Nahon L, Meierhenrich U J and D'Hendecour L L S 2014 Enantiomeric excesses induced in amino acids by ultraviolet circularly polarized light irradiation of extraterrestrial ice analogs: a possible source of asymmetry for prebiotic chemistry *Astrophys. J.* **788** 79
[70] Modica P, Martins Z, Meinert C, Zanda B and D'Hendecourt L L S 2018 The amino acid distribution in laboratory analogs of extraterrestrial organic matter: a comparison to CM chondrites *Astrophys. J.* **865** 41–51
[71] Muñoz Caro G M, Meierhenrich U J, Schutte W A, Barbier B, Arcones Segovia A, Rosenbauer H, Thiemann W H-P, Brack A and Greenberg J M 2002 Amino acids from ultraviolet irradiation of interstellar ice analogues *Nature* **416** 403–6
[72] Myrgorodska I, Meinert C and Martins Z *et al* 2016 Quantitative enantioseparation of amino acids by comprehensive two-dimensional gas chromatography applied to non-terrestrial samples *J. Chromatogr.* A **1433** 131–6
[73] Brinton K L F, Engrand C, Glavin D P, Bada J L and Maurette M 1998 A search for extraterrestrial amino acids in carbonaceous antarctic micrometeorites *Origins Life Evol. Biosphere* **28** 413–24
[74] Clemett S J, Maechling C R, Zare R N, Swan P D and Walker R M 1993 Identification of complex aromatic molecules in individual interplanetary dust particles *Science* **262** 721–5
[75] Clemett S J, Chillier X D F, Gillette S, Zare R N, Maurette M, Engrand C and Kurat G 1998 Observation of indigenous polycyclic aromatic hydrocarbons in 'Giant' carbonaceous antarctic micrometeorites *Origins Life Evol. Biosphere* **28** 425–48

[76] Dartois E *et al* 2013 Ultra carbonaceous antarctic micrometeorites, probing the Solar System beyond the nitrogen snow-line *Icarus* **224** 243–52
[77] Duprat J *et al* 2010 Extreme deuterium excesses in ultracarbonaceous micrometeorites from Central Antarctic Snow *Science* **328** 742–5
[78] Flynn G J, Keller L P, Feser M, Wirick S and Jacobsen C 2003 The origin of organic matter in the Solar System: evidence from the interplanetary dust particles *Geochim. Cosmochim. Acta* **67** 4791–806
[79] Flynn G J, Keller L P, Jacobsen C and Wirick S 2004 An assessment of the amount and types of organic matter contributed to the Earth by interplanetary dust *Adv. Space Res.* **33** 57–66
[80] Glavin D P, Matrajt G and Bada J L 2004 Re-examination of amino acids in Antarctic micrometeorites *Adv. Space Res.* **33** 106–13
[81] Keller L P, Messenger S, Flynn G J, Clemett S, Wirick S and Jacobsen C 2004 The nature of molecular cloud material in interplanetary dust *Geochim. Cosmochim. Acta* **68** 2577–89
[82] Martins Z 2019 Organic molecules in meteorites and their astrobiological significance *Handbook of Astrobiology* (Boca Raton, FL: CRC Press) pp 177–94
[83] Martins Z and Sephton M A 2009 Extraterrestrial amino acids *Amino Acids, Peptides and Proteins in Organic Chemistry* ed A B Hughes (Weinheim: Wiley-VCH Publishers) pp 3–42
[84] Matrajt G, Pizzarello S and Taylor S *et al* 2004 Concentration and variability of the AIB amino acid in polar micrometeorites: implications for the exogenous delivery of amino acids to the primitive Earth *Meteorit. Planet. Sci.* **39** 1849–58
[85] Matrajt G, Muñoz Caro G M and Dartois E *et al* 2005 FTIR analysis of the organics in IDPs: comparison with the IR spectra of the diffuse interstellar medium *Astron. Astrophys.* **433** 979–95
[86] Martins Z 2020 Detection of organic matter and biosignatures in space missions *Astrobiology: Current, Evolving and Emerging Perspectives* ed A Antunes (Poole: Caister Academic Press) pp 53–74
[87] Martins Z, Chan Q H S, Bonal L, King A and Yabuta H 2020 Organic matter in the Solar System—implications for future on-site and sample return missions *Space Sci. Rev.* **216** 54
[88] Chan M A *et al* 2019 Deciphering biosignatures in planetary contexts *Astrobiology* **19** 1075–102
[89] Des Marais D J, Nuth J A III, Allamandola L J, Boss A P, Farmer J D, Hoehler T M, Jakosky B M, Meadows V S, Pohorille A and Spormann A M 2008 The NASA astrobiology roadmap *Astrobiology* **8** 715–30
[90] Wayne R K, Leonard J A and Cooper A 1999 Full of sound and fury: the recent history of ancient DNA *Annual Rev. Ecol. Syst.* **30** 457–77
[91] Glavin D P, Burton A S, Elsila J E, Aponte J C and Dworkin J P 2020 The search for chiral asymmetry as a potential biosignature in our Solar System *Chem. Rev.* **120** 4660–89
[92] Parnell J *et al* 2007 Searching for life on Mars: selection of molecular targets for ESA's Aurora ExoMars Mission *Astrobiology* **7** 578–604
[93] Olson S L, Reinhard C T and Lyons T W 2016 Limited role for methane in the mid-Proterozoic greenhouse *PNAS* **113** 11447–52
[94] Reinhard C T, Olson S L, Schwieterman E W and Lyons T W 2017 False negatives for remote life detection on ocean-bearing planets: lessons from the early Earth *Astrobiology* **17** 287–97

[95] Schwieterman E W, Kiang N Y, Parenteau M N, Harman C E, DasSarma S and Fisher T M *et al* 2018 Exoplanet biosignatures: a review of remotely detectable signs of life *Astrobiology* **18** 663–708
[96] Arney G, Domagal-Goldman S D and Meadows V S 2018 Organic haze as a biosignature in anoxic Earth-like atmospheres *Astrobiology* **18** 311–29
[97] Domagal-Goldman S D, Meadows V S, Claire M W and Kasting J F 2011 Using biogenic sulfur gases as remotely detectable biosignatures on anoxic planets *Astrobiology* **11** 419–41
[98] Seager S, Schrenk M and Bains W 2012 An astrophysical view of Earth-based metabolic biosignature gases *Astrobiology* **12** 61–82
[99] Des Marais D J, Harwit M O, Jucks K W, Kasting J F, Lin D N C, Lunine J I, Schneider J, Seager S, Traub W A and Woolf N J 2002 Remote sensing of planetary properties and biosignatures on extrasolar terrestrial planets *Astrobiology* **2** 153–81
[100] Seager S, Bains W and Hu R 2013 Biosignature Gases in H_2-dominated atmospheres on rocky exoplanets *Astrophys. J.* **777** 95
[101] Segura A, Kasting J F, Meadows V, Cohen M, Scalo J and Crisp D *et al* 2005 Biosignatures from Earth-like planets around M dwarfs *Astrobiology* **5** 706–25
[102] Sousa-Silva C, Seager S, Ranjan S, Petkowski J J, Zhan Z, Hu R and Bains W 2020 Phosphine as a biosignature gas in exoplanet atmospheres *Astrobiology* **20** 235–68
[103] Zhan Z, Seager S, Petkowski J J, Sousa-Silva C, Ranjan S, Huang J and Bains W 2021 Assessment of isoprene as a possible biosignature gas in exoplanets with anoxic atmospheres arXiv:2103.14228 [astro-ph.EP] *Astrobiology*
[104] Huang J, Seager S, Petkowski J, Ranjan S and Zhan Z 2021 Assessment of ammonia as a biosignature gas in exoplanet atmospheres *Astrobiology* **22** 171–91
[105] Seager S, Bains W and Hu R 2013 A biomass-based model to estimate the plausibility of exoplanet biosignature gases *Astrophys. J.* **775** 104
[106] Grenfell J L 2018 Atmospheric biosignatures *Handbook of Exoplanets* ed H J Deeg and J A Belmonte (Cham: Springer International Publishing) pp 1–14
[107] Kaltenegger L 2017 How to characterize habitable worlds and signs of life *Annu. Rev. Astron. Astrophys.* **55** 433–85
[108] Morowitz H and Sagan C 1967 Life in the clouds of Venus? *Nature* **215** 1259
[109] Seager S, Petkowski J J, Gao P, Bains W, Bryan N C, Ranjan S and Greaves J 2021 The venusian lower atmosphere haze as a depot for desiccated microbial life: a proposed life cycle for persistence of the venusian aerial biosphere *Astrobiology* **21** 1206–23
[110] Cavalazzi B *et al* 2019 The dallol geothermal area, northern Afar (Ethiopia)—an exceptional planetary field analog on earth *Astrobiology* **19** 553–78
[111] Kotopoulou E, Delgado Huertas A, Garcia-Ruiz J M, Dominguez-Vera J M, Lopez-Garcia J M, Guerra-Tschuschke I and Rull F 2018 A polyextreme hydrothermal system controlled by iron: the case of Dallol at the Afar Triangle *ACS Earth Sp. Chem.* **3** 90–9
[112] Limaye S S, Mogul R, Smith D J, Ansari A H, Słowik G P and Vaishampayan P 2018 Venus' spectral signatures and the potential for life in the clouds *Astrobiology* **18** 1181–98
[113] Oyama V I *et al* 1980 Pioneer Venus gas chromatography of the lower atmosphere of Venus *J. Geophys. Res. Sp. Phys.* **85** 7891–902
[114] Mukhin L M *et al* 1982 VENERA-13 and VENERA-14 gas chromatography analysis of the Venus atmosphere composition *Sov. Astron. Lett.* **8** 216–8

[115] Rimmer P B, Jordan S, Constantinou T, Woitke P, Shorttle O, Paschodimas A and Hobbs R 2021 Hydroxide salts in the clouds of Venus: their effect on the sulfur cycle and cloud droplet pH *Planet. Sci. J.* arXiv:2101.08582
[116] Greaves J S, Bains W, Petkowski J J, Seager S, Sousa-Silva C and Ranjan S *et al* 2021 On the robustness of phosphine signatures in Venus' clouds *arXiv preprint* arXiv:2012.05844
[117] Greaves J S, Richards A, Bains W, Rimmer P B, Clements D L and Seager S *et al* 2021 Recovery of spectra of phosphine in Venus' clouds *arXiv preprint* arXiv:2104.09285
[118] Greaves J S *et al* 2020 Phosphine gas in the cloud decks of Venus *Nat. Astron.* **5** 655–64
[119] Mogul R, Limaye S S, Way M J and Cordova J A 2021 Venus' mass spectra show signs of disequilibria in the middle clouds *Geophys. Res. Lett.* **48** e2020GL091327
[120] Surkov Y A, Andrejchikov B M and Kalinkina O M 1973 On the content of ammonia in the Venus atmosphere based on data obtained from Venera 8 automatic station *Akad. Nauk SSSR Dokl.* **213** 296–8
[121] Colin L 1980 The pioneer Venus program *J. Geophys. Res.* **85** 7575
[122] Sagdeev R Z *et al* 1986 The VEGA Venus balloon experiment *Science* **231** 1407
[123] Archer P D *et al* 2014 Abundances and implications of volatile-bearing species from evolved gas analysis of the Rocknest aeolian deposit, Gale Crater, Mars *J. Geophys. Res.: Planets* **119** 237–54
[124] Freissinet C *et al* MSL Science Team 2015 Organic molecules in the Sheepbed Mudstone, Gale Crater, Mars *J. Geophys. Res.: Planets* **120** 495–514
[125] Glavin D P *et al* 2013 Evidence for perchlorates and the origin of chlorinated hydrocarbons detected by SAM at the Rocknest aeolian deposit in Gale Crater *J. Geophys. Res.: Planets* **118** 1955–73
[126] Leshin L A *et al* 2013 Volatile, isotope, and organic analysis of Martian fines with the Mars curiosity rover *Science* **341** 1238937-1–1239
[127] Ming D W *et al* 2014 Volatile and organic compositions of sedimentary rocks in Yellowknife Bay, Gale Crater, Mars *Science* **343** 1245267-1–15
[128] Vago J L *et al* 2017 Habitability on early Mars and the search for biosignatures with the ExoMars Rover *Astrobiology* **17** 471–510
[129] Liuzzi G *et al* NOMAD Team 2019 Methane on Mars: new insights into the sensitivity of CH_4 with the NOMAD/ExoMars spectrometer through its first in-flight calibration *Icarus* **321** 671–90
[130] Mumma M J, Villanueva G L, Novak R E, Hewagama T, Bonev B P, DiSanti M A, Mandell A M and Smith M D 2009 Strong release of methane on Mars in northern summer 2003 *Science* **323** 1041–5
[131] Formisano V, Atreya S, Encrenaz T, Ignatiev N and Giuranna M 2004 Detection of methane in the atmosphere of Mars *Science* **306** 1758–61
[132] Geminale A, Formisano V and Sindoni G 2011 Mapping methane in Martian atmosphere with PFS-MEX data *Planet. Space Sci.* **59** 137–48
[133] Fonti S and Marzo G A 2010 Mapping the methane on Mars *Astron. Astrophys.* **512** A51–7
[134] Fonti S, Mancarella F, Liuzzi G, Roush T L, Chizek Frouard M, Murphy J and Blanco A 2015 Revisiting the identification of methane on Mars using TES data *Astron. Astrophys.* **581** A136-1–A136-11
[135] Webster C R *et al* 2015 Mars methane detection and variability at Gale crater *Science* **347** 415–7

[136] Webster C R *et al* 2018 Background levels of methane in Mars' atmosphere show strong seasonal variations *Science* **360** 1093–6
[137] Korablev O, Vandaele A C and Montmessin F *et al* 2019 No detection of methane on Mars from early ExoMars Trace Gas Orbiter observations *Nature* **568** 517–20
[138] Iess L *et al* 2014 The gravity field and interior structure of Enceladus *Science* **344** 78–80
[139] Thomas P C, Tajeddine R, Tiscareno M S, Burns J A, Joseph J, Loredo T J, Helfenstein P and Porco C 2016 Enceladus's measured physical libration requires a global subsurface ocean *Icarus* **264** 37–47
[140] Postberg F *et al* 2018 Macromolecular organic compounds from the depths of Enceladus *Nature* **558** 564–8
[141] Waite J H *et al* 2006 Cassini ion and neutral mass spectrometer: Enceladus plume composition and structure *Science* **311** 1419–22
[142] Grasset O *et al* 2013 JUpiter ICy moons Explorer (JUICE): an ESA mission to orbit Ganymede and to characterise the Jupiter system *Planet. Space Sci.* **78** 1–21
[143] Kissel J and Krueger F R 1987 The organic component in dust from comet Halley as measured by the PUMA mass spectrometer on board Vega 1 *Nature* **326** 755–60
[144] Cody G D *et al* 2008 Quantitative organic and light-element analysis of comet 81P/Wild 2 particles using C-, N-, and O-μ-XANES *Meteorit. Planet. Sci.* **43** 353–65
[145] Sandford S A *et al* 2006 Organics captured from Comet 81P/Wild 2 by the Stardust Spacecraft *Science* **314** 1720–4
[146] De Gregorio B T, Stroud R M, Cody G D, Nittler L R, David Kilcoyne A L and Wirick S 2011 Correlated microanalysis of cometary organic grains returned by Stardust *Meteor. Planet. Sc.* **46** 1376–96
[147] Elsila J E, Glavin D P and Dworkin J P 2009 Cometary glycine detected in samples returned by Stardust *Meteorit. Planet. Sci.* **44** 1323–30
[148] Fray N *et al* 2016 High-molecular-weight organic matter in the particles of comet 67P/Churyumov–Gerasimenko *Nature* **538** 72–4
[149] Capaccioni F 2015 The organic-rich surface of comet 67P/Churyumov–Gerasimenko as seen by VIRTIS/Rosetta *Science* **347** aaa0628-1–aaa4
[150] Goesmann F *et al* 2015 Organic compounds on comet 67P/Churyumov–Gerasimenko revealed by COSAC mass spectrometry *Science* **349** aab0689-1–aab4
[151] Wright I P, Sheridan S, Barber S J, Morgan G H, Andrews D J and Morse A D 2015 CHO-bearing organic compounds at the surface of 67P/Churyumov–Gerasimenko revealed by Ptolemy *Science* **349** aab0673-1–aab3
[152] Altwegg K *et al* 2016 Prebiotic chemicals—amino acid and phosphorus—in the coma of comet 67P/Churyumov–Gerasimenko *Sci. Adv.* **2** e1600285–e15
[153] Nakamura T *et al* 2011 Itokawa dust particles: a direct link between S-type asteroids and ordinary chondrites *Science* **333** 1113–6
[154] Uesugi M *et al* 2014 Sequential analysis of carbonaceous materials in Hayabusa-returned samples for the determination of their origin *Earth, Planets Space* **66** 102-1–102-11
[155] Wada K *et al* 2018 Asteroid Ryugu before the Hayabusa2 encounter *Prog. Earth Planet. Sci.* **5** 82 1–30
[156] Naraoka H 2023 Soluble organic molecules in samples of the carbonaceous asteroid (162173) Ryugu *Science* **379** abn9033
[157] Yabuta H 2023 Macromolecular organic matter in samples of the asteroid (162173) Ryugu *Science* **379** eabn9057

[158] Lauretta D S *et al* 2017 OSIRIS-REx: sample return from asteroid (101955) Bennu *Space Sci. Rev.* **212** 925–84
[159] Gardner J P, Mather J C, Clampin M, Doyon R, Greenhouse M A, Hammel H B, Hutchings J B, Jakobsen P, Lilly S J and Long K S *et al* 2006 The James Webb space telescope *Space Sci. Rev.* **123** 485–606
[160] Seager S and Sasselov D D 2000 Theoretical transmission spectra during extrasolar giant planet transits *Astrophys. J.* **537** 916
[161] Gillon M, Triaud A H M J, Demory B-O, Jehin E, Agol E and Deck K M *et al* 2017 Seven temperate terrestrial planets around the nearby ultracool dwarf star TRAPPIST-1 *Nature* **542** 456–60
[162] Turbet M, Bolmont E, Bourrier V, Demory B O, Leconte J, Owen J and Wolf E T 2020 A review of possible planetary atmospheres in the TRAPPIST-1 system *Space Sci. Rev.* **216** 100
[163] Gilmozzi R and Spyromilio J 2007 The European extremely large telescope (E-ELT) *The Messenger* **127** 11 https://ui.adsabs.harvard.edu/abs/2007Msngr.127…11G
[164] Sanders G H 2013 The Thirty Meter Telescope (TMT): an international observatory *J. Astrophys. Astron.* **34** 81–6
[165] Bernstein R A, McCarthy P J, Raybould K, Bigelow B C, Bouchez A H and Filgueira J M *et al* 2014 Overview and status of the Giant Magellan Telescope project *Ground-based and Airborne Telescopes* V vol 9145 (Bellingham, WA: SPIE) p 91451C
[166] Johns M, McCarthy P, Raybould K, Bouchez A, Farahani A, Filgueira J, Jacoby G, Shectman S and Sheehan M 2012 Giant Magellan telescope: overview *Ground-based and Airborne Telescopes IV* (Bellingham, WA: SPIE)vol 8444 p 84441H
[167] Anglada-Escudé G, Amado P J, Barnes J, Berdiñas Z M, Butler R P and Coleman G A L *et al* 2016 A terrestrial planet candidate in a temperate orbit around Proxima Centauri *Nature* **536** 437–40
[168] Spitzer L 1962 The beginnings and future of space astronomy *Am. Sci.* **50** 473–84
[169] Seager S, Turnbull M, Sparks W, Thomson M, Shaklan S B, Roberge A, Kuchner M, Kasdin N J, Domagal-Goldman S and Cash W *et al* 2015 The Exo-S probe class starshade mission *Tech. Instrum. Detect. Exopl. VII* **9605** 96050W
[170] LUVOIR Team 2019 The LUVOIR Mission Concept Study Final Report *ArXiv E-Prints* arXiv:191206219T https://asd.gsfc.nasa.gov/luvoir/reports/LUVOIR_FinalReport_2019-08-26.pdf
[171] Feng F, Tuomi M, Jones H R A, Barnes J, Anglada-Escudé G, Vogt S S and Butler R P 2017 Color difference makes a difference: four planet candidates around τ ceti *Astron.* J **154** 135
[172] Tuomi M, Jones H R A, Jenkins J S, Tinney C G, Butler R P and Vogt S S *et al* 2013 Signals embedded in the radial velocity noise. Periodic variations in the τ Ceti velocities *Astron. Astrophys.* **551** A79
[173] Chan Q H S, Stroud R, Martins Z and Yabuta H 2020 Concerns of organic contamination for sample return space missions *Space Sci. Rev.* **216** 56
[174] Dhingra R D *et al* 2019 Observational evidence for summer rainfall at Titan's north pole *Geophys. Res. Lett.* **46** 1205–12
[175] Poch O, Coll P, Buch A, Ramírez S I and Raulin F 2012 Production yields of organics of astrobiological interest from H_2O–NH_3 hydrolysis of Titan's tholins *Planet. Space Sci.* **61** 114–23

[176] Eshleman V R 1979 Gravitational lens of the Sun: its potential for observations and communications over interstellar distances *Science* **205** 1133–5
[177] Landis G A 2017 Mission to the gravitational focus of the Sun: a critical analysis *55th AIAA Aerospace Sciences Meeting* (American Institute of Aeronautics and Astronautics)
[178] Turyshev S G, Shao M, Toth V T, Friedman L D, Alkalai L and Mawet D *et al* 2020 Direct multipixel imaging and spectroscopy of an exoplanet with a solar gravity lens mission *ArXiv E-Prints* 2020 arXiv:200211871T
[179] Licklider J C R 1960 Man-computer symbiosis *IRE Trans. Hum. Factors Electron.* **HFE-1** 4–11
[180] Schwab K 2021 The Fourth Industrial Revolution: What It Means, How To Respond *Word Economic Forum* (https://weforum.org/agenda/2016/01/the-fourth-industrialrevolution-what-it-means-and-how-to-respond/)
[181] Wiener N 1948 *Cybernetics: or the Control and Communication in the Animal and the Machine* (New York: Wiley)
[182] Ferrucci D *et al* 2010 Building Watson: an overview of the Deepqa project *AI Mag.* **31** 59–79
[183] Boden M 2014 GOFAI *The Cambridge Handbook of Artificial Intelligence* ed F Keith and W M Ramsey (Cambridge: Cambridge University Press)
[184] Newell A and Simon H A 1976 Computer science as empirical inquiry: symbols and search (ACM 1975 Turing award lecture) *Commun. ACM* **19** 113–26
[185] Franklin S 2014 History, motivations, and core themes *The Cambridge Handbook of Artificial Intelligence* ed F Keith and W M Ramsey (Cambridge: Cambridge University Press)
[186] Feldman R A and Ballard D H 1982 Connectionist models and their properties *Cogn. Sci.* **6** 205–54
[187] James W 1890 *The Principles of Psychology* vol 1 (Cambridge, MA: Harvard University Press)
[188] Little W A 1974 The existence of persistent states in the brain *Math. Biosci.* **19** 101–20
[189] Hopfield J J 1982 Neural neural network and physical systems with emergent collective computational abilities *Proc. Natl Acad. Sci.* **79** 2554–88
[190] Hinton G E and Sejnowski T J 1986 Learning and relearning in Boltzmann machines *Parallel Distributed Processing: Explorations in the Microstructure of Cognition* ed D E Rumelhart, J L McClelland and The PDP Research Group (Cambridge, MA: MIT Press) pp 282–317
[191] Abbas A, Sutter D, Zoufal C, Lucchi A, Figalli A and Woerner S 2021 The power of quantum neural networks *Nat. Comput. Sci.* **1** 403–9
[192] Dunjko V and Briegel H J 2018 Machine learning and artificial intelligence in the quantum domain: a review of recent progress *Rep. Prog. Phys.* **81** 074001
[193] McCulloch W S and Pitts W 1943 A logical calculus of ideas immanent in nervous activity *Bull. Math. Biophys.* **5** 115–33
[194] Rosenblatt F 1958 The perceptron: a probabilistic model for information storage and organization in the brain *Psychol. Rev.* **65** 386–408
[195] Widrow B and Hoff M E 1960 Adaptive switching circuits *IRE WESCON Convention Record (New York)* pp 96–104
[196] Minsky M and Papert S 1969 *Perceptrons: An Introduction to Computational Geometry* (Cambridge, MA: MIT Press)

[197] Rumelhart D E, Hinton G E and Williams R J 1986 Learning representations by back-propagating errors *Nature* **323** 533–6
[198] Werbos P 1974 Beyond regression: new tools for prediction and analysis in the behavioural sciences *Masters Thesis* Harvard University
[199] Medler D A 1998 A brief history of connectionism *Neural Comput. Surv.* **1** 61–101
[200] Hochreiter S and Schmidhuber J 1997 Long short-term memory *Neural Comput.* **9** 1735–80
[201] LeCun Y, Bottou L, Bengio Y and Haffner P 1998 Gradient-based learning applied to document recognition *Proc. IEEE* **86** 2278–324
[202] Krizhevsky A, Sutskever I and Hinton G 2012 Imagenet classification with deep convolutional neural networks *Advances in Neural Information Processing Systems* ed F Pereira, C J C Burges, L Bottou and K Q Weinberger (Cambridge, MA: MIT Press)vol 25
[203] Goodfellow I, Bengio Y and Courville A 2016 *Deep Learning* (Cambridge, MA: MIT Press)
[204] Schmidhuber J 2014 Deep learning in neural networks: an overview *arXiv preprint* (arXiv:1404.7828 v2)
[205] Mao J, Xu W, Huang Y Y and Yuille A 2015 Deep captioning with multimodal recurrent neural networks (m-RNN) *Proc. of the 3rd Int. Conf. on Learning Representations (ICLR)*
[206] Brown T B *et al* 2020 Language models are few-shot learners arXiv:2005.14165
[207] Danks D 2014 Learning *The Cambridge Handbook of Artificial Intelligence* ed F Keith and W M Ramsey (Cambridge: Cambridge University Press)
[208] Silver D, Huang A, Maddison C J, Guez A, Sifre L and Van Den Driessche G *et al* 2016 Mastering the game of Go with deep neural networks and tree search *Nature* **529** 484–9
[209] Hu Z, Tang J, Wang Z, Zhang K, Zhang L and Sun Q 2018 Deep learning for image-based cancer detection and diagnosis—a survey *Pattern Recognit.* **83** 134–49
[210] Holzinger A 2016 Interactive machine learning for health informatics: when do we need the human-in-the-loop? *Brain Inform.* **3** 119–31
[211] Miotto R, Wang F, Wang S, Jiang X and Dudley J T 2018 Deep learning for healthcare: review, opportunities and challenges *Brief. Bioinform* **19** 1236–46
[212] Holzinger A, Langs G, Denk H, Zatloukal K and Müller H 2019 Causability and explainability of artificial intelligence in medicine *Wiley Interdiscip. Rev.: Data Min. Knowl. Discov.* **9** e1312
[213] IEEE Robots 2021 (https://robots.ieee.org/)
[214] Cao H *et al* 2019 Robot-enhanced therapy: development and validation of a supervised autonomous robotic system for autism spectrum disorders therapy *IEEE Rob. Autom Mag.* **26** 49–58
[215] Zhang S, Yao L, Sun A and Tay Y 2019 Deep learning based recommender system: a survey and new perspectives *ACM Comput. Surv. (CSUR)* **52** 1–38
[216] Buolamwini J and Gebru T 2018 Gender shades: intersectional accuracy disparities in commercial gender classification *Conf. on Fairness, Accountability and Transparency Proc. of Machine Learning Research* pp 77–91
[217] Barlow A and Sriskandarajah S 2019 *Artificial Intelligence—Application to the Sports Industry* (https://pwc.com.au/industry/sports/artificial-intelligence-application-to-thesports-industry.pdf)
[218] Hawk-Eye 2021 (https://hawkeyeinnovations.com/)
[219] Shaw D 2017 *How Wimbledon is Using IBM Watson Ai to Power Highlights, Analytics and Enriched Fan Experiences* (https://ibm.com/blogs/watson/2017/07/ibm-watsons-ai-ispowering-wimbledon-highlights-analytics-and-a-fan-experiences/)

[220] AlphaGo 2021 (https://deepmind.com/research/case-studies/alphago-the-story-so-far)
[221] Bartneck C, Belpaeme T, Eyssel F, Kanda T, Keijsers M and Šabanović S 2020 *Human–Robot Interaction: An Introduction* (Cambridge: Cambridge University Press)
[222] Vinanzi S, Patacchiola M, Chella A and Cangelosi A 2019 Would a robot trust you? Developmental robotics model of trust and theory of mind *Phil. Trans. R. Soc.* B **374** 20180032
[223] Sandini G, Sciutti A and Vernon D 2021 Cognitive robotics *Encyclopedia of Robotics* ed M Ang, O Khatib and B Siciliano (Berlin: Springer)
[224] Leite I, Martinho C and Paiva A 2013 Social robots for long-term interaction: a survey *Int. J. Soc. Robot.* **5** 291–308
[225] Mou W, Ruocco M, Zanatto D and Cangelosi A 2020 When would you trust a robot? A study on trust and theory of mind in human–robot interactions *Proc. of RO-MAN2020, 29th IEEE Int. Conf. on Robot and Human Interactive Communication (Naples, August 2020)*
[226] Vinanzi S, Cangelosi A and Goerick C 2021 The collaborative mind: intention reading and trust in human–robot interaction *Science* **24** 102130
[227] Balog M, Gaunt A L, Brockschmidt M, Nowozin S and Tarlow D 2016 DeepCoder: learning to write programs *arXiv preprint* arXiv:1611.01989
[228] Hewitt L B, Le T A and Tenenbaum J B 2020 Learning to infer program sketches Proc. of the 36th Conf. on Uncertainty in Artificial Intelligence
[229] Heaven W D 2020 *OpenAI's New Language Generator GPT-3 Is Shockingly Good—and Completely Mindless* (MIT Technology Review)
[230] Cangelosi A and Schlesinger M 2015 *Developmental Robotics: From Babies to Robots* (Cambridge, MA: MIT Press)
[231] Silver D, Schrittwieser J, Simonyan K, Antonoglou I, Huang A, Guez A, Hubert T, Baker L, Lai M and Bolton A *et al* 2017 Mastering the game of go without human knowledge *Nature* **550** 354
[232] OECDAI 2021 National AI policies & strategies https://oecd.ai/dashboards
[233] Alupo C D, Omeiza D and Vernon D 2022 Realizing the potential of AI in Africa ed M I Aldinhas Ferreira and O Tokhi *Towards Trustworthy Artificial Intelligence Systems, Intelligent Systems, Control and Automation: Science and Engineering* (Berlin: Springer)
[234] Novitske L 2018 *The AI Invasion Is Coming to Africa (and It's a Good Thing)* (Stanford Social Innovation Review)
[235] Pillay N and Access Partnership 2018 *Artificial Intelligence for Africa: An Opportunity for Growth, Development, and Democratization* (White Paper, University of Pretoria)
[236] EUAI 2021 *European Commission Ethics Guidelines for Trustworthy AI* (https://ec.europa.eu/futurium/en/ai-alliance-consultation)
[237] Besaw C and Filitz J 2019 AI and global governance: AI in Africa is a double-edged sword *Tech. rep.* (United Nations University) (https://cpr.unu.edu/ai-in-africa-is-a-doubleedged-sword.html)
[238] Wilson B, Hoffman J and Morgenstern J 2019 Predictive inequity in object detection *arXiv preprint* arXiv:1902.11097
[239] Larson J, Mattu S, Kirchner L and Angwin J 2016 How we analyzed the COMPAS recidivism algorithm *ProPublica* May 2016 9
[240] Wolpert D 2011 *The Real Reason for Brains* (https://youtube.com/watch?v=7s0CpRfyYp8)

[241] Maturana H and Varela F 1987 *The Tree of Knowledge—The Biological Roots of Human Understanding* (Boston, MA and London: New Science Library)
[242] Friston K J 2010 The free-energy principle: a unified brain theory? *Nat. Rev. Neurosci.* **11** 127–38
[243] Verschure P F M J 2016 Synthetic consciousness: the distributed adaptive control perspective *Phil. Trans. R. Soc.* B **371** 20150448
[244] Laird J E 2012 *The Soar Cognitive Architecture* (Cambridge, MA: MIT Press)
[245] Anderson J R, Bothell D, Byrne M D, Douglass S, Lebiere C and Qin Y 2004 An integrated theory of the mind *Psychol. Rev.* **111** 1036–60
[246] Sun R 2016 *Anatomy of the Mind: Exploring Psychological Mechanisms and Processes with the Clarion Cognitive Architecture* (Oxford: Oxford University Press)
[247] Langton C G 1997 *Artificial Life: An Overview* (Cambridge, MA: MIT Press)
[248] Adami C 1998 *Introduction to Artificial Life* (New York: Springer)
[249] Aguilar W, Bonfil G S, Froese T and Gershenson C 2014 The past, present, and future of artificial life *Front. Robotics AI* **1** 8
[250] Langton C G 1987 *Artificial Life: The Proc. of an Interdisciplinary Workshop on the Synthesis and Simulation of Living Systems (Los Alamos, NM, Sept. 1987)* (Addison-Wesley)
[251] Bedau M, McCaskill J, Packard P, Rasmussen S, Green D, Ikegami T, Kaneko K and Ray T 2000 Open problems in artificial life *Artif. Life* **6** 363–76
[252] von Neumann J 1966 *The Theory of Self-Reproducing Automata* ed A W Burks (Champaign, IL: University of Illinois Press)
[253] Shelling T C 1971 Dynamic models of segregation *J. Math. Sociol.* **1** 143–86
[254] Berlekamp E R, Conway J H and Guy R K 1982 *Winning Ways for Your Mathematical Plays Games in Particular* vol 2 (London: Academic)
[255] Wolfram S 1983 Statistical mechanics of cellular automata *Rev. Mod. Phys.* **55** 601–44
[256] Wuensche A and Lesser M J 1992 *The Global Dynamics of Cellular Automata; An Atlas of Basin of Attraction Fields of One-Dimensional Cellular Automata* (Reading, MA: Santa Fe Institute Studies in the Sciences of Complexity, Addison-Wesley)
[257] Mitchell M, Hraber P T and Crutchfield J P 1993 Revisiting the edge of chaos: evolving cellular automata to perform computations *Complex Syst.* **7** 89 130
[258] Epstein J M and Axtell R L 1996 *Growing Artificial Societies: Social Science from the Bottom Up* (Cambridge, MA: Brookings Institution Press MIT Press)
[259] Kauffman S A 1969 Metabolic stability and epigenesis in randomly constructed genetic nets *J. Theor. Biol.* **22** 437 467
[260] Aldana-González M, Coppersmith S and Kadanoff L P 2003 Boolean dynamics with random couplings In ed E Kaplan, J E Marsden and K R Sreenivasan *Perspectives and Problems in Nonlinear Science. A Celebratory Volume in Honor of Lawrence Sirovich, Applied Mathematical Sciences Series* (Berlin: Springer)
[261] Gershenson C 2004 Introduction to random Boolean networks *Workshop and Tutorial Proc., 9th Int. Conf. on the Simulation and Synthesis of Living Systems (ALife IX) (Boston, MA)* ; M Bedau, P Husbands, T Hutton, S Kumar and H Suzuki pp 160–73
[262] Gershenson C 2012 Guiding the self-organization of random Boolean networks *Theory Biosci.* **131** 181–91
[263] Reynolds C W 1987 Flocks, herds, and schools: a distributed behavioral model *Comput. Graph.* **21** 25–34

[264] Sipper M 1998 Fifty years of research on self-replication: an overview *Artif. Life* **4** 237–57
[265] Ray T S 1994 An evolutionary approach to synthetic biology: zen and the art of creating life *Artif. Life* **1** 195–226
[266] Chris Adami and Titus Brown C 1994 Evolutionary learning in the 2D artificial life system 'Avida' *Proc. Artificial Life IV* ed R Brooks and P Maes (Cambridge, MA: MIT Press) pp 377–81
[267] Lenski R E, Ofria C, Collier T C and Adami C 1999 Genome complexity, robustness and genetic interactions in digital organisms *Nature* **400** 661–4
[268] Lenski R E, Ofria C, Pennock R T and Adami C 2003 The evolutionary origin of complex features *Nature* **423** 139–44
[269] Adami C, Ofria C and Collier T C 2000 Evolution of biological complexity *Proc. Natl Acad. Sci.* **97** 4463–8
[270] Fontana W 1991 Algorithmic chemistry: a model for functional self-organization *Artificial Life II* ed C G Langton, C Taylor, J D Farmer and S Rasmussen (Boston, MA: Addison-Wesley) pp 159–202
[271] Dittrich P, Ziegler J and Banzhaf W 2001 Artificial chemistries—a review *Artif. Life* **7** 225–75 2014/07/08
[272] Hiroki S 2008 Swarm chemistry *Artif. Life* **15** 105–14 2014/07/08
[273] Karl S 1994 Evolving 3D morphology and behavior by competition *Artif. Life* **1** 353–72
[274] Jakobi N 1997 Evolutionary robotics and the radical envelope of noise hypothesis *Adapt. Behav.* **6** 325–68
[275] Lipson H and Pollack J B 2000 Automatic design and manufacture of robotic lifeforms *Nature* **406** 974–8
[276] Bongard J, Zykov V and Lipson H 2006 Resilient machines through continuous self-modeling *Science* **314** 1118–21
[277] Brooks R A 1991 Intelligence without representation *Artif. Intell.* **47** 139 –159
[278] Steels L and Brooks R A 1995 *The Artificial Life Route to Artificial Intelligence: Building Embodied, Situated Agents* (New York City: Lawrence Erlbaum Associates)
[279] Beer R D 2014 Dynamical systems and embedded cognition *The Cambridge Handbook of Artificial Intelligence* ed K Frankish and W Ramsey (Cambridge: University Press)
[280] Maes P 1994 Modeling adaptive autonomous agents *Artif. Life* **1** 135–62
[281] Beer R D 1990 *Intelligence as Adaptive Behavior: An Experiment in Computational Neuroethology* (San Diego, CA: Academic)
[282] Braitenberg V 1986 *Vehicles: Experiments in Synthetic Psychology* (Cambridge, MA: MIT Press)
[283] Gershenson C 2004 Cognitive paradigms: which one is the best? *Cognit. Syst. Research* **5** 135–56
[284] Cliff D, Husbands P and Harvey I 1993 Explorations in evolutionary robotics *Adapt. Behav.* **2** 73–110
[285] Nolfi S and Floreano D 2000 *Evolutionary Robotics: The Biology, Intelligence, and Technology of Self-Organizing Machines* (Cambridge, MA: MIT Press)
[286] Harvey I, Di Paolo E A, Wood R, Quinn M and Tuci E A 2005 Evolutionary robotics: A new scientific tool for studying cognition *Artif. Life* **11** 79–98
[287] Dorigo M *et al* 2004 Evolving self-organizing behaviors for a swarm-bot *Auton. Robots* **17** 223–45

[288] Zykov V, Mytilinaios E, Adams B and Lipson H 2005 Robotics: self-reproducing machines *Nature* **435** 163 164
[289] Halloy J *et al* 2007 Social integration of robots into groups of cockroaches to control self-organized choices *Science* **318** 1155–8
[290] Rubenstein M, Cornejo A and Nagpal R 2014 Programmable self-assembly in a thousand-robot swarm *Science* **345** 795–9
[291] Vásárhelyi G, Virágh C, Somorjai G, Nepusz T, Eiben A E and Vicsek. T 2018 Optimized flocking of autonomous drones in confined environments *Sci. Robot.* **3**
[292] Luisi P L 2002 Toward the engineering of minimal living cells *Anat. Rec.* **268** 208–14
[293] Hanczyc M M, Fujikawa S M and Szostak J W 2003 Experimental models of primitive cellular compartments: encapsulation, growth, and division *Science* **302** 618–22
[294] Rasmussen S, Bedau M A, Chen L, Deamer D, Krakauer D C, Packard N H and Stadler P F 2008 *Protocells: Bridging Nonliving and Living Matter* (Cambridge, MA: MIT Press)
[295] Rasmussen S, Chen L, Deamer D, Krakauer D C, Packard N H, Stadler P F and Bedau M A 2004 Transitions from nonliving to living matter *Science* **303** 963–5
[296] Bachmann P A, Luisi P L and Lang J 1992 Autocatalytic self-replicating micelles as models for prebiotic structures *Nature* **357** 57
[297] Walde P, Wick R, Fresta M, Mangone A and Luisi P L 1994 Autopoietic self-reproduction of fatty acid vesicles *JACS* **116** 11649–54
[298] Čejková J, Novak M, Štěpánek F and Hanczyc M M 2014 Dynamics of chemotactic droplets in salt concentration gradients *Langmuir* **30** 11937–44
[299] Hanczyc M M, Toyota T, Ikegami T, Packard N and Sugawara T 2007 Fatty acid chemistry at the oil- water interface: self-propelled oil droplets *J. Am. Chem. Soc.* **129** 9386–91
[300] Čejková J, Hanczyc M M and Štěpánek F 2018 Multi-armed droplets as shape-changing protocells *Artif. Life* **24** 71–9
[301] Čejkova J, Stepanek F and Hanczyc M M 2016 Evaporation-induced pattern formation of decanol droplets *Langmuir* **32** 4800–5
[302] Jitka Č, Schwarzenberger K, Eckert K and Tanaka S 2019 Dancing performance of organic droplets in aqueous surfactant solutions *Colloids Surf.,* A **566** 141–7
[303] Qiao Y, Li M, Booth R and Mann S 2017 Predatory behaviour in synthetic protocell communities *Nat. Chem.* **9** 110–9
[304] Čejková J, Banno T, Hanczyc M M and Štěpánek F 2017 Droplets as liquid robots *Artif. Life* **23** 528–49
[305] Kriegman S, Blackiston D, Levin M and Bongard J 2020 A scalable pipeline for designing reconfigurable organisms *Proc. Natl Acad. Sci.* **117** 1853–9
[306] Blackiston D, Lederer E, Kriegman S, Garnier S, Bongard J and Levin M 2021 A cellular platform for the development of synthetic living machines *Sci. Robot.* **6**
[307] Taylor T and Dorin A 2020 *Rise of the Self-Replicators* (Berlin: Springer)
[308] Bedau M A, McCaskill J S, Packard N H and Rasmussen S 2009 Living technology: exploiting life's principles in technology *Artif. Life* **16** 89–97 2011/11/03
[309] Bedau M A, McCaskill J S, Packard N H, Parke E C, S R and Rasmussen 2013 Introduction to recent developments in living technology *Artif. Life* **19** 291–8 2014/07/08
[310] Standish R K 2003 Open-ended artificial evolution *Int. J. Comput. Intell. Appl.* **3** 167–75
[311] Moreno A and Ruiz-Mirazo K 2006 The maintenance and open-ended growth of complexity in nature: information as a decoupling mechanism in the origins of life

Reframing Complexity: Perspectives from the North and South ed F Capra, A Juarrero, P Sotolongo and J van Uden (ISCE Publishing)

[312] Taylor T, Bedau M, Channon A, Ackley D, Banzhaf W, Beslon G, Dolson E, Froese T, Hickinbotham S and Ikegami T *et al* 2016 Open-ended evolution: perspectives from the oee workshop in york *Artif. Life* **22** 408–23

[313] Roli A and Kauffman S A 2020 Emergence of organisms *Entropy* **22**

[314] Hernández-Orozco S, Hernández-Quiroz F and Zenil H 2018 Undecidability and irreducibility conditions for open-ended evolution and emergence *Artif. Life* **24** 56–70

[315] Kurt G 1931 Über formal unentscheidbare sätze der principia mathematica *u*nd verwandter systeme i *Monatsh. Math. Phys.* **38** 173–98

[316] Turing A M 1936 On computable numbers, with an application to the Entscheidungsproblem *Proc. London Math. Soc., Ser.* **2** 230–65

[317] Chaitin G J 1975 Randomness and mathematical proof *Sci. Am.* **232** 47–52

[318] Rahwan I *et al* 2019 Machine behaviour *Nature* **568** 477–86

[319] Nicolis G and Prigogine I 1977 *Self-Organization in Non-Equilibrium Systems: From Dissipative Structures to Order Through Fluctuations* (Chichester: Wiley)

[320] Martyushev L M and Seleznev V D 2006 Maximum entropy production principle in physics, chemistry and biology *Phys. Rep.* **426** 1–45

[321] Ramaswamy S 2017 Active matter *J. Stat. Mech: Theory Exp.* **2017** 054002

[322] van Leeuwenhoek A 1700 IV. Part of a letter from Mr Antony van Leeuwenhoek, concerning the worms in sheeps livers, gnats, and animalcula in the excrements of frogs *Phil. Trans. R. Soc.* **22** 509–18

[323] Corti B 1774 *Osservazioni Microscopische sulla Tremella e sulla Circolazione del Fluido in Una Pianta Acquajuola* (Italy: Appresso Giuseppe Rocchi, Lucca)

[324] Brown R 1828 A brief account of microscopical observations made in the months of June, July, and August, 1827, on the particles contained in the pollen of plants; and on the general existence of active molecules in organic and inorganic bodies *Phil. Mag.* **4** 161–73

[325] Engelmann R W 1882 Ueber sauerstoffausscheidung van pfalnzenzellen im mikrospektrum *Pflügers Arch. Gesamte Physiol. Menschen Tiere* **27** 485–73

[326] Secchi E, Rusconi R, Buzzaccaro S, Salek M M, Smriga S, Piazza R and Stocker R 2016 Intermittent turbulence in flowing bacterial suspensions *J. R. Soc. Interface* **13** 20160175

[327] Haas P A, Höhn S, Honerkamp-Smith A R, Kirkegaard J B and Goldstein R E 2018 The noisy basis of morphogenesis: mechanisms and mechanics of cells sheet folding inferred from developmental variability *PLoS Biol.* **16** e2005536

[328] Besson S and Dumais J 2011 Universal rule for the symmetric division of plant cells *Proc. Natl. Acad. Sci. USA* **108** 6294–9

[329] Ratcliff W C, Denison R F, Borrello M and Travisano M 2012 Experimental evolution of multicellularity *Proc. Natl Acad. Sci. USA* **109** 1595–600

[330] Brunet T, Larsen B T, Linden T A, Vermeij M J A, McDonald K and King N 2019 Light-regulated collective contractility in a multicellular choanoflagellate *Science* **366** 326–34

[331] ESA 2020 Space for the oceans http://www.esa.int/Enabling_Support/Preparing_for_the_Future/Space_for_Earth/Space_for_the_oceans

[332] Hodgkin A L and Huxley A F 1952 A quantitative description of membrane current and its application to conductance and excitation in nerve *J. Physiol.* **117** 500–44

[333] Franklin R E and Goslin R G 1953 Molecular configuration in sodium thymonucleate *Nature* **171** 740–1

[334] Watson J D and Crick F H 1953 Molecular structure of nucleic acids: a structure for deoxyribose nucleic acid *Nature* **171** 737–8
[335] Cole K S 1949 Dynamic electrical characteristics of the squid axon membrane *Arch. Sci. Physiol.* **3** 253–8
[336] Meron E 1992 Pattern formation in excitable media *Phys. Rep.* **218** 1–66
[337] Bragg W L 1913 The diffraction of short electromagnetic waves by a crystal *Proc. Camb. Phil. Soc.* **17** 43–57
[338] Murray J D 1989 *Mathematical Biology* (Berlin: Springer)
[339] Rayleigh L 1916 On convection currents in a horizontal layer of fluid, when the higher temperature is on the under side *Phil. Mag.* **32** 529–46
[340] Keller E F 2003 *Making Sense of Life. Explaining Biological Development with Models, Metaphors, and Machines* (Cambridge, MA: Harvard University Press)
[341] Castets V, Dulos E, Boissonade J and De Kepper P 1990 Experimental evidence of a sustained standing turing-type nonequilibrium chemical pattern *Phys. Rev. Lett.* **64** 2953–6
[342] De Kepper P, Castets V, Dulos E and Boissonade J 1991 Turing-type chemical patterns in the chlorite-iodide-malonic acid reaction *Physica* D **49** 161–9
[343] Ouyang Q and Swinney H L 1991 Transition from a uniform state to hexagonal and striped turing patterns *Nature* **352** 610–2
[344] Goldstein R E 2018 Coffee stains, cell receptors, and time crystals: lessons from the old literature *Phys. Today* **71** 32–8
[345] Keller E F and Segel L A 1971 Model for chemotaxis *J. Theor. Biol.* **30** 225–34
[346] Lee K J, Cox E C and Goldstein R E 1996 Competing patterns of signaling activity in *dictyostelium discoideum Phys. Rev. Lett.* **76** 1174–7
[347] Taylor G I 1951 Analysis of the swimming of microscopic organism. *Proc. R. Soc.* A **209** 447–61
[348] Lighthill M J 1952 On the squirming motion of nearly spherical deformable bodies through liquids at very small Reynolds numbers *Commun. Pure Appl. Math.* **5** 109–18
[349] Purcell E M 1977 Life at low Reynolds number *Am. J. Phys.* 45–11
[350] Berg H C and Purcell E M 1977 Physics of chemoreception *Biophys. J.* **20** 193–219
[351] Steinberg M S 1962 On the mechanism of tissue reconstruction by dissociated cells, I. Population kinetics, differential adhesiveness, and the absence of directed migration *Proc. Natl Acad. Sci. USA* **48** 1577–82
[352] Foty R A, Forgacs G, Pfleger C M and Steinberg M S 1994 Liquid properties of embryonic tissues: measurement of interfacial tensions *Phys. Rev. Lett.* **72** 2298–301
[353] de Gennes P G 1979 *Scaling Concepts in Polymer Physics* (Ithaca, NY: Cornell University Press)
[354] Flory P J 1953 *Principles of Polymer Chemistry* (Ithaca, NY: Cornell University Press)
[355] Langer J S 1980 Instabilities and pattern formation in crystal growth *Rev. Mod. Phys.* **52** 1–28
[356] Helfrich W 1973 Elastic properties of lipid bilayers: theory and possible experiments *Z. Naturforsch.* C **28** 693–703
[357] Smith S B, Finzi L and Bustamante C 1992 Direct mechanical measurements of the elasticity of single DNA molecules by using magnetic beads *Science* **258** 1122–6
[358] Marko J F and Siggia E D 1995 Stretching DNA *Macromolecules* **28** 8759–70
[359] Svoboda K, Schmidt C F, Schnapp B J and Block S M 1993 Direct observation of kinesin stepping by optical trapping interferometry *Nature* **365** 721–7

[360] Magnasco M O 1993 Forced thermal ratchets *Phys. Rev. Lett.* **71** 1477–80
[361] Rousselet J, Salome L, Ajdari A and Prost J 1994 Directional motion of Brownian particles induced by a periodic asymmetric potential *Nature* **370** 446–7
[362] Jülicher F, Ajdari A and Prost J 1997 Modeling molecular motors *Rev. Mod. Phys.* **69** 1269–81
[363] Bustamante C, Keller D and Oster G 2001 The physics of molecular motors *Acc. Chem. Res.* **34** 412–20
[364] Lubkins S and Rand R 1994 Oscillatory reaction-diffusion equations on rings *J. Math. Biol.* **32** 617–32
[365] Hänggi P and Marchesoni F 2009 Artificial Brownian motors: controlling transport on the nanoscale *Rev. Mod. Phys.* **81** 387–442
[366] Guerin T, Prost J, Martin P and Joanny J F 2010 Coordination and collective properties of molecular motors: theory *Curr. Opin. Cell Biol.* **22** 14–20
[367] Nadrowski B, Martin P and Jülicher F 2004 Active hair-bundle motility harnesses noise to operate near an optimum of mechanosensitivity *Proc. Natl Acad. Sci. USA* **101** 12195–200
[368] Crocker J C and Grier D G 1996 Methods of digital video microscopy for colloidal studies *J. Coll. Int. Sci.* **179** 298–310
[369] Polin M, Tuval I, Drescher K, Gollub J P and Goldstein R E 2009 *Chlamydomonas* swis with two 'gears' in a eukaryotic version of run-and-tumble locomotion *Science* **325** 487–90
[370] Wan K Y and Goldstein R E 2018 Time-irreversibility and criticality in the motility of a flagellate microorganism *Phys. Rev. Lett.* **121** 058103
[371] Squires T M and Quake S R 2005 Microfluidics: fluid physics at the nanoliter scale *Rev. Mod. Phys.* **77** 977–1026
[372] Huebner J S, Jakobsson E, Dam H G, Parsegian V A and Austin R H 1997 How should physicists, biologists work together? The 'Harness the hubris' debate continues *Phys. Today* **50** 11–95
[373] Parsegian V A 1997 Harness the hubris: useful things physicists could do in biology *Phys. Today* **50** 23–7
[374] Finlayson B A and Scriven L E 1969 Convective instability by active stress *Proc. R. Soc.* A **310** 183–219
[375] Marchetti M C, Joanny J F, Ramaswamy S, Liverpool T B, Prost J, Rao M and Simha R A 2013 Hydrodynamics of soft active matter *Rev. Mod. Phys.* **85** 1143–89
[376] Ramaswamy S 2019 Active fluids *Nat. Rev. Phys.* **1** 640–64
[377] Gompper G, Winkler R G, Speck T, Solon A, Nardini C, Peruani F, Löwen H, Golestanian R, Kaupp U B and Alvarez L 2020 The 2020 motile active matter roadmap *J. Phys. Condens. Matter* **32** 193001
[378] Shaebani M R, Wysocki A, Winkler R G, Gompper G and Rieger H 2020 Computational models for active matter *Nat. Rev. Phys.* **2** 181–99
[379] Prost J and Bruinsma R 1996 Shape fluctuations of active membranes *Europhys. Lett.* **33** 321–6
[380] Ramaswamy S, Prost J and Toner J 2000 Nonequilibrium fluctuations, travelling waves, and instabilities in active membranes *Phys. Rev. Lett.* **84** 3494–7
[381] Nédélec F J, Surrey T, Maggs A C and Leibler S 1997 Self-organization of microtubules and motors *Nature* **389** 305–8
[382] Toner J and Tu Y 1995 Long-range order in a two-dimensional dynamical XY model: how birds fly together *Phys. Rev. Lett.* **75** 4326–9

[383] Simha R A and Ramaswamy S 2002 Hydrodynamic fluctuations and instabilities in ordered suspensions of self-propelled particles *Phys. Rev. Lett.* **89** 058101
[384] Saintillan D and Shelley M J 2008 Instabilities and pattern formation in active particle suspensions: kinetic theory and continuum simulations *Phys. Rev. Lett.* **100** 178103
[385] Dombrowski C, Cisneros L, Chatkaew S, Kessler J O and Goldstein R E 2004 Self-concentration and large-scale coherence in bacterial dynamics *Phys. Rev. Lett.* **93** 098103
[386] Lacoste D and Bassereau P 2014 An update on active membranes ed G Pabst, N KuÄerka, M-P Nieh and J Katsaras *Liposomes, Lipid Bilayers and Model Membranes: From Basic Research to Application* pp 271–87 (Boca Raton, FL: CRC Press, Taylor and Francis Group)
[387] Turlier H and Betz T 2019 Unveiling the active nature of living-membrane fluctuations and mechanics *Annu. Rev. Condens. Matter Phys.* **10** 213–32
[388] Turlier H, Fedosov D A, Audoly B, Auth T, Gov N S, Sykes C, Joanny J-F, Gompper G and Betz T 2016 Equilibrium physics breakdown reveals the active nature of red blood cell flickering *Nat. Phys.* **12** 513–9
[389] Kruse K, Joanny J F, Jülicher F, Prost J and Sekimoto K 2005 Generic theory of active polar gels: a paradigm for cytoskeletal dynamics *Eur. Phys. J.* E **16** 5–16
[390] Prost J, Jülicher F and Joanny J F 2015 Active gel physics *Nat. Phys.* **11** 111–7
[391] Doostmohammadi A, Ignés-Mullol J, Yeomans J M and Sagués F 2018 Active nematics *Nat. Commun.* **9** 3246
[392] Stenhammar J, Wittkowski R, Marenduzzo D and Cates M E 2015 Activity-induced phase separation and self-assembly in mixtures of active and passive particles *Phys. Rev. Lett.* **114** 018301
[393] Banani S F, Lee H O, Hyman A A and Rosen M K 2017 Biomolecular condensates: organizers of cellular biochemistry *Nat. Rev. Mol. Cell Biol.* **18** 285–98
[394] Shin Y, Chang Y-C, Lee D S W, Berry J, Sanders D W, Ronceray P, Wingreen N S, Haataja M and Brangwynne C P 2018 Liquid nuclear condensates mechanically sense and restructure the genome *Cell* **175** 1481–91
[395] Zwicker D, Hyman A A and Jülicher F 2015 Suppression of Ostwald ripening in active emulsions *Phys. Rev.* E **92** 012317
[396] Guillot C and Lecuit T 2013 Mechanics of epithelial tissue homeostasis and morphogenesis *Science* **340** 1185–9
[397] Collinet C, Rauzi M, Lenne P-F and Lecuit T 2015 Local and tissue-scale forces drive oriented junction growth during tissue extension *Nat. Cell Biol.* **17** 1247–58
[398] Ranft J, Basan M, Elgeti J, Joanny J-F, Prost J and Jülicher F 2010 Fluidization of tissues by cell division and apoptosis *Proc. Natl Acad. Sci. USA* **107** 20863–8
[399] PopoviÄ M, Nandi A, Merkel M, Etournay R, Eaton S, Jülicher F and Salbreux G 2017 Active dynamics of tissue shear flow *New J. Phys.* **19** 033006
[400] Girkin J M and Carvalho M T 2018 The light-sheet microscopy revolution *J. Opt.* **20** 053002
[401] Takebe T and Wells J M 2019 Organoids by design *Science* **364** 956–9
[402] Haas P A and Goldstein R E 2019 Nonlinear and nonlocal elasticity in coarse-grained differential-tension models of epithelia *Phys. Rev.* E **99** 022411
[403] Vagne Q, Vrel J-P and Sens P 2020 A minimal self-organisation model of the Golgi apparatus *eLife* **9** e47318

[404] Thompson D W 1942 *On Growth and Form* 2nd edn (Cambridge: Cambridge University Press)
[405] Discher D E, Janmey P and Wang Y-L 2005 Tissue cells feel and respond to the stiffness of their substrate *Science* **310** 1139–43
[406] Harris A R, Jreij P and Fletcher D A 2016 Mechanotransduction by the actin cytoskeleton: converting mechanical stimuli into biochemical signals *Annu. Rev. Biophys.* **47** 617–31
[407] Engler A J, Sen S, Sweeney H L and Discher D E 2006 Matrix elasticity directs stem cell lineage specification *Cell* **126** 677–89
[408] Fernandez-Sanchez M-E, Brunet T, Röper J-C and Farge E 2015 Mechanotransduction's impact on animal development, evolution, and tumorigenesis *Annu. Rev. Cell Dev. Biol.* **31** 373–97
[409] Broders-Bondon F, Nguyen Ho-Bouldoires T H, Fernandez-Sanchez M-E and Farge E 2018 Mechanotransduction in tumor progression: the dark side of the force *J. Cell Biol.* **217** 1571–87
[410] Roca-Cusachs P, Conte V and Trepat X 2017 Quantifying forces in cell biology *Nat. Cell Biol.* **19** 742–51
[411] Geiger B, Bershadsky A, Pankov R and Yamada K M 2001 Transmembrane crosstalk between the extracellular matrix and the cytoskeleton *Nat. Rev. Mol. Cell Biol.* **2** 793–805
[412] Martino F, Perestrelo A R, Vinarský V, Pagliari S and Forte G 2018 Cellular mechanotransduction: from tension to function *Front. Physiol.* **9** 824
[413] Charras G and Yap A S 2018 Tensile forces and mechanotransduction at cell–cell junctions *Curr. Biol.* **28** R445–57
[414] Gottlieb P A (ed) 2017 *Piezo Channels, Volume 79 of Current Topics in Membranes* (New York: Academic)
[415] Eder D, Aegerter C and Basler K 2017 Forces controlling organ growth and size *Mech. Develop.* **144** 53–61
[416] Van Essen D C, Smith S M, Barch D M, Behrens T E J, Yacoub E and Ugurbil K 2013 The WU-Minn human connectome project: an overview *NeuroImage* **80** 62–79
[417] Zecchi K A and Heimburg T 2021 Non-linear conductance, rectification, and mechanosensitive channel formation of lipid membranes *Front. Cell Dev. Biol.* **8** 1751
[418] Deubner J, Coulon P and Diester I 2019 Optogenetic approaches to study the mammalian brain *Curr. Opin. Struct. Biol.* **57** 157–63
[419] Calarco J A and Samuel A D T 2019 Imaging whole nervous systems: insights into behavior from brains inside bodies *Nat. Meth.* **16** 14–5
[420] Dragomir E I, Åtih V and Portugues R 2020 Evidence accumulation during a sensorimotor decision task revealed by whole-brain imaging *Nat. Neurosci.* **23** 85–93
[421] Gao R *et al* 2019 Cortical column and whole-brain imaging with molecular contrast and nanoscale resolution *Science* **363** 543–8
[422] Richards B A *et al* 2019 A deep learning framework for neuroscience *Nat. Neurosci.* **22** 1761–70
[423] Bassett D S and Sporns O 2017 Network neuroscience *Nat. Neurosci.* **20** 353–64
[424] Schrödinger E 1944 *What is Life? The Physical Aspect of the Living Cell* (Cambridge: Cambridge University Press)
[425] Xu C, Hu S and Chen X 2016 Artificial cells: from basic science to applications *Mat. Today* **19** 516–32
[426] https://nature.com/collections/ngmpdftlqt/

[427] Zwicker D, Seyboldt R, Weber C A, Hyman A A and Jülicher F 2017 Growth and division of active droplets provides a model for protocells *Nat. Phys.* **13** 408–13
[428] Jia H and Schwille P 2019 Bottom-up synthetic biology: reconstitution in space and time *Curr. Opin. Biotech.* **60** 179–87
[429] Gibson D G *et al* 2010 Creation of a bacterial cell controlled by a chemically synthesized genome *Science* **329** 52–6
[430] Breuer M *et al* 2019 Essential metabolism for a minimal cell *eLife* **8** e36842
[431] Braun D, Goddard N L and Libchaber A 2003 Exponential DNA replication by laminar convection *Phys. Rev. Lett.* **91** 158103
[432] Kreysing M, Keil L, Lanzmich S and Braun D 2015 Heat flux across an open pore enables the continuous replication and selection of oligonucleotides towards increasing length *Nat. Chem.* **7** 203–8
[433] Bell G and Mooers A O 1997 Size and complexity among multicellular organisms *Biol. J. Linn. Soc.* **60** 345–63
[434] Weismann A 1892 *Essays on Heredity and Kindred Biological Problems* (Oxford: Oxford University Press)
[435] Huxley J S 1912 *The Individual in the Animal Kingdom* (Cambridge: Cambridge University Press)
[436] Solari C A, Kessler J O and Michod R E 2006 A hydrodynamics approach to the evolution of multicellularity: flagellar motility and germ-soma differentiation in volvocalean green algae *Am. Nat.* **167** 537–54
[437] Goldstein R E 2015 Green algae as model organisms for biological fluid dynamics *Annu. Rev. Fluid Mech.* **47** 343–75
[438] Brunet T and King N 2017 The origin of animal multicellularity and cell differentiation *Dev. Cell* **43** 124–40
[439] Sella G and Hirsh A E 2005 The application of statistical physics to evolutionary biology *Proc. Natl Acad. Sci. USA* **102** 9541
[440] Drossel B 2001 Biological evolution and statistical physics *Adv. Phys.* **50** 209–95
[441] Wolf Y I, Katsnelson M I and Koonin E V 2018 Physical foundations of biological complexity *Proc. Natl Acad. Sci. USA* **115** E8678
[442] Kasting J F 1993 Earth's early atmosphere *Science* **259** 920–6
[443] Kasting J F, Toon O B and Pollack J B 1988 How climate evolved on the terrestrial planets *Sci. Am.* **258** 90–7
[444] Bottke W F, Vokrouhlický D, Marchi S, Swindle T, Scott E R D, Weirich J R and Levison H 2015 Dating the Moon-forming impact event with asteroidal meteorites *Science* **348** 321–3
[445] Schlichting H E and Mukhopadhyay S 2018 Atmosphere impact losses *Space Sci. Rev.* **214** 34
[446] Lebrun T, Massol H, ChassefièRe E, Davaille A, Marcq E, Sarda P, Leblanc F and Brandeis G 2013 Thermal evolution of an early magma ocean in interaction with the atmosphere *J. Geophys. Res. (Planets)* **118** 1155–76
[447] Stüeken E E, Som S M and Claire M *et al* 2020 Mission to planet Earth: the first two billion years *Space Sci. Rev.* **216** 31
[448] Pahlevan K, Schaefer L and Hirschmann M M 2019 Hydrogen isotopic evidence for early oxidation of silicate Earth *Earth Planet. Sci. Lett.* **526** 115770
[449] Sleep N H 2010 The Hadean-Archaean environment *Cold Spring Harb. Perspect. Biol.* **2** a002527

[450] Bekaert D V, Broadley M W and Marty B 2020 The origin and fate of volatile elements on Earth revisited in light of noble gas data obtained from comet 67P/Churyumov–Gerasimenko *Sci. Rep.* **10** 5796
[451] Mezger K, Maltese A and Vollstaedt H 2021 Accretion and differentiation of early planetary bodies as recorded in the composition of the silicate earth *Icarus* **365** 114497
[452] Mojzsis S J, Brasser R, Kelly N M, Abramov O and Werner S C 2019 Onset of Giant planet migration before 4480 million years ago *Astrophys. J.* **881** 44
[453] Fuller-Rowell T, Solomon S, Roble R and Viereck R 2004 Impact of solar EUV, XUV, and x-ray variations on Earth's atmosphere *Solar Variability and its Effects on Climate. Geophysical Monograph 141* (AGU Publications)vol 141 p 341
[454] Lammer H, Leitzinger M and Scherf M *et al* 2020 Constraining the early evolution of Venus and Earth through atmospheric Ar, Ne isotope and bulk K/U ratios *Icarus* **339** 113551
[455] Ribas I, Guinan E F, Güdel M and Audard M 2005 Evolution of the solar activity over time and effects on planetary atmospheres. I. High-energy irradiances (1–1700 Å) *Astrophys. J.* **622** 680–94
[456] Sagan C and Mullen G 1972 Earth and Mars: evolution of atmospheres and surface temperatures *Science* **177** 52–6
[457] Catling D C and Kasting J F 2007 *Planetary Atmospheres and Life* (London: Cambridge University Press)
[458] Elkins-Tanton L T 2008 Linked magma ocean solidification and atmospheric growth for Earth and Mars *Earth Planet. Sci. Lett.* **271** 181–91
[459] Guzmán-Marmolejo A, Segura A and Escobar-Briones E 2013 Abiotic production of methane in terrestrial planets full access *Astrobiology* **13** 550–9
[460] Atreya S K, Adams E Y, Niemann H B, Demick-Montelara J E, Owen T C, Fulchignoni M, Ferri F and Wilson E H 2006 Titan's methane cycle *Planet. Space Sci.* **54** 1177–87
[461] Pavlov A A, Brown L L and Kasting J F 2001 UV shielding of NH_3 and O_2 by organic hazes in the Archean atmosphere *J. Geophys. Res.* **106** 23267–88
[462] Heller R, Duda J-P, Winckler M, Reitner J and Gizon L 2021 Habitability of the early Earth: liquid water under a faint young Sun facilitated by strong tidal heating due to a nearby Moon *Palaontol. Z.* **95** 563–75
[463] Pope E C, Bird D K and Rosing M T 2012 Isotope composition and volume of Earth's early oceans *Proc. Natl Acad. Sci.* **109** 4371–6
[464] Sharp Z D, McCubbin F M and Shearer C K 2013 A hydrogen-based oxidation mechanism relevant to planetary formation *Earth Planet. Sci. Lett.* **380** 88–97
[465] Marty B, Avice G, Bekaert D V and Broadley M W 2018 Salinity of the Archaean oceans from analysis of fluid inclusions in quartz *C.R. Geosci.* **350** 154–63
[466] Matthes K, Funke B and Andersson M E *et al* 2017 Solar forcing for CMIP6 (v3.2) *Geosci. Model Dev.* **10** 2247–302
[467] Pascal R, Pross A and Sutherland J D 2013 Towards an evolutionary theory of the origin of life based on kinetics and thermodynamics *Open Biol* **3** 130156
[468] James Cleaves H, Chalmers J H, Lazcano A, Miller S L and Bada J L 2008 A reassessment of prebiotic organic synthesis in neutral planetary atmospheres *Origins Life Evol. Biosphere* **38** 105–15
[469] Martin W F, Baross J, Kelley D and Russell M J 2008 Hydrothermal vents and the origin of life *Nat. Rev. Microbiol.* **6** 805–14

[470] Shock E L and Schulte M D 1998 Organic synthesis during fluid mixing in hydrothermal systems *J. Geophys. Res.* **103** 28513–28
[471] Bertrand M, Chabin A, Brack A, Cottin H, Chaput D and Westall F 2012 The PROCESS experiment: exposure of amino acids in the EXPOSE—experiment on the International Space Station and in laboratory simulations *Astrobiology* **12** 426–35
[472] Marty B, Alexander C M O and Raymond S N 2013 Primordial Origins of Earth's Carbon *Rev. Mineral. Geochem.* **75** 149–181
[473] Duprat J, Dobrică E and Engrand C *et al* 2010 Extreme deuterium excesses in ultra-carbonaceous micrometeorites from central antarctic snow *Science* **328** 742
[474] Schmitt-Kopplin P, Gabelica Z and Gougeon R D *et al* 2010 High molecular diversity of extraterrestrial organic matter in Murchison meteorite revealed 40 years after its fall *Proc. Natl Acad. Sci.* **107** 2763–8
[475] Lowe D R, Byerly G R and Kyte F T *et al* 2003 Spherule beds 3.47–3.24 billion years old in the Barberton Greenstone Belt, South Africa: a record of large meteorite impacts and their influence on early crustal and biological evolution *Astrobiology* 3 7–48
[476] Lowe D R, Byerly G R and Kyte F T 2014 Recently discovered 3.42–3.23 Ga impact layers, Barberton Belt, South Africa: 3.8 Ga detrital zircons, Archean impact history, and tectonic implications *Geology* 42 747–50
[477] Gourier D, Binet L and Calligaro T *et al* 2019 Extraterrestrial organic matter preserved in 3.33 Ga sediments from Barberton, South Africa *Geochim. Cosmochim. Acta* **258** 207–25
[478] Sasselov D D, Grotzinger J P and Sutherland J D 2020 The origin of life as a planetary phenomenon *Sci. Adv.* **6** eaax3419
[479] Pascal R 2012 Suitable energetic conditions for dynamic chemical complexity and the living state *J. Syst. Chem.* **3**
[480] Baross J A and Hoffman S E 1985 Submarine hydrothermal vents and associated gradient environments as sites for the origin and evolution of life *Orig. Life* **15** 327–45 :
[481] Russell M J and Hall A J 1997 The emergence of life from iron monosulphide bubbles at a submarine hydrothermal redox and pH front *J. Geol. Soc.* **154** 377–402
[482] Russell M J, Hall A J and Martin W 2010 Serpentinization as a source of energy at the origin of life *Geobiology* **8** 355–71
[483] Westall F, Hickman-Lewis K and Hinman N *et al* 2018 A hydrothermal-sedimentary context for the origin of life *Astrobiology* **18** 259–93
[484] Cottin H, Guan Y Y and Noblet A *et al* 2012 The PROCESS experiment: an astrochemistry laboratory for solid and gaseous organic samples in low-earth orbit *Astrobiology* **12** 412–25
[485] Deamer D W, Singaram S, Rajamani S, Kompanichenko V and Guggenheim S 2006 Self-assembly processes in the prebiotic environment *Phil. Trans. R. Soc.* B **361** 1809–18
[486] Tartese R, Chaussidon M, Gurenko A, Delarue F and Robert F 2017 Archean oceans reconstructed from oxygen isotope composition of early-life remnants *Geochem. Persp. Lett.* **3** 55 65
[487] Usoskin I G 2017 A history of solar activity over millennia *Living Rev. Sol. Phys.* **14** 3
[488] Badalyan O G and Obridko V N 2011 North-south asymmetry of the sunspot indices and its quasi-biennial oscillations *Nature* **16** 357–65
[489] Kane R P 2005 Differences in the quasi-biennial oscillation and quasi-triennial oscillation characteristics of the solar, interplanetary, and terrestrial parameters *J. Geophys. Res. (Space Phys.)* **110** A01108

[490] Broomhall A-M, Fletcher S T and Salabert D *et al* 2011 Are short-term variations in solar oscillation frequencies the signature of a second solar dynamo? *J. Phys.: Conf. Ser.* **271** 012025 (GONG-SoHO 24: A New Era of Seismology of the Sun and Solar-Like Stars)
[491] Manuel G 2007 The Sun in time: activity and environment *Living Rev. Sol. Phys.* **4** 3
[492] Claire M W, Sheets J, Cohen M, Ribas I, Meadows V S and Catling D C 2012 The evolution of solar flux from 0.1 nm to 160 μm: quantitative estimates for planetary studies *Astrophys. J.* **757** 95
[493] Bahcall J N, Pinsonneault M H and Basu S 2001 Solar models: current epoch and time dependences, neutrinos, and helioseismological properties *Astrophys. J.* **555** 990–1012
[494] Lean J L, Rottman G J, Lee Kyle H, Woods T N, Hickey J R and Puga L C 1997 Detection and parameterization of variations in solar mid- and near- ultraviolet radiation (200–400 nm) *J. Geophys. Res.* **102** 29939–56
[495] Soderblom D R, Stauffer J R, MacGregor K B and Jones B F 1993 The evolution of angular momentum among zero-age main-sequence solar-type stars *Astrophys. J.* **409** 624
[496] David Dorren J and Guinan E F 1994 HD 129333: the Sun in its infancy *Astrophys. J.* **428** 805
[497] Brun A S and Browning M K 2017 Magnetism, dynamo action and the solar-stellar connection *Living Rev. Sol. Phys.* **14** 4
[498] Canuto V M, Levine J S, Augustsson T R and Imhoff C L 1982 UV radiation from the young Sun and oxygen and ozone levels in the prebiological palaeoatmosphere *Nature* **296** 816–20
[499] Meert J G, Levashova N M, Bazhenov M L and Landing E 2016 Rapid changes of magnetic field polarity in the late Ediacaran: linking the Cambrian evolutionary radiation and increased UV-B radiation *Gondwana Res.* 34 149–57
[500] Airapetian V S, Glocer A, Gronoff G, Hébrard E and Danchi W 2016 Prebiotic chemistry and atmospheric warming of early Earth by an active young Sun *Nat. Geosci.* **9** 452–5
[501] Austin J, Tourpali K and Rozanov E *et al* 2008 Coupled chemistry climate model simulations of the solar cycle in ozone and temperature *J. Geophys. Res. (Atmos.)* **113** D11306
[502] Gray L J, Beer J, Geller M and Haigh J D *et al* 2010 Solar influences on climate *Rev. Geophys.* **48** RG4001
[503] Haigh J D 1996 The impact of solar variability on climate *Science* **272** 981–4
[504] Matthes K, Kuroda Y, Kodera K and Langematz U 2006 Transfer of the solar signal from the stratosphere to the troposphere: northern winter *J. Geophys. Res.* **111** D06108
[505] Matthes K, Biastoch A and Wahl S *et al* 2020 The flexible ocean and climate infrastructure version 1 (FOCI1): mean state and variability *Geosci. Model Dev.* **13** 2533–68
[506] Sinnhuber M, Nieder H and Wieters N 2012 Energetic particle precipitation and the chemistry of the mesosphere/lower thermosphere *Surv. Geophys.* **33** 1281–334
[507] Dunne E M, Gordon H and Kürten A *et al* 2016 Global atmospheric particle formation from CERN CLOUD measurements *Science* **354** 1119–24
[508] Mojzsis S J, Harrison T M and Pidgeon R T 2001 Oxygen-isotope evidence from ancient zircons for liquid water at the Earth's surface 4,300 Myr ago *Nature* **409** 178–81
[509] Wilde S A, Valley J W, Peck W H and Graham C M 2001 Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago *Nature* **409** 175–8
[510] Whitehouse M J, Nemchin A A and Pidgeon R T 2017 What can Hadean detrital zircon really tell us? A critical evaluation of their geochronology with implications for the interpretation of oxygen and hafnium isotopes *Gondwana Res.* **51** 78 91

[511] Arndt N T and Nisbet E G 2012 Processes on the young earth and the habitats of early life *Annu. Rev. Earth Planet. Sci.* **40** 521–49
[512] Kamber B S 2015 The evolving nature of terrestrial crust from the Hadean, through the Archaean, into the Proterozoic *Precambrian Res.* **258** 48 82
[513] Wang Z and Becker H 2013 Ratios of S, Se and Te in the silicate Earth require a volatile-rich late veneer *Nature* **499** 328–31
[514] Morbidelli A and Wood B J 2015 *Late Accretion and the Late Veneer* (Washington, DC: American Geophysical Union (AGU))
[515] Biggin A J, de Wit M J, Langereis C G, Zegers T E, Voûte S, Dekkers M J and Drost K 2011 Palaeomagnetism of Archaean rocks of the Onverwacht Group, Barberton Greenstone Belt (southern Africa): evidence for a stable and potentially reversing geomagnetic field at ca. 3.5 Ga *Earth Planet. Sci. Lett.* **302** 314–28
[516] Usui Y, Tarduno J A, Watkeys M, Hofmann A and Cottrell R D 2009 Evidence for a 3.45-billion-year-old magnetic remanence: hints of an ancient geodynamo from conglomerates of South Africa *Geochem. Geophys. Geosyst.* **10** Q09Z07
[517] Tarduno J A, Cottrell R D and Bono R K *et al* 2020 Paleomagnetism indicates that primary magnetite in zircon records a strong Hadean geodynamo *Proc. Natl Acad. Sci.* **117** 2309–18
[518] Borlina C S, Weiss B P and Lima E A *et al* 2020 Reevaluating the evidence for a Hadean-Eoarchean dynamo *Sci. Adv.* **6** eaav9634
[519] Stevenson D J 2001 Mars' core and magnetism *Nature* **412** 214–9
[520] Lockwood M, Harrison R G, Woollings T and Solanki S K 2010 Are cold winters in Europe associated with low solar activity? *Environ. Res. Lett.* **5** 024001

Chapter 5

Abou Allaban A, Wang W and Padr T 2020a A systematic review of robotics research in support of in-home care for older adults *Information* **11** 75
Acemoglu A, Kriegstein J and Caldwell D G *et al* 2020b 5G robotic telesurgery: remote transoral laser microsurgeries on a Cadaver *IEEE Trans. Med. Robot. Bionics* **2** 511–8
Acemoglu A, Peretti G, Hysenbelli J, Trimarchi M and Caldwell D G *et al* 2020a Operating from a distance: the first 5G telesurgery experience *Ann. Intern. Med.* **173** 940–1
Adams R M, Mora T, Walczak A M and Kinney J B 2016 Measuring the sequence-affinity landscape of antibodies with massively parallel titration curves *eLife* **5** e23156
Agostinis P *et al* 2011 Photodynamic therapy of cancer: an update *CA. A Cancer J. Clin.* 250–81
Aleta A *et al* 2020 Modelling the impact of testing, contact tracing and household quarantine on second waves of COVID-19 *Nat. Human Behav.* **4** 964–71
Althouse B M *et al* 2020 Superspreading events in the transmission dynamics of SARS-CoV-2: opportunities for interventions and control *PLoS Biol.* **18** e3000897
Amaldi U *et al* 2021 Sigrum-A Superconducting Ion Gantry with Riboni's Unconventional Mechanics. No. CERN-ACC-NOTE-2021-0014
Anderson B, Rasch M, Hochlin K, Jensen F H, Wismar P and Fredriksen J E 2006 Decontamination of rooms, medical equipment and ambulances using an aerosol of hydrogen peroxide disinfectant *J. Hosp. Infect.* **62** 149–55
Antoniou S A, Antoniou G A, Antoniou A I and Granderath F A 2015 Past, present, and future of minimally invasive abdominal surgery *JSLS* **19** e2015.00052

Arenas A *et al* 2020 Modeling the spatiotemporal epidemic spreading of COVID-19 and the impact of mobility and social distancing interventions *Phys. Rev.* X **10** 041055

Ašner F M 1999 *High Field Superconducting Magnets* (Oxford: Oxford University Press)

Barbosa H *et al* 2018 Human mobility: models and applications *Phys. Rep.* **734** 1–74

Baronchelli F, Zucchella C, Serrao I D and Bartolo M 2021 The effect of robotic assisted gait training with Lokomat® on balance control after stroke: systematic review and meta-analysis *Front. Neurol.*

Barrat A *et al* 2013 Empirical temporal networks of face-to-face human interactions *Eur. Phys. J. Spec. Top.* **222** 1295–309

Beal A, Mahida N, Staniforth K, Vaughan N, Clarke M and Boswell T 2016 First UK trial of Xenex PX-UV, an automated ultraviolet room decontamination device in a clinical haematology and bone marrow transplantation unit *J. Hosp. Infect.* **93** 164–8

Beccani M, Aiello G, Gkotsis N and Tunc H *et al* 2016 Component based design of a drug delivery capsule robot *Sens. Actuators* A **245** 180–8

Best J 2021 Wearable technology: COVID-19 and the rise of remote clinical monitoring *Brit. Med. J.* **372** n413

Bloss R 2011 Mobile hospital robots cure numerous logistic needs *Ind. Robot* **38** 567–71

Bottura L, de Rijk G, Rossi L and Todesco E 2012 Advanced accelerator magnets for upgrading the LHC *IEEE Trans. Appl. Supercond.* **22** 8

Bottura L and Rossi L 2015 Magnets for particle accelerators *Applied Superconductivity—Handbook on Devices and Applications* ed P Seidel (New York: Wiley-VCH) pp 448–86

Brändén G and Neutze R 2021 Advances and challenges in time-resolved macromolecular crystallography *Science* **373** eaba0954

Brouwer L *et al* 2020 Design and test of a curved superconducting dipole magnet for proton therapy *Nucl. Instrum. Meth. Phys. Res. Sect. A, Accel., Spect., Detect. Assoc. Equip.* **957** 163414

Brüning O and Rossi L 2015 *The High Luminosity Large Hadron Collider Advanced Series on Direction in High Energy Physics* (Singapore: World Scientific)vol 24

Brüning O and Rossi L 2019 The high-luminosity large hadron collider *Nat. Rev.—Phys.* **1** 241–3

Bubar K M *et al* 2021 Model-informed COVID-19 vaccine prioritization strategies by age and serostatus *Science* **371** 916–21

Buettner R, Wannenwetsch K and Loskan D 2020 A systematic literature review of computer support for surgical interventions *2020 IEEE 44th Annual Computers, Software, and Applications Conf. (COMPSAC)* pp 729–34

Burley S K *et al* 2022 A comprehensive review of 3D structure holdings and worldwide utilization by researchers, educators, and students *Biomolecules* **12** 1425

Bush K *et al* 2011 Tackling antibiotic resistance *Nat. Rev. Microbiol.* **9** 894–6

Čaić M, Mahr D and Oderkerken-Schröder G 2019 Value of social robots in services: social cognition perspective *J. Serv. Mark.* **33** 463–78

Cao W, Song W, Li X, Zheng S, Zhang G and Wu Y *et al* 2019 Interaction with social robots: improving gaze toward face but not necessarily joint attention in children with autism spectrum disorder *Front. Psychol.* **10** 1503

Carling P C and Huang S S 2013 Improving healthcare environmental cleaning and disinfection current and evolving issues *Infect. Control Hosp. Epidemiol.* **34** 507–13

Carr J H and Shepherd R B 1987 *A Motor Relearning Programme for Stroke* (Oxford: Butterworth Heinemann)

Castro M, Ares S, Cuesta J A and Manrubia S 2020 The turning point and end of an expanding epidemic cannot be precisely forecast *Proc. Natl Acad. Sci.* **117** 26190–6

Chakraborty A K and Barton J P 2017 Rational design of vaccine targets and strategies for HIV: a crossroad of statistical physics, biology, and medicine *Rep. Prog. Phys.* **80** 032601

Chang M C and Boudier-Revéret M 2020 Usefulness of telerehabilitation for stroke patients during the COVID-19 pandemic *Am. J. Phys. Med. Rehabil.* **99** 582

Chapman H N 2019 X-ray free-electron lasers for the structure and dynamics of macromolecules *Annu. Rev. Biochem.* **88** 35–58

Charron P M, Kirby R L and MacLeod D A 1995 Epidemiology of walker-related injuries and deaths in the United States *Am. J. Phys. Med. Rehabil.* **74** 237–9

Chinazzi M *et al* 2020 The effect of travel restrictions on the spread of the 2019 novel coronavirus (COVID-19) *Science* **368** 395–400

Choi P J, Oskouian R J and Tubbs R S 2018 Telesurgery: past, present, and future *Cureus* **10** e2716

Chowell G 2017 Fitting dynamic models to epidemic outbreaks with quantified uncertainty: a primer for parameter uncertainty, identifiability, and forecasts *Infect. Dis. Model.* **2** 379–98

Chowell G, Vespignani A, Viboud C and Simonsen L 2018 The RAPIDD Ebola Forecasting Challenge, Special Issue *Epidemics* **22** 1

CLIC Project n.d. (http://clic-study.web.cern.ch/clic-study/)

CNAO n.d. Fondazione CNAO, Pavia, Italy (https://fondazionecnao.it/)

Colizza V, Barrat A, Barthélemy M and Vespignani A 2006 The role of the airline transportation network in the prediction and predictability of global epidemics *Proc. Natl Acad. Sci.* **103** 2015–20

Dabiri F, Massey T, Noshadi H and Hagopian H *et al* 2009 A telehealth architecture for networked embedded systems: a case study in *in vivo* health monitoring *IEEE Trans. Inf. Technol. Biomed.* **13** 351–9

Danon L *et al* 2011 Networks and the epidemiology of infectious disease *Interdisciplinary Perspectives on Infectious Diseases* **2011** e284909

Davies B 2000 A review of robotics in surgery *Proc. Inst. Mech. Eng.* **214** 129–40

Davies N G *et al* 2020 Age-dependent effects in the transmission and control of COVID-19 epidemics *Nat. Med.* **26** 1205–11

Dawe J, Sutherland C, Barco A and Broadbent E 2019 Can social robots help children in healthcare contexts? A scoping review *BMJ Paediatr. Open.* **3** e000371

de Boer J F, Leitgeb R and Wojtkowski M 2017 Twenty-five years of optical coherence tomography: the paradigm shift in sensitivity and speed provided by Fourier domai—OCT *Biomed. Opt. Express* **8** 3248–80

de Graaf M M A, Ben Allouch S and van Dijk J A G M 2015 What makes robots social? A user's perspective on characteristics for social human–robot interaction *Social Robot* ed A Tapus, E André, J-C Martin, F Ferland and M Ammi (Cham: Springer International Publishing)

De Marchi F, Contaldi E, Magistrelli L and Cantello R *et al* 2021 Telehealth in neuro-degenerative diseases: opportunities and challenges for patients and physicians *Brain Sci.* **11** 237

De Michieli L, Mattos L S, Caldwell D G, Metta G and Cingolani R 2020 Technology and telemedicine *Encyclopedia of Gerontology and Population Aging* ed D Gu and M E Dupre (Cham: Springer International Publishing)

Degiovanni O A and Amaldi U 2015 History of Hadron therapy accelerators *Physica Med.* **31** 322–32

Desai M M and Fisher D S 2007 Beneficial mutation–selection balance and the effect of linkage on positive selection *Genetics* **176** 1759–98

Di Natali C and Poliero *et al* 2019 Design and evaluation of a soft assistive lower limb exoskeleton *Robotica* **37** 2014–34

Di Natali C, Sadeghi A and Mondini A *et al* 2020 Pneumatic quasi-passive actuation for soft assistive lower limbs exoskeleton *Front. Neurorobot.* **14** 31

Ding X and Clifton D *et al* 2020 Wearable sensing and telehealth technology with potential applications in the coronavirus pandemic *IEEE Rev. Biomed. Eng.* **14** 48–70

D. O. E. United NationsAffairs S 2017 World population ageing 2017 highlights (Accessed 11 March 2021)

Eames K, Bansal S, Frost S and Riley S 2015 Six challenges in measuring contact networks for use in modelling *Epidemics* **10** 72–7

Elhanati Y, Sethna Z, Callan C G, Mora T and Walczak A M 2018 Predicting the spectrum of TCR repertoire sharing with a data-driven model of recombination *Immunol. Rev.* **284** 167–79

Evans L 2018 *The Large Hadron Collider: A Marvel of Technology* (EPFL Press) 2nd edn

Fabbricatore P *et al* 2011 The construction of the model of the curved fast ramped superconducting dipole for FAIR SIS300 synchrotron *IEEE Trans. Appl. Supercond.* **21** 1863–7 Part: 2 Published: Jun

Faus-Golfe A 2020 Design of a compact 140 MeV electron linear accelerator *ARIES D3.4* (https://edms.cern.ch/ui/file/1817163/1.0/ARIES-Del-D3.4-Final.pdf)

Ferretti L *et al* 2020 Quantifying SARS-CoV-2 transmission suggests epidemic control with digital contact tracing *Science*

Fiedler F 2008 *PhD Thesis* FZD Rossendorf/TU Dresden

Fujimoto J and Swanson E 2016 The development, commercialization, and impact of optical coherence tomography *Invest—Ophthalmol. Vis. Sci.* **57** OCT1–OCT13

Funk S, Salathé M and Jansen V A A 2010 Modelling the influence of human behaviour on the spread of infectious diseases: a review *J. R. Soc. Interface* **7** 1247–56

Gallotti R, Valle F, Castaldo N, Sacco P and De Domenico M 2020 Assessing the risks of 'infodemics' in response to COVID-19 epidemics *Nat. Hum. Behav.* **4** 1285–93

Gatto M *et al* 2020 Spread and dynamics of the COVID-19 epidemic in Italy: effects of emergency containment measures *Proc. Natl Acad. Sci.* **117** 10484–91

Gérard A *et al* 2020 High-throughput single-cell activity-based screening and sequencing of antibodies using droplet microfluidics *Nat. Biotechnol.* **38** 715–21

Gorpas D *et al* 2011 Autofluorescence lifetime augmented reality as a means for real-time robotic surgery guidance in human patients *Sci. Rep.* **9** 1187

Gostic K M *et al* 2020 Practical considerations for measuring the effective reproductive number, Rt *PLoS Comput. Biol.* **16** e1008409

Guimerà R, Mossa S, Turtschi A and Amaral L a N 2005 The worldwide air transportation network: anomalous centrality, community structure, and cities' global roles *Proc. Natl Acad. Sci.* **102** 7794–9

Haberer T *et al* 2004 The Heidelberg ion therapy center *Radiother. Oncol.* **73** S186–90

Henschel A, Laban G and Cross E S 2021 What makes a robot social? A review of social robots from science fiction to a home or hospital near you *Curr Robot Rep.* **2** 9–19

HITRIplus n.d. *Heavy Ion Therapy Research Integration* (https://hitriplus.eu/)

Hosseinizadeh O A, Breckwoldt N, Fung R, Sepehr R, Schmidt M, Schwander P, Santra R and Ourmazd A 2021 Few-fs resolution of a photoactive protein traversing a conical intersection *Nature* **599** 697–701

Huang P-S, Boyken S E and Baker D 2016 The coming of age of de novo protein design *Nature* **537** 320–7

Hull J R, Wilson M N, Bottura L, Rossi L, Green M A, Iwasa Y, Hahn S, Duchateau J and Kalsi S S 2015 *Superconducting Magnets Applied Superconductivity—Handbook on Devices and Applications* (Germany: Wiley- VCH Verlag Gmbh & Co. KGa) ch 4

Huysamen K, Bosch T, de Looze M, Stadler K S, Graf E and O'Sullivan L W 2018 Evaluation of a passive exoskeleton for static upper limb activities *Appl. Ergon.* **70** 148–55

I.FAST n.d. Innovation Fostering in Accelerator Science and Technology (https://ifast-project.eu/home)

Iwata Y *et al* 2012 Design of a superconducting rotating gantry for heavy-ion therapy *Phys. Rev. Spec. Top. PRST-AB. Accel. Beams.* **15** 044701

Jaeschke E, Khan S, Schneider J R and Hastings J B 2020 *Synchrotron Light Sources and Free-Electron Lasers* (Berlin: Springer)

Jaskolski M, Dauter Z and Wlodawer A 2014 A brief history of macromolecular crystallography, illustrated by a family tree and its Nobel fruits *FEBS J.* **281** 3985–4009

Johanson D L, Ho S A, Sutherland C J, Brown B, MacDonald B A and Jong Y L *et al* 2020 Smiling and use of first-name by a healthcare receptionist robot: effects on user perceptions, attitudes, and behaviours *Paladyn J. Behav. Robot.* **11** 40–51

Jumper J *et al* 2021 Highly accurate protein structure prediction with alphafold *Nature* **596** 583–9

Karppinen M, Ferrantino V, Kokkinos C and Ravaioli E 2022 Design of a curved superconducting combined function bending magnet demonstrator for hadron therapy *IEEE Trans. Appl. Supercond.* **32** 1–5

Kermack W O, McKendrick A G and Walker G T 1927 A contribution to the mathematical theory of epidemics *Proc. R. Soc.* A **115** 700–21

Kirby G *et al* 2020 Assembly and test of the HL-LHC twin aperture orbit corrector based on canted cos-theta design *J. Phys.: Conf. Ser.* **1559** 012070

Kiss I Z, Miller J and Simon P L 2017 *Mathematics of Epidemics on Networks: From Exact to Approximate Models* (Cham: Springer International Publishing)

Kivelä M *et al* 2014 Multilayer networks *J. Complex Netw.* **2** 203–71

Krafft C, von Eggeling F, Guntinas-Lichius O, Hartmann A, Waldner M J, Neurath M F and Popp J 2018 Perspectives, potentials and trends of *ex vivo* and *in vivo* optical molecular pathology *J. Biophotonics* **11** e201700236

Kühlbrandt W 2014 Cryo-EM enters a new era *eLife* **3** e03678

Kwoh Y S, Hou J and Jonckheere E A *et al* 1988 A robot with improved absolute positioning accuracy for CT guided stereotactic brain surgery *IEEE Trans. Biomed. Eng.* **35** 53–161

Laffranchi M and D'Angella S *et al* 2021 User-centered design and development of the modular TWIN lower limb exoskeleton *Front. Neurorobot.* **15**

Lässig M, Mustonen V and Walczak A M 2017 Predicting evolution *Nat Ecol Evol* **1** 1–9

Last update in the search for the Higgs boson 2012 Seminar held at CERN, 4 July (https://indico.cern.ch/conferenceDisplay.py?confId=197461)

Leochico C F D 2020 Adoption of telerehabilitation in a developing country before and during the COVID-19 pandemic *Ann. Phys. Rehabil. Med.* **63** 563–4

LHC DESIGN Report 2004 Vol. I The LHC Main Ring Design Report, CERN Report, CERN-2004-003, 4 June

Li J, Esteban-Fernández de Ávila B, Gao W, Zhang L and Wang J 2017 Micro/nanorobots for biomedicine: delivery, surgery, sensing, and detoxification *Sci. Robot.* **2** eaam6431

López J A M *et al* 2021 Anatomy of digital contact tracing: role of age, transmission setting, adoption and case detection *Sci. Adv.* **7** eabd8750

Łuksza M and Lässig M 2014 A predictive fitness model for influenza *Nature* **507** 57–61

Masuda N and Holme P 2013 Predicting and controlling infectious disease epidemics using temporal networks *F1000Prime Reports* **5** 6

Matanfack Azemtsop G, Rüger J, Stiebing C, Schmitt M and Popp J 2020 Imaging the invisible—bioorthogonal Raman probes for imaging of cells and tissues *J. Biophotonics* **13** e202000129

Mattos L S, Caldwell D G, Peretti G, Mora F, Guastini L and Cingolani R 2016 Microsurgery robots: addressing the needs of high-precision surgical interventions *Swiss Med. Wkly.* **146** w14375

MedAustron n.d. *The Center for Ion Therapy and Research, Wiener Neustadt, Austry* (https://medaustron.at/en)

Mess K-H, Schmüser P and Wolff S 1996 *Superconducting Accelerator Magnets* (Singapore: World Scientific)

Meyer T, Schmitt M, Guntinas-Lichius O and Popp J 2019 Toward an all-optical bi—sy *Opt. Photonics News* **30** 26–33

Minervina A A *et al* 2021 Longitudinal high-throughput TCR repertoire profiling reveals the dynamics of T-cell memory formation after mild COVID-19 infection *eLife* **10** e63502

Moses H, Matheson D H, Dorsey E R, George E R, Sadoff D and Yoshimura S 2013 The anatomy of health care in the United States *JAMA* **310** 1947–63

Murugan A, Mora T, Walczak A M and Callan C G 2012 Statistical inference of the generation probability of T-cell receptors from sequence repertoires *Proc. Natl Acad. Sci.* **109** 16161–6

Neher R A, Russell C A and Shraiman B I 2014 Predicting evolution from the shape of genealogical trees *eLife* **3** e03568

Nelson B J, Kaliakatsos I K and Abbot J J 2010 Microrobots for minimally invasive medicine *Annu. Rev. Biomed. Eng.* **12** 55–85

Neutze R, Wouts R, van der Spoel D, Weckert E and Hajdu J 2000 Potential for biomolecular imaging with femtosecond x-ray pulses *Nature* **406** 753–7

Nourmohammad A, Otwinowski J and Plotkin J B 2016 Host-pathogen coevolution and the emergence of broadly neutralizing antibodies in chronic infections *PLoS Genet.* **12** e1006171

Oliver N *et al* 2020 Mobile phone data for informing public health actions across the COVID-19 pandemic life cycle *Sci. Adv.* **6** eabc0764

OMRON 2022 Automating UV Disinfection Process Safely and Wisely (https://web.omron-ap.com/th/ld-uvc) Accessed 10 January 2022

Organisation for Economic Co-operation and Development (OECD) 2009 *Health at a Glance 2009: OECD Indicators* (Paris: OECD Publishing)

Organisation for Economic Co-operation and Development (OECD) 2020 *Historical Population Data and Projections (1950–2050)* (https://stats.oecd.org/) (Accessed 1 Aug 2020)

Osibona O, Solomon B D and Fecht D 2021 Lighting in the home and health: a systematic review *Int. J. Environ. Res. Public Health* **18** 609

Pandey A K and Gelin R 2018 A mass-produced sociable humanoid robot: pepper: the first machine of its kind *IEEE Robot. Autom. Mag.* **25** 40–8

Parker V M, Wade D T and Langton H R 1986 Loss of arm function after stroke: measurement, frequency, and recovery *Int. Rehab. Med.* **8** 69–73

Pastor-Satorras R, Castellano C, Van Mieghem P and Vespignani A 2015 Epidemic processes in complex networks *Rev. Mod. Phys.* **87** 925–79

Perelson A S, Neumann A U, Markowitz M, Leonard J M and Ho D D 1996 HIV-1 dynamics *in vivo*: virion clearance rate, infected cell life-span, and viral generation time *Science* **271** 1582–6

Perelson A S and Weisbuch G 1997 Immunology for physicists *Rev. Mod. Phys.* **69** 1219–68

Perra N 2021 Non-pharmaceutical interventions during the COVID-19 pandemic: a review *Phys. Rep.* **913** 1–52

Poletto C, Meloni S, Colizza V, Moreno Y and Vespignani A 2013 Host mobility drives pathogen competition in spatially structured populations *PLoS Comput. Biol.* **9** e1003169

Poliero T, Mancini L, Caldwell D G and Ortiz J 2019 Enhancing backsupport exoskeleton versatility based on human activity recognition *2019 Wearable Robotics Association Conf. (WearRAcon)* (IEEE) pp 86–91

Pons J L 2008 *Wearable Robots: Biomechatronic Exoskeletons* (New York: Wiley)

Popp J (ed) 2014 *Ex-vivo and In-vivo Optical Molecular Pathology* (Weinheim: Wiley-VCH)

Popp J and Bauer M (ed) 2015 *Modern techniques for Pathogen Detection* (Weinheim: Wiley-VCH)

Popp J and Strehle M (ed) 2006 *Biophotonics* (Weinheim: Wiley-VCH)

Popp J, Tuchin V V, Chiou A and Heinemann S H (ed) 2011 *Handbook of Biophotonics* vol 1–3 (Weinheim: Wiley-VCH)

Priplata A A, Niemi J B, Harry J D, Lipsitz L A and Collins J J 2003 Vibrating insoles and balance control in elderly people *Lancet* **362** 1123–4

Prvu Bettger J and Resnik L J 2020 Tele-rehabilitation in the age of COVID-19: an opportunity for learning health system research *Phys. Ther.* **100** 1913–6

Pullano G *et al* 2020 Underdetection of COVID-19 cases in France threatens epidemic control *Nature* **590** 1–9

Ramalingam B, Yin J, Rajesh Elara M, Tamilselvam Y K, Mohan Rayguru M, Muthugala M and Félix Gómez B 2020 A human support robot for the cleaning and maintenance of door handles using a deep-learning framework *Sensors* **20** 3543

Richardson C A, Glynn N W, Ferrucci L G and Mackey D C 2015 Walking energetics, fatigability, and fatigue in older adults: the study of energy and aging pilot *J. Gerontol. Ser. A: Biomed. Sci. Med. Sci.* **70** 487–94

Robinson C 1995 Rehabilitation engineering, science and technology ed J Bronzino *Biomedical Engineering Handbook* (Boca Raton, FL: CRC Press) pp 2045–54

Rossi L 2010 Superconductivity: its role, its success and its setbacks in the Large Hadron Collider of CERN *Supercond. Sci. Technol.* **23** 034001

Rossi L *et al* 2022a Preliminary study of 4 T superconducting dipole for a light rotating gantry for ion-therapy *IEEE-Trans. Appl. Supercon.* **32** 4400506

Rossi L *et al* 2022b A European collaboration to investigate superconducting magnets for next generation heavy ion therapy *IEEE-Trans. Appl. Supercon.* **32** 4400207

Rossi L and Bottura L 2012 Superconducting magnets for particle accelerators *Rev. Accel. Sci. Technol.* **5** 51–89

Rossi L and Bruning O 2016 The LHC upgrade plan and technology challenges *Challenges and Goals for ACCELERATORS in the XXI Century* ed O Bruning and S Myers (Singapore: World Scientific Publisher) pp 467–97

Rossi L and Brüning O 2019 *Progress with the High Luminosity LHC Project at Cern Proceedings of IPAC2019 (Melbourne, 19–24 May)* (Jacow Publisher) pp 17–22

Rossi L and Senatore C 2021 HTS accelerator magnet and conductor development in Europe *Instruments* **5** 33

Rossi L and Todesco E 2006 Electromagnetic design of superconducting quadrupoles *Phys. Rev. Spec. Top. Accel Beams* **9** 102401 1–20

Rossi L and Todesco E 2007 Electromagnetic design of superconducting dipoles based on sector coils *Phys. Rev. Spec. Top. Accel. Beams* **10** 112401

Rossi L and Todesco E 2011 Conceptual design of the 20 T dipoles for high-energy LHC *Proc. of the High-Energy Large Hadron Collider Workshop (Malta, Oct. 2010)* ; E Todesco and F Zimmermann CERN-2011-003 (8 April 2011) pp 13–9

Saglia J A *et al* 2019 Design and development of a novel core, balance and lower limb rehabilitation robot: Hunova® *2019 IEEE 16th Int. Conf. on Rehabilitation Robotics (ICORR) (2019)* pp 417–22

Saglia J A, Tsagarakis N, Dai J S and Caldwell D G 2013 Control strategies for patient-assisted training using the ankle rehabilitation robot (ARBOT) *IEEE/ASME Trans. Mechatron.* **18** 1799–808

Satava R 2002 Surgical robotics: the early chronicles *Surg. Laparosc., Endosc. Percutan. Techn.* **12** 6–16

Schlichting I 2015 Serial femtosecond crystallography: the first five years *IUCrJ* **2** 246–55

Schlosser F *et al* 2020 COVID-19 lockdown induces disease-mitigating structural changes in mobility networks *Proc. Natl Acad. Sci.* **117** 32883–90

Sorbi M *et al* 2013 Measurements and analysis of the SIS-300 dipole prototype during the functional test at LASA *IEEE Trans. Appl. Supercond.* **23** 400205

Soto F, Wang J, Ahmed R and Demirci U 2020 Medical micro/nanorobots in precision medicine *Adv. Sci.* **7** 2002203

Spence J C H 2017 XFELs for structure and dynamics in biology *IUCrJ* **4** 322–39

Stahl B C and Coeckelbergh M 2016 Ethics of healthcare robotics: towards responsible research and innovation *Robot. Auton. Syst.* **86** 152–61

Starr T N *et al* 2020 Deep mutational scanning of SARS-CoV-2 receptor binding domain reveals constraints on folding and ACE2 binding *Cell* **182** 1295–1310.e20

Stower R 2019 The role of trust and social behaviours in children's learning from social robots *8th Int. Conf. Affect. Comput. Intell. Interact. Work Demos (Cambridge, UK, 2019)* pp 1–5

Tannert A, Grohs R, Popp J and Neugebauer U 2019 Phenotypic antibiotic susceptibility testing of pathogenic bacteria using photonic readout methods: recent achievements and impact *Appl. Microbiol. Biotechnol.* **103** 549–66

Tollestrup A and Todesco E 2008 *Review of Accelerator Science and Technology* ed A Chao and W Chou (Singapore: World Scientific)vol 11 pp 185–210

Toxiri S, Koopman A S, Lazzaroni M, Ortiz J, Power V, de Looze M P, O'Sullivan L and Caldwell D G 2018 Rationale, implementation and evaluation of assistive strategies for an active back-support exoskeleton *Front. Robot. AI* **5** 53

Toxiri S, Naf M B, Lazzaroni M, Fernandez J, Sposito M, Poliero T, Monica L, Anastasi S, Caldwell D G and Ortiz J 2019 Back-support exoskeletons for occupational use: an overview of technological advances and trends *IISE Trans. Occup. Ergon. Hum. Factors* **7** 237–49

Tsagarakis N G, Metta G, Sandini G and Vernon C D G 2007 iCub: the design and realization of an open humanoid platform for cognitive and neuroscience research *Adv. Robot* **21** 1151–75

Tsimring L S, Levine H and Kessler D A 1996 RNA virus evolution via a fitness-space model *Phys. Rev. Lett.* **76** 4440–3

Vanderborght B *et al* 2013 Variable impedance actuators: a review *Rob. Autom. Syst.* **61** 1601–14

Very High Energy 2020 Electron Radiotherapy Workshop (VHEE'2020) (https://indico.cern.ch/event/939012/)

Volz E *et al* 2021 Assessing transmissibility of SARS-CoV-2 lineage B.1.1.7 in England *Nature* 1–17

Wang S *et al* 2015 Manipulating the selection forces during affinity maturation to generate cross-reactive HIV antibodies *Cell* **160** 785–97

Wang X V and Wang L 2021 A literature survey of the robotic technologies during the COVID-19 pandemic *J. Manuf. Syst.* **60** 823–36

Wilson M N 1983 *Superconducting Magnets* (Oxford: Oxford University Press)

Wilson M N 1999 Superconductivity and accelerators: the good companions *IEEE Trans. Appl. Supercond.* **9** 111–21

World Health Organization (WHO) 2008 10 facts on health workforce crisis(http://who.int/features/factfiles/health_workforce/en/) Accessed 6 Aug 2020

Wu J T, Leung K and Leung G M 2020 Nowcasting and forecasting the potential domestic and international spread of the 2019-nCoV outbreak originating in Wuhan, China: a modelling study *Lancet* **395** 689–97

Wu Y H, Wrobel J, Cornuet M, Kerhervé H, Damnée S and Rigaud A S 2014 Acceptance of an assistive robot in older adults: a mixed-method study of human–robot interaction over a 1-month period in the Living Lab setting *Clin. Interv. Aging.* **8** 801–11

Yang G Z, Bellingham J and Dupont P *et al* 2018 The grand challenges of science robotics *Sci. Robot.* **3**

Zemmar A, Lozano A M and Nelson B J 2020 The rise of robots in surgical environments during COVID-19 *Nat. Mach. Intell.* **2** 566–72

Zhang S-Q *et al* 2018 High-throughput determination of the antigen specificities of T cell receptors in single cells *Nat. Biotechnol.* **36** 1156–9

Chapter 6

[1] Boers N, Goswami B, Rheinwalt A, Bookhagen B, Hoskins B and Kurths J 2019 Complex networks reveal global pattern of extreme-rainfall teleconnections *Nature* **566** 373–7

[2] Steffen W, Sanderson R A, Tyson P D, Jäger J, Matson P A, Moore B, Oldfield F, Richardson K, Schellnhuber H-J and Turner B L 2006 *Global Change and the Earth System: A Planet Under Pressure* (Berlin: Springer Science & Business Media)

[3] Mann M E, Steinman B A, Brouillette D J and Miller S K 2021 Multidecadal climate oscillations during the past millennium driven by volcanic forcing *Science* **371** 1014–9

[4] Ge Y, Jin Y, Stein A, Chen Y, Wang J, Wang J, Cheng Q, Bai H, Liu M and Atkinson P M 2019 Principles and methods of scaling geospatial Earth science data *Earth Sci. Rev.* **197** 102897

[5] Fan J, Meng J, Ludescher J, Chen X, Ashkenazy Y, Kurths J, Havlin S and Schellnhuber H J 2020 Statistical physics approaches to the complex Earth system *Phys. Rep.* **896** 1–84

[6] Bradley R S 2015 *Paleoclimatology: Reconstructing Climates of the Quaternary* (New York: Academic)

[7] Muller R A and MacDonald G J 2002 *Ice Ages and Astronomical Causes: Data, Spectral Analysis and Mechanisms* (Berlin: Springer Science & Business Media)

[8] Poincaré H 1890 Sur le problème des trois corps et les équations de la dynamique *Acta Math.* **13** A3–270
[9] Nicolis G and Nicolis C 2012 *Foundations of Complex Systems: Emergence, Information and Predicition* (Singapore: World Scientific)
[10] Kantz H and Schreiber T 2004 *Nonlinear Time Series Analysis* (Cambridge: Cambridge University Press)vol 7
[11] Eckmann J 1987 Recurrence plots of dynamical systems *Europhys. Lett.* **5** 973–7
[12] Marwan N, Romano M C, Thiel M and Kurths J 2007 Recurrence plots for the analysis of complex systems *Phys. Rep.* **438** 237–329
[13] Pikovskij A, Rosenblum M and Kurths J 2007 *Synchronization: A Universal Concept in Nonlinear Sciences* (Cambridge: Cambridge University Press)
[14] Torrence C and Compo G P 1998 A practical guide to wavelet analysis *Bull. Am. Meteorol. Soc.* **79** 61–78
[15] Newman M E J 2010 *Networks: An Introduction* (Oxford: Oxford University Press)
[16] Jafarimanesh A, Mignan A and Danciu L 2018 Origin of the power-law exponent in the landslide frequency-size distribution *Nat. Hazards Earth Syst. Sci. Discuss.* 1–28
[17] Gutenberg B and Richter C F 1944 Frequency of earthquakes in California *Bull. Seismol. Soc. Am.* **34** 185–8
[18] Gutenberg B and Richter C F 1956 Earthquake magnitude, intensity, energy, and acceleration: (second paper) *Bull. Seismol. Soc. Am.* **46** 105–45
[19] Frohlich C and Davis S D 1993 Teleseismic b values; or, much ado about 1.0 *J. Geophys. Res.: Solid Earth* **98** 631–44
[20] Blöschl G 1996 *Scale and Scaling in Hydrology* (Techn. Univ., Inst. f. Hydraulik, Gewässerkunde u. Wasserwirtschaft)
[21] Peters-Lidard C D, Pan F and Wood E F 2001 A re-examination of modeled and measured soil moisture spatial variability and its implications for land surface modeling *Adv. Water Res.* **24** 1069–83
[22] Kumar P and Foufoula-Georgiou E 1993 A multicomponent decomposition of spatial rainfall fields: 1. Segregation of large- and small-scale features using wavelet transforms *Water Resour. Res.* **29** 2515–32
[23] Schuster A 1898 On the investigation of hidden periodicities with application to a supposed 26 day period of meteorological phenomena *J. Geograph. Res.* **3** 13–41
[24] Eroglu D, McRobie F H, Ozken I, Stemler T, Wyrwoll K-H, Breitenbach S F, Marwan N and Kurths J 2016 See–saw relationship of the Holocene East Asian–Australian summer monsoon *Nat. Commun.* **7** 1–7
[25] Malik N, Marwan N and Kurths J 2010 Spatial structures and directionalities in Monsoonal precipitation over South Asia *Nonlinear Processes Geophys.* **17** 371–81
[26] Pacheco J F, Scholz C H and Sykes L R 1992 Changes in frequency–size relationship from small to large earthquakes *Nature* **355** 71–3
[27] Zhan Z 2017 Gutenberg–Richter law for deep earthquakes revisited: a dual-mechanism hypothesis *Earth Planet. Sci. Lett.* **461** 1–7
[28] Scholz C H 1968 The frequency-magnitude relation of microfracturing in rock and its relation to earthquakes *Bull. Seismol. Soc. Am.* **58** 399–415
[29] Tormann T, Enescu B, Woessner J and Wiemer S 2015 Randomness of megathrust earthquakes implied by rapid stress recovery after the Japan earthquake *Nat. Geosci.* **8** 152–8

[30] Wiemer S and McNutt S R 1997 Variations in the frequency-magnitude distribution with depth in two volcanic areas: Mount St. Helens, Washington, and Mt. Spurr, Alaska *Geophys. Res. Lett.* **24** 189–92
[31] De Geer G 1926 On the solar curve: as dating the ice age, the New York Moraine, and Niagara Falls through the Swedish Timescale *Geogr. Ann.* **8** 253–83
[32] Berger A L 1978 Long-term variations of caloric insolation resulting from the Earth's orbital elements *Quat. Res.* **9** 139–67
[33] Westerhold T, Marwan N, Drury A J, Liebrand D, Agnini C, Anagnostou E, Barnet J S, Bohaty S M, De Vleeschouwer D and Florindo F 2020 An astronomically dated record of Earth's climate and its predictability over the last 66 million years *Science* **369** 1383–7
[34] Burke K D, Williams J W, Chandler M A, Haywood A M, Lunt D J and Otto-Bliesner B L 2018 Pliocene and Eocene provide best analogs for near-future climates *Proc. Natl. Acad. Sci.* **115** 13288–93
[35] Pai D S and Nair R M 2009 Summer monsoon onset over Kerala: new definition and prediction *J. Earth Syst. Sci.* **118** 123–35
[36] Stolbova V, Surovyatkina E, Bookhagen B and Kurths J 2016 Tipping elements of the Indian monsoon: prediction of onset and withdrawal: tipping elements of monsoon *Geophys. Res. Lett.* **43** 3982–90
[37] Ludescher J *et al* 2021 Network-based forecasting of climate phenomena *Proc. Natl Acad. Sci.* **118** e1922872118
[38] Stark C P and Hovius N 2001 The characterization of landslide size distributions *Geophys. Res. Lett.* **28** 1091–4
[39] Malamud B D, Turcotte D L, Guzzetti F and Reichenbach P 2004 Landslides, earthquakes, and erosion *Earth Planet. Sci. Lett.* **229** 45–59
[40] West G B 2017 *Scale: The Universal Laws of Growth, Innovation, Sustainability, and the Pace of Life in Organisms, Cities, Economies, and Companies* (London: Penguin)
[41] Liu Z, Nadim F, Garcia-Aristizabal A, Mignan A, Fleming K and Luna B Q 2015 A three-level framework for multi-risk assessment *Georisk: Assess. Manag. Risk Eng. Syst. Geohazards* **9** 59–74
[42] von Specht S, Ozturk U, Veh G, Cotton F and Korup O 2019 Effects of finite source rupture on landslide triggering: the 2016 *MW* 7.1 Kumamoto earthquake *Solid Earth* **10** 463–86
[43] Ozturk U, Marwan N, Korup O, Saito H, Agarwal A, Grossman M J, Zaiki M and Kurths J 2018 Complex networks for tracking extreme rainfall during typhoons *Chaos* **28** 075301
[44] Saito H, Korup O, Uchida T, Hayashi S and Oguchi T 2014 Rainfall conditions, typhoon frequency, and contemporary landslide erosion in Japan *Geology* **42** 999–1002
[45] Agarwal A, Caesar L, Marwan N, Maheswaran R, Merz B and Kurths J 2019 Network-based identification and characterization of teleconnections on different scales *Sci. Rep.* **9** 8808
[46] Rahmstorf S 2002 Ocean circulation and climate during the past 120,000 years *Nature* **419** 207–14
[47] Caesar L, McCarthy G D, Thornalley D J R, Cahill N and Rahmstorf S 2021 Current Atlantic meridional overturning circulation weakest in last millennium *Nat. Geosci.* **14** 118–20
[48] Crutzen P and Stoermer E 2000 International geosphere biosphere programme (IGBP) *Newsletter* 41

[49] Rai R and Sahu C K 2020 Driven by data or derived through physics? A review of hybrid physics guided machine learning techniques with cyber-physical system (cps) focus *IEEE Access* **8** 71050–73
[50] Karpatne A, Atluri G, Faghmous J H, Steinbach M, Banerjee A, Ganguly A, Shekhar S, Samatova N and Kumar V 2017 Theory-guided data science: a new paradigm for scientific discovery from data *IEEE Trans. Knowl. Data Eng.* **29** 2318–31
[51] Reichstein M, Camps-Valls G, Stevens B, Jung M, Denzler J and Carvalhais N 2019 Deep learning and process understanding for data-driven Earth system science *Nature* **566** 195–204
[52] Faghmous J H and Kumar V 2014 A big data guide to understanding climate change: the case for theory-guided data science *Big Data* **2** 155–63
[53] Xu T and Valocchi A J 2015 Data-driven methods to improve baseflow prediction of a regional groundwater model *Comput. Geosci.* **85** 124–36
[54] Dietz M *et al* 2022 More than heavy rain turning into fast-flowing water – a landscape perspective on the 2021 Eifel floods *Nat. Hazards Earth Syst. Sci.* **22** 1845–56
[55] Bozzolan E, Holcombe E, Pianosi F and Wagener T 2020 Including informal housing in slope stability analysis–an application to a data-scarce location in the humid tropics *Nat. Hazards Earth Syst. Sci.* **20** 3161–77
[56] Hao Z, Singh V P and Hao F 2018 Compound extremes in hydroclimatology: a review *Water* **10** 718
[57] Zscheischler J, Martius O, Westra S, Bevacqua E, Raymond C, Horton R M, van den Hurk B, AghaKouchak A, Jézéquel A and Mahecha M D 2020 A typology of compound weather and climate events *Nat. Rev. Earth Environ.* **1** 333–47
[58] Raymond C, Horton R M, Zscheischler J, Martius O, AghaKouchak A, Balch J, Bowen S G, Camargo S J, Hess J and Kornhuber K 2020 Understanding and managing connected extreme events *Nat. Clim. Change* **10** 611–21
[59] Hao Z and Singh V P 2020 Compound events under global warming: a dependence perspective *J. Hydrol. Eng.* **25** 03120001
[60] Boers N, Kurths J and Marwan N 2021 Complex systems approaches for Earth system data analysis *J. Phys.: Complex.* **2** 011001
[61] Perez R and Perez M 2015 A fundamental look at energy reserves for the planet *Int. Energy Agency SHC Program. Sol. Updat* (https://iea-shc.org/data/sites/1/publications/2015-11-A-Fundamental-Look-at-Supply-Side-Energy-Reserves-for-the-Planet.pdf)
[62] Solarmap 2021 (https://google.com/search?q=global+solar+energy+distribution&client=firefox-b-e&source=lnms&tbm=isch&sa=X&ved=2ahUKEwjjjYnAzrnyAhWICewKHTdvAnsQ_AUoAnoECAIQBA&biw=1264&bih=573#imgrc=3jhhX0D-D8vxUM)
[63] Shockley W and Queisser H J 1961 Detailed balance limit of efficiency of p-n junction solar cells *J. Appl. Phys.* **32** 510
[64] NREL *Best Research-Cell Efficiency Chart* (https://nrel.gov/pv/cell-efficiency.html) Accessed 13 September 2021.
[65] Stieglitz R and Heinzel V 2012 *Thermische Solarenergie—Grundlagen, Technologie, Anwendungen* (Heidelberg: Springer)
[66] International Technology Roadmap for Photovoltaic (ITRPV) 2020 *Results* 12th edn (https://itrpv.vdma.org/)
[67] Philipps S and Warmuth W 2021 *Photovoltaics Report* (https://ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html) Accessed 27 July 2021

[68] Lee M *et al* 2012 Efficient hybrid solar cells based on meso-superstructured organometal halide perovskites *Science*
[69] Al-Ashouri A *et al* 2020 Monolithic perovskite/silicon tandem solar cell with >29% efficiency by enhanced hole extraction *Science*
[70] Pitz-Paal R 2020 *Concentrating Solar Power in Future Energy* (Amsterdam: Elsevier) 3rd edn pp 413–30
[71] DLR 2021 *German Aerspace Center: Solar Thermal Power Plants, Heat Electricity and Fuels Form Concentrating Solar Power* (https://dlr.de/sf/en/DownloadCount.aspx?raid=533626&docid=13013&rn=adfa4881-0ef9-4df1-b131-7bd11bfb8758)
[72] EASAC 2011 *Concentrating Solar Power: Its Potential Contribution to a Sustainable Energy Future* EASAC Policy Report 16 (European Academies Science Advisory Council EASAC) 2011, Halle (Saale) (https://easac.eu/publications/details/concentrating-solar-power-its-potential-contribution-to-asustainable-energy-future/) Accessed 05 February 2021
[73] IEA 2020 *World Energy Outlook 2020* (Paris: IEA) https://iea.org/reports/world-energy-outlook-2020
[74] Heagel N *et al* 2019 *Terawatt-Scale Photovoltaics: Transform Global Energy* (United States: N.p.) (https://doi.org/10.1126/science.aaw1845)
[75] REN21 2020 *Renewables 2020—Global Status Report* UN Environment Programme, REN21 Secretariat, Paris (https://ren21.net/wp-content/uploads/2019/05/gsr_2020_full_report_en.pdf) Accessed 18 December 2020
[76] Denholm P and Hand M 2011 Grid flexibility and storage required to achieve very high penetration of variable renewable electricity *Energy Policy* (Amsterdam: Elsevier)vol 39 pp 1817–30
[77] IRENA 2020 *Renewable Power Generation Costs in 2019* (Abu Dhabi: International Renewable Energy Agency) https://irena.org/publications/2020/Jun/Renewable-Power-Costs-in-2019)
[78] Solar Energy Technologies Office, U. S. Department of Energy 2017 *The Sunshot 2030 Goals: 3¢ per Kilowatt Hour for PV and 5¢ per Killowatt Hour for Dispatchable CSP. The Sunshot Goals, DOE/EE-1501* (Office of Energy Efficiency & Renewable Energy) (https://energy.gov/sites/prod/files/2020/09/f79/SunShot%202030%20White%20Paper.pdf)
[79] IRENA 2018 *Global Energy Transformation: A Roadmap to 2050* (https://irena.org/publications/2018/Apr/Global-Energy-Transition-A-Roadmap-to-2050)
[80] MCC 2021 *Mercator Research Institute on Global Commons and Climate Change: Remaining Carbon Budget* (https://mcc-berlin.net/forschung/co2-budget.html)
[81] IEA 2021 *Net Zero by 2050, IEA Flagship Report* (https://iea.blob.core.windows.net/assets/beceb956-0dcf-4d73–89fe-1310e3046d68/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf)
[82] Wagner H-J 2018 *Introduction to Wind Energy Systems: Basics, Technology and Operation* (Berlin: Springer) 3rd edn
[83] Vermeiren P, Adriansens W, Moreels J P and Leysen R 1998 The composite Zirfon separator for alkaline water electrolysis *Hydrogen Power: Theoretical and Engineering solutions* (Dordrecht: Springer)
[84] Hall D E 1981 Electrodes for alkaline water electrolysis *J. Electrochem. Soc.* **128** 740
[85] The Engineer 2017 Hot rocks offer solution to grid-scale energy storage *The Engineer* Nov 2017

[86] Santhanam S, Heddrich M P, Riedel M and Friedrich K A 2017 Theoretical and experimental study of reversible solid oxide cell (r-SOC) systems for energy storage *Energy* **141** 202–14
[87] Phase change materials for thermal energy storage | Climate Technology Centre & Network | Tue, 11/08/2016 (ctc-n.org).
[88] advanced-chemistryprize2019.pdf (https://nobelprize.org).
[89] How to prevent short-circuiting in next-gen lithium batteries | MIT News | Massachusetts Institute of Technology
[90] Battery prices have fallen 88 percent over the last decade | Ars Technica
[91] Xu Wangwang and Wang Ying 2019 Recent progress on zinc-ion rechargeable batteries *Nano-Micro Lett.* **11** 90
[92] https://ec.europa.eu/environment/international_issues/relations_china_en.htm
[93] Eddington A 1920 The internal constitution of the stars *Nature* **106** 14
[94] Bethe H A 1939 Energy production in stars *Phys. Rev.* **55** 434
[95] Bigot B 2019 Progress toward ITER's first plasma *Nucl. Fusion* **59** 112001
[96] Progress in ITER Physics Basis 2007 Overview and summary *Nucl. Fusion* **47** S1–S404
[97] Federici G *et al* 2019 Overview of the DEMO staged design approach in Europe *Nucl. Fusion* **59** 066013
[98] Alfvén H 1942 Existence of electromagnetic-hydrodynamic waves *Nature* **150** 405
[99] Huijsmans G T A and Loarte A 2013 Non-linear MHD simulation of ELM energy deposition *Nucl. Fusion* **53** 123023
[100] Giancarli L M *et al* 2020 Overview of recent ITER TBM Program activities *Fusion Eng. Design* **158** 111674
[101] Ibarra A *et al* 2018 The IFMIF-DONES project: preliminary engineering design *Nucl. Fusion* **58** 105002
[102] Classification of Radioactive Waste 2004 *No. GSG-1, General Safety Guide* IAEA.
[103] BP Statistical Review of World Energy 2021 (www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html)
[104] Key World Energy Statistics 2020 International Energy Agency (www.iea.org/reports/key-world-energy-statistics-2020)
[105] IAEA Power Reactor Information System (PRIS) 2021 (pris.iaea.org/PRIS/home.aspx) *IAEA*
[106] Projected Costs of Generating Electricity 2020 (www.iea.org/reports/projected-costs-of-generating-electricity-2020)© *OECD/IEA and OECD/NEA 2020*
[107] Climate Change 2014 *Mitigation of Climate Change—Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)* Cambridge University Press (www.ipcc.ch/report/ar5/wg3/)
[108] Poinssot C *et al* 2014 Assessment of the environmental footprint of nuclear energy systems. Comparison between closed and open fuel cycles *Energy* **69** 199–211
[109] Uranium 2018 *Resources, Production and Demand* (OECD) (www.oecd-nea.org/jcms/pl5080/) *NEA No. 7413*, 2018
[110] Implementation of Defence in Depth 2016 *at Nuclear Power Plants—Lessons Learnt from the Fukushima Daiichi Accident* (OECD) (www.oecd-nea.org/jcms/pl14950)
[111] Human and Organizational 2016 *Aspects of Assuring Nuclear Safety* (IAEA).
[112] Storage and Disposal of Radioactive Waste *2016–2021 World Nuclear Association, Registered in England and Wales, Number 01215741*

[113] Status and Trends in Spent 2018 *Fuel and Radioactive Waste Management* IAEA (www.iaea.org/publications/11173/status-and-trends-in-spent-fuel-and-radioactive-waste-management)
[114] Disposal of Radioactive 2011 *Waste—Specific Safety Requirements No. SSR-5* IAEA (www.iaea.org/publications/8420/disposal-of-radioactive-waste)
[115] StakeHolder-based Analysis 2019–2022 of Research for Decommissioning, share-h2020.eu *Research Funded by Euratom, Grant Agreement ID: 847626*
[116] Nifenecker H, Meplan O and David S 2001 *Accelerator Driven Subcritical Reactors* (Bristol: Institute of Physics Publishing)
[117] Aït Abderrahim H *et al* 2020 Partitioning and transmutation contribution of MYRRHA to an EU strategy for HLW management and main achievements of MYRRHA related FP7 and H2020 projects: MYRTE, MARISA, MAXSIMA, SEARCH, MAX, FREYA, ARCAS *EPJ Nucl. Sci. Technol.* **6** 33
[118] Strategic Research Agenda of EURAD 2019–2024 European Joint Programme on Radioactive Waste Management (www.ejp-eurad.eu/sites/default/files/2020-01/2._eurad_sra.pdf)*Research Funded by Euratom, Grant Agreement ID: 847593*
[119] Climate Change and Nuclear Power 2020 (www.iaea.org/publications/14725/climate-change-and-nuclear-power-2020)
[120] Global Warming 2019 *of 1.5 °C—An IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty* (www.ipcc.ch/sr15/). Intergovernmental Panel on Climate Change.
[121] Net Zero by 2050 2021 *A Roadmap for the Global Energy Sector* (www.iea.org/reports/net-zero-by-2050)
[122] Nuclear Power in a Clean Energy System 2019 International Energy Agency (webstore.iea.org/nuclear-power-in-a-clean-energy-system)
[123] Generation IV International Forum^{SM} (www.gen-4.org)
[124] Sustainable Nuclear Energy Technology Platform (snetp.eu/)
[125] Pakhomov I 2018 BN-600 and BN-800 operating experience *Gen IV International Forum*^{SM} (www.gen4.org/gif/upload/docs/application/pdf/2019-01/gifiv_webinar_pakhomov_19_-dec_2018_final.pdf).
[126] Advances in Small Modular 2020 Reactor Technology Developments—A Supplement to: IAEA Advanced Reactors Information System (ARIS) 2020 edn (aris.iaea.org/sites/Publications.html)
[127] Small Modular Reactors 2021 *Challenges and Opportunities* OECD (www.oecd-nea.org/jcms/pl) (57979/small-modular-reactors-challenges-and-opportunities), NEA No.7560
[128] IPCC 2018 Summary for policymakers *Global Warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty* ed V Masson-Delmotte *et al* (https://ipcc.ch/sr15/chapter/spm/)
[129] United Nations Environment Programme 2019 *Emissions Gap Report 2019* (Nairobi: UNEP)https://unep.org/resources/emissions-gap-report-2019
[130] www.iea.org/data-and-statistics

[131] Hoffmann B 2019 *Air pollution in cities: urban and transport planning determinants and health in cities Integrating Human Health into Urban and Transport Planning* ed M Nieuwenhuijsen and H Khreis (Cham: Springer)
[132] European Environment Agency 2020 *Air Quality in Europe* https://op.europa.eu/en/publication-detail/-/publication/447035cd-344e-11eb-b27b-01aa75ed71a1/language-en
[133] MacKay D J C 2009 *Sustainable Energy—Without the Hot Air* p 231 (http://withouthotair.com/)
[134] European Environment Agency 2020 Monitoring CO2 Emissions From Passenger Cars and Vans in 2018 https://op.europa.eu/en/publication-detail/-/publication/6bac010d-dc45-11ea-adf7-01aa75ed71a1/language-en
[135] WLTP 2017 *Worldwild Harmonised Light Vehicle Test Procedure*
[136] Colclasure A M and Kee R J 2010 Thermodynamically consistent modeling of elementary electrochemistry in lithium-ion batteries *Electrochim. Acta* **55** 8960–73
[137] IEA 2020 *Global EV Outlook 2020* (Paris: IEA) https://iea.org/reports/global-ev-outlook-2020
[138] Bloomberg New Energy Finance 2018 *Electric Buses in Cities Driving Towards Cleaner Air and Lower CO_2* (https://about.bnef.com/blog/electric-buses-cities-driving-towards-cleaner-air-lower-co2/)
[139] https://iea.org/data-and-statistics/charts/new-electric-bus-registrations-in-china-2015–2019
[140] https://wri.org/insights/how-did-shenzhen-china-build-worlds-largest-electric-bus-fleet
[141] https://sustainable-bus.com/fuel-cell-bus/fuel-cell-bus-hydrogen/
[142] IRENA 2019 *Innovation Outlook: Smart Charging for Electric Vehicles* (Abu Dhabi: International Renewable Energy Agency) https://irena.org/publications/2019/May/Innovation-Outlook-Smart-Charging
[143] Tran-Quoc T and Le Pivert X 2016 Stochastic approach to assess impacts of electric vehicles on the distribution network *IEEE PES 3rd Innovative Smart Grid Technologies EUROPE (ISGT Europe) (October 2012) (Berlin, Germany)*
Tuan Tran Q and Van Linh Nguyen L V Integration of electric vehicles into industrial network: impact assessment and solutions *IEEE/PES, General Meeting(17–21 July) (Boston, MA)*
[144] Hautier G 2019 Finding the needle in the haystack: materials discovery and design through computational ab initio high-throughput screening *Comput. Mater. Sci.* **163** 108–16
[145] Curtarolo S, Hart G L W, Nardelli M B, Mingo N, Sanvito S and Levy O 2013 *The high-throughput highway to computational materials design Nat. Mater.* **12** 191–201
[146] Saal J E, Kirklin S, Aykol M, Meredig B and Wolverton C 2013 *Materials design and discovery with high-throughput density functional theory: the open quantum materials database (OQMD) JOM* **65** 1501–9
[147] Cheng L *et al* 2015 Accelerating electrolyte discovery for energy storage with high-throughput screening *J. Phys. Chem. Lett.* **6** 283–91
[148] Aykol M *et al* 2016 High-throughput computational design of cathode coatings for Li-ion batteries *Nat. Commun.* **7** 13779
[149] Hautier G *et al* 2011 Phosphates as lithium-ion battery cathodes: an evaluation based on high-throughput ab initio calculations *Chem. Mater.* **23** 3495–508
[150] Wallace S K, Bochkarev A S, van Roekeghem A, Carrasco J, Shapeev A and Mingo N 2021 Free energy of $(CoxMn_{1-x})_3O_4$ mixed phases from machine-learning-enhanced ab initio calculations *Phys. Rev. Mater.* **5** 035402

[151] Wallace S K, van Roekeghem A, Bochkarev A S, Carrasco J, Shapeev A and Mingo N 2021 Modeling the high-temperature phase coexistence region of mixed transition metal oxides from ab initio calculations *Phys. Rev. Res.* **3** 013139
[152] Gubaev K, Podryabinkin E V, Hart G L W and Shapeev A V 2019 Accelerating high-throughput searches for new alloys with active learning of interatomic potentials *Comput. Mater. Sci.* **156** 148–56
[153] Novikov I S, Gubaev K, Podryabinkin E V and Shapeev A V 2021 The MLIP package: moment tensor potentials with MPI and active learning *Mach. Learn.: Sci. Technol.* **2** 025002
[154] Chandesris M, Caliste D, Jamet D and Pochet P 2019 Thermodynamics and related kinetics of staging in intercalation compounds *J. Phys. Chem.* C **123** 23711–20
[155] Onsager L 1931 Reciprocal relations in irreversible processes I *Phys. Rev.* **37** 405–26
[156] Feng X, Ouyang M, Liu X, Lu L, Xia Y and He X 2018 Thermal runaway mechanism of lithium ion battery for electric vehicles: a review *Energy Storage Mater.* **10** 246–67
[157] Lopez-Haro M, Guetaz L, Printemps T, Morin A, Escribano S, Jouneau P H, Bayle-Guillemaud P, Chandezon F and Gebel G 2014 Three-dimensional analysis of Nafion layers in fuel cell electrodes *Nat. Commun.* **5** 5229
[158] Dupre N, Moreau P, De Vito E, Quazuguel L, Boniface M, Bordes A, Rudisch C, Bayle-Guillemaud P and Guyomard D 2016 Multiprobe study of the solid electrolyte interphase on silicon-based electrodes in full-cell configuration *Chem. Mater.* **28** 2557–72
[159] Leriche J B *et al* 2010 An electrochemical cell for operando study of lithium batteries using synchrotron radiation *J. Electrochem. Soc.* **157** A606–10
[160] Tonin G, Vaugham G B M, Bouchet R, Allouin F, Di Michiel M and Barchasz C Operando investigation of the lithium/sulfur battery system by coupled x-ray absorption tomography and x-ray diffraction computed tomography *J. Power Sources* **468** 228287
[161] Bianchini M, Leriche J B, Laborier J L, Gendrin L, Suard E, Croguennec L and Masquelier C 2013 A new null matrix electrochemical cell for rietveld refinements of in situ or operando neutron powder diffraction data *J. Electrochem. Soc.* **160** A2176–83
[162] Tardif S, Dufour N, Colin J F, Gebel G, Burghammer M, Johannes A, Lyonnard S and Chandesris M 2021 Combining operando x-ray experiments and modelling to understand the heterogeneous lithiation of graphite electrodes *J. Mater. Chem.* A **9** 4281–90
[163] Tripathi A M, Wei-Nien Su W N and Hwang B J 2018 In situ analytical techniques for battery interface analysis *Chem. Rev. Soc.* **47** 736–851
[164] Benayad A, Morales-Ugarte J E, Santini C C, Bouchet R and Operando X P S 2021 A novel approach for probing the lithium/electrolyte interphase dynamic evolution *J. Phys. Chem.* A **125** 1069–81
[165] Satija R, Jacobson D L, Arif M and Werner S A 2004 In situ neutron imaging technique for evaluation of water management systems in operating PEM fuel cells *J. Power Sources* **129** 238–45
[166] Xu F, Diat O, Gebel G and Morin A 2007 Determination of transverse water concentration profile through MEA in a fuel cell using neutron scattering *J. Electrochem. Soc.* **154** B1389–98
[167] Martinez N, Porcar L, Escribano S, Micoud F, Rosini S, Tengattini A, Atkins D, Gebel G, Lyonnard S and Morin A 2019 Combined operando high resolution SANS and neutron imaging reveals in situ local water distribution in an operating fuel cell *ACS Appl. Energy Mater.* **2** 8425–33

[168] IEA 2019 *The Future of Hydrogen* (Paris: IEA) https://iea.org/reports/the-future-of-hydrogen
[169] The Royal Society 2019 *Sustainable Synthetic Carbon Based Fuels for Transport* (https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/sustainable-synthetic-carbon-based-fuels-for-transport/)
[170] Geelen L H W T, Kamps P T W J and Olsthoorn T N 2017 From overexploitation to sustainable use, an overview of 160 years of water extraction in the Amsterdam dunes, the Netherlands *J. Coast Conserv.* **21** 657–68
[171] Paull J 2009 A century of synthetic fertilizer: 1909–2009 *Element.—J. Bio-Dynam. Tasmania* **94** 16–20
[172] Binetti R, Costamagna F M and Marcello I 2008 Exponential growth of new chemicals and evolution of information relevant to risk control *Ann. Ist Super Sanità* **44** 13–5
[173] Daley J 2017 Science is falling woefully behind in testing new chemicals *Smithsonian Magazine*
[174] United Nations Environment Assembly of the United Nations Environment Programme (UNEP) 2019 *Global Chemicals Outlook II: Summary for Policymakers* (Geneva, Switzerland: UNEP/EA.4/21, UNEP)
[175] Card M L, Gomez-Alvarez V, Lee W-H, Lynch D G, Orentas N J, Lee M T, Wong E M and Boethling R S 2017 History of EPI Suite™ and future perspectives on chemical property estimation in US Toxic Substances Control Act new chemical risk assessments *Environ. Sci.: Processes Impacts* **19** 203–12
[176] Matthies M, Solomon K, Vighi M, Gilman A and Tarazona J V 2016 The origin and evolution of assessment criteria for persistent, bioaccumulative and toxic (PBT) chemicals and persistent organic pollutants (POPs) *Environ. Sci.: Processes Impacts* **18** 1114–28
[177] Allen J G These toxic chemicals are everywhere—even in your body. And they won't ever go away, 'Opinions' article published in the *Washington Post* 02 January 2018 (https://washingtonpost.com/opinions/these-toxic-chemicals-are-everywhere-and-they-wont-ever-go-away/2018/01/02/82e7e48a-e4ee-11e7-a65d-1ac0fd7f097e_story.html) (Accessed 15 March 2021)
[178] Gouin T, Mackay D, Jones K C, Harner T and Meijer S N 2004 Evidence for the 'grasshopper' effect and fractionation during long-range atmospheric transport of organic contaminants *Environ. Pollut.* **128** 139–48
[179] Fiedler H, Kallenborn R, de Boer J and Sydnes L K 2019 The Stockholm convention: a tool for the global regulation of persistent organic pollutants *Chem. Int.* **41** 4–11
[180] Sontake A R and Wagh S M 2014 The phase-out of perfluorooctane sulfonate (PFOS) and the global future of aqueous film forming foam (AFFF), innovations in fire fighting foam *Chem. Eng. Sci.* **2** 11–4
[181] Holmquist P H, Schellenberger S, van der Veen I, Peters G M, Leonards P E G and Cousins I T 2016 Properties, performance and associated hazards of state-of-the-artdurable water repellent (DWR) chemistry for textile finishing *Environ. Intern.* **91** 251–24
[182] Brandsma S H, Koekkoek J C, van Velzen M J M and de Boer J 2019 The PFOA alternative substitute GenX detected in grass and leaves near a fluoropolymer manufactory plant in the Netherlands *Chemosphere* **220** 493–500
[183] Cousins I T *et al* 2019 The concept of essential use for determining when uses of PFASs can be phased out *Environ. Sci.: Processes Impacts* **21** 1803–15

[184] de Boer J and Stapleton H M 2019 Toward fire safety without chemical risk *Science* **364** 231–2
[185] Autrup H *et al* 2020 Human exposure to synthetic endocrine disrupting chemicals (S-EDCs) is generally negligible as compared to natural compounds with higher or comparable endocrine activity. How to evaluate the risk of the S-EDCs? *Arch.Toxicol.* **94** 2549–57
[186] Zoeller R T *et al* 2014 A path forward in the debate over health impacts of endocrine disrupting chemicals *Environ. Health* **13** 118
[187] Daughton C G and Ternes T A 1999 Pharmaceuticals and personal care products in the environment: agents of subtle change? *Environ. Health Persp.* **107** 906–10
[188] Legler J and van Straalen N 2018 Decision-making in a storm of discontent *Science* **360** 958–60
[189] Blaquière T, Smagghe G, van Gestel C A M and Mommaerts V 2012 Neonicotinoids in bees: a review on concentrations, side-effects and risk assessment *Ecotoxicol* **21** 973–92
[190] Walters R 2010 Toxic atmospheres air pollution, trade and the politics of regulation *Crit. Crim.* **18** 307–23
[191] Skoczynska E 2021 Development and appliucation of comprehensive chemical analytical; methods for the analysis of polyaromatic compounds *PhD Thesis* Vrije Universiteit, Amsterdam, The Netherlands p 190
[192] Hassaan M A and El Nemr A 2017 Health and environmental impacts of dyes: mini review *Am. J. Environ. Sci. Eng.* **1** 64–7
[193] Kdasi A, Idris A, Saed K and Guan C T 2004 Treatment of textile wastewater by advanced oxidation processes: a review *Global Nest. Int.* J **6** 222–30
[194] Mohan V, Rao C and Karthikeyan J 2002 Adsorptive removal of direct azo dye from aqueous phase onto coal based sorbents: a kinetic and mechanistic study *J. Hazard. Mater.* **90** 189–204
[195] Wallington T J, Srinivasan J, Nielsen O J and Highwood E J 2009 Greenhouse gases and global warming *Environmental and Ecological Chemistry* ed A Sablic (Oxford: Eolss Publ. Co. Ltd)vol 1
[196] Plummer L N and Busenberg E 2000 Chlorofluorocarbons *Environmental Tracers in Subsurface Hydrology* ed P G Cook and A L Herczeg (Boston, MA: Springer)
[197] Birmpili T 2018 Montreal Protocol at 30: the governance structure, the evolution, and the Kigali Amendment *C. R. Geosci.* **350** 425–31
[198] Molina M J and Rowland F S 1974 Stratospheric sink for chlorofluoromethanes: chlorine atom-catalysed destruction of ozone *Nature* **249** 810–2
[199] Crutzen P J 1970 The influence of nitrogen oxides on the atmospheric ozone content *R. Meteorol. Suc. Quart. J.* **96** 320–5
[200] Rowland F S 1996 Stratospheric ozone Depletion by chlorofluorocarbons (Nobel lecture) *Angew. Chem. Int. Ed. Engl.* **35** 1786–98
[201] McKenzie R, Bernhard G and Liley B *et al* 2019 Success of Montreal Protocol demonstrated by comparing high-quality UV measurements with 'World Avoided' calculations from two chemistry-climate models *Sci. Rep.* **9** 12332
[202] Montzka S A, Velders G J M, Krummel P B, Mühle J, Orkin V L, Park S, Shah N, H and Walter-Terrinoni 2018 Hydrofluorocarbons *Scientific Assessment of Ozone Depletion, Ch. 2: Global Ozone Research and Monitoring Project-Report No. 58* (Geneva: Chemical Sciences Laboratory)

[203] Flerlage H, Velders G J M and de Boer. J 1992 A review of bottom-up and top-down emission estimates of hydrofluorocarbon(HFCs) in different parts of the worlds *Chemosphere* **283** 131208
[204] Fujika M and Tajima S The pollution of Minamata Bay by mercury *Water Sci. Technol.* **25** 133–40
[205] de Boer M A and Lammertsma K 2013 Scarcity of reare earth elements *ChemSusChem* **6** 2045–55 2013
[206] Boekhout van Solinge T 2008 Crime, conflicts and ecology in Africa *Global Harms: Ecological Crime and Speciesism* ed T Sollund (Nova Science Publ.) pp 13–35
[207] Aoun M, El Samrani A G, Lartiges B S, Kazpard V and Saad Z 2010 Releases of phosphate fertilizer industry in the surrounding environment: Investigation on heavy metals and polonium-210 in soil *J. Environ. Sci.* **22** 1387–97
[208] Zagà V, Lygidakis C, Chaouachi K and Gattavecchia E 2011 Polonium and lung cancer *J. Oncol.* **2011** 860103
[209] Day R H 1980 The occurrence and characteristics of plastic pollution in Alaska's marine birds *M.S. Thesis* University of Alaska. Fairbanks, AK, USA p 111
[210] Moore C J, Moore S L, KLeecaster M and Weisberg S B 2001 A comparison of plastic and Plankton in the North Pacific Central Gyre *Mar. Pollut. Bull.* **42** 1297–300
[211] Law K L 2017 Plastics in the environment *Ann. Rev. Mar. Sci.* **9** 205–29
[212] Landrigan P 2017 Air pollution and health *Lancet* **2** E4–5
[213] Lelieveld J, Evans J S, Fnais M, Giannadaki D and Pozzer A 2015 The contribution of outdoor air pollution sources to premature mortality on a global scale *Nature* **525** 367–71
[214] Kriebel D, Tickner J, Epstein P, Lemons J, Levins R, Loechler E L, Quinn M, Rudel R, Schettler T and Stoto M 2001 The precautionary principle in environmental science *Environ. Health Perspect.* **109** 871–6
[215] Hendriks H S, Meijer M, Muilwijk M, Van den Berg M and Westerink R H S 2014 A comparison of the *in vitro* cyto- and neurotoxicity of brominated and halogen-free flame retardants: prioritization in search for safe(r) alternatives *Arch. Toxicol.* **88** 857–69
[216] Hák T, Janoušková S and Moldan B 2016 Sustainable development goals: a need for relevant indicators *Ecol. Indic.* **60** 565–73
[217] Stafford-Smith M, Griggs D, Gaffney O, Ullah F, Reyers B, Kanie N, Stigson B, Shrivastava P, Leach M and O'Connell D 2017 Integration: the key to implementing the sustainable development goals *Sustain. Sci.* **12** 911–9
[218] EPA 2019 Chemical safety for sustainability national research program strategic research action plan 2019–2022 *Office of Research and Development Chemical Safety for Sustainability, No. CSS FY2019-FY2022 StRAP* (Washington DC: EPA)
[219] https://www.mondaq.com/china/chemicals/775388/china-publishes-draft-regulation-on-the-environmental-risk-assessment-and-control-of-chemical-substances-the-real-china-reach
[220] Robinson R M and Behnke R A 2001 *The U.S. National Space Weather Program: A retrospective* (Washington, DC: American Geophysical Union Geophysical Monograph Series)125 10
[221] Hapgood M A 2011 Towards a scientific understanding of the risk from extreme space weather *Adv. Space Res.* **47** 2059–72
[222] Schrijver C J *et al* 2015 Understanding space weather to shield society: a global road map for 2015–2025 commissioned by COSPAR and ILWS *Adv. Space Res.* **55** 2745–807

[223] Green L and Baker D 2015 Coronal mass ejections: a driver of severe space weather *Weather* **70** 31–5
[224] Richardson I G, Cliver E W and Cane H V 2001 Sources of geomagnetic storms for solar minimum and maximum conditions during 1972–2000 *Geophys. Res. Lett.* **28** 2569–72
[225] National Academies Press 2008 *Severe Space Weather Events–Understanding Societal and Economic Impacts* (National Academies Press)
[226] Kreutzer R 2009 Space weather *Global Risk Dialogue* (Berlin: Springer) pp 12–7
[227] Eastwood J P, Biffis E, Hapgood M A, Green L, Bisi M M, Bentley R D, Wicks R, McKinnell L A, Gibbs M and Burnett C 2017 The economic impact of space weather: where do we stand *Risk Anal.* **37** 206–18
[228] Cannon P S 2013 Extreme space weather—a report published by the UK Royal Academy of Engineering *Space Weather* **11** 138–9
[229] Pete R 2012 On the probability of occurrence of extreme space weather events *Space Weather* **10** 02012
[230] Schrijver C J, Dobbins R, Murtagh W and Petrinec S M 2014 Assessing the impact of space weather on the electric power grid based on insurance claims for industrial electrical equipment *Space Weather* **12** 487–98
[231] Howard J W Jr and Hardage D M 1999 Spacecraft environments interactive: space radiation and its effects on electronic system *Technical Report, NASAs* https://ntrs.nasa.gov/citations/19990116210
[232] https://euweather.eu/stations_stats.php?en
[233] Odstrcil D 2003 Modeling 3-D solar wind structure *Adv. Space Res.* **32** 497–506
[234] Pomoell J and Poedts S 2018 EUHFORIA: European heliospheric forecasting information asset *J. Space Weather Space Clim.* **8** A35
[235] Poedts S *et al* 2020 The virtual space weather modelling centre *J. Space Weather Space Clim.* **10** 14
[236] Vainio R and Laitinen T 2007 Monte Carlo simulations of coronal diffusive shock acceleration in self-generated turbulence *Astrophys. J.* **658** 622–30
[237] Afanasiev A, Battarbee M and Vainio R 2015 Self-consistent Monte Carlo simulations of proton acceleration in coronal shocks: effect of anisotropic pitch-angle scattering of particles *Astron. Astrophys.* **584** A81
[238] Pomoell J, Aran A, Jacobs C, Rodrguez-Gasén R, Poedts S and B S 2015 Modelling large solar proton events with the shock-and-particle model. Extraction of the characteristics of the MHD shock front at the cobpoint *J. Space Weather Space Clim.* **5** A12
[239] Wijsen N, Aran A, Sanahuja B, Pomoell J and Poedts S 2020 The effect of drifts on the decay phase of SEP events *Astron. Astrophys.* **634** A82
[240] Wijsen N, Samara E, Aran À, Lario D, Pomoell J and Poedts S 2021 A self-consistent simulation of proton acceleration and transport near a high-speed solar wind stream *Astrophys. J. Lett.* **908** L26
[241] Lakka A, Pulkkinen T I, Dimmock A P, Kilpua E, Ala-Lahti M, Honkonen I, Palmroth M and Raukunen O 2019 GUMICS-4 analysis of interplanetary coronal mass ejection impact on Earth during low and typical Mach number solar winds *Ann. Geophys.* **37** 561–79
[242] Eggington J W B, Eastwood J P, Mejnertsen L, Desai R T and Chittenden J P 2020 Dipole tilt effect on magnetopause reconnection and the steady-state magnetosphere-ionosphere system: global MHD simulations *J. Geophys. Res. (Space Phys.)* **125** e27510

[243] Pierrard V and Voiculescu M 2011 The 3D model of the plasmasphere coupled to the ionosphere *Geophys. Res. Lett.* **38** L12104
[244] Bourdarie S A and Maget V F 2012 Electron radiation belt data assimilation with an ensemble Kalman filter relying on the Salammbô code *Ann. Geophys.* **30** 929–43
[245] cf http://ccmc.gsfc.nasa.gov/
[246] https://clasp.engin.umich.edu/research/theory-computational-methods/center-for-space-environment-modeling/
[247] Raeder J, Larson D, Li W, Kepko E L and Fuller-Rowell T 2008 OpenGGCM simulations for the THEMIS mission *Space Sci. Rev.* **141** 535–55
[248] Opgenoorth H J *et al* 2019 Assessment and recommendations for a consolidated European approach to space weather—as part of a global space weather effort *J. Space Weather Space Clim.* **9** A37
[249] Scolini C, Rodriguez L, Mierla M, Pomoell J and Poedts S 2019 Observation-based modelling of magnetised coronal mass ejections with EUHFORIA *Astron. Astrophys.* **626** A122
[250] Scolini C *et al* 2020 CME-CME interactions as sources of CME geoeffectiveness: the formation of the complex ejecta and intense geomagnetic storm in 2017 Early September *Astrophys. J. Suppl.* **247** 21
[251] Kilpua E K J, Olspert N, Grigorievskiy A, Käpylä M J, Tanskanen E I, Miyahara H, Kataoka R, Pelt J and Liu Y D 2015 Statistical study of strong and extreme geomagnetic disturbances and solar cycle characteristics *Astrophys. J.* **806** 272
[252] Horwitz J L, Gallagher D L and Peterson W K 1998 *Geospace Mass and Energy Flow: Results from the International Solar-Terrestrial Physics Program* (Washington, DC: American Geophysical Union Geophysical Monograph Series) p 104
[253] Lilensten J *et al* 2021 Quo vadis, European Space Weather community? *J. Space Weather Space Clim.* **11** 26
[254] Antiochos S K, DeVore C R and Klimchuk J A 1999 A model for solar coronal mass ejections *Astrophys. J.* **510** 485–93
[255] Lodders K 2003 Solar system abundances and condensation temperatures of the elements *Astrophys. J.* **591** 1220–47
[256] Reames D V 1999 Particle acceleration at the Sun and in the heliosphere *Space Sci. Rev.* **90** 413–91
[257] Daly E J 2001 *ESA Space Weather Activities* ed I A Daglis (Hazards: Space Storms and Space Weather) p 459
[258] https://cordis.europa.eu/

Chapter 7

[1] Feynman R P 1982 Simulating physics with computers *Int. J. Theor. Phys.* **21** 467
[2] Nielsen M A and Chuang I L 2011 *Quantum Computation and Quantum Information: 10th Anniversary Edition* 10th edn (New York: Cambridge University Press)
[3] Aaronson S 2013 *Quantum Computing Since Democritus* (New York: Cambridge University Press)
[4] Arute F *et al* 2019 Quantum supremacy using a programmable superconducting processor *Nature* **574** 505
[5] Zhong H-S *et al* 2020 Quantum computational advantage using photons *Science* **370** 1460

[6] Wu Y *et al* 2021 Strong quantum computational advantage using a superconducting quantum processor *Phys. Rev. Lett.* **127** 180501
[7] Preskill J 2018 Quantum computing in the NISQ era and beyond *Quantum* **2** 79
[8] Bharti K *et al* 2021 Noisy intermediate-scale quantum (NISQ) algorithms *Rev. Mod. Phys.* **94** 015004
[9] Montanaro A 2016 Quantum algorithms: an overview *npj Quantum Inf.* **2** 15023
[10] Bauer B, Bravyi S, Motta M and Chan G K-L 2020 Quantum algorithms for quantum chemistry and quantum materials science *Chem. Rev.* **120** 12685
[11] Biamonte J, Wittek P, Pancotti N, Rebentrost P, Wiebe N and Lloyd S 2017 Quantum machine learning *Nature* **549** 195
[12] Blais A, Girvin S M and Oliver W D 2020 Quantum information processing and quantum optics with circuit quantum electrodynamics *Nat. Phys.* **16** 247
[13] Blatt R and Roos C F 2012 Quantum simulations with trapped ions *Nat. Phys.* **8** 277
[14] Browaeys A and Lahaye T 2020 Many-body physics with individually controlled Rydberg atoms *Nat. Phys.* **16** 132
[15] Einstein A, Podolsky B and Rosen N 1935 Can quantum-mechanical description of physical reality be considered complete? *Phys. Rev.* **47** 777
[16] Bell J S 1964 On the Einstein Podolsky Rosen paradox *Phys. Phys. Fiz.* **1** 195
[17] Aspect A, Grangier P and Roger G 1982 Experimental realization of Einstein–Podolsky–Rosen–Bohm Gedanken experiment: a new violation of Bell's inequalities *Phys. Rev. Lett.* **49** 91
[18] DiVincenzo D P 1995 Two-bit gates are universal for quantum computation *Phys. Rev.* A **51** 1015
[19] Deutsch D 1985 Quantum theory, the Church–Turing principle and the universal quantum computer *Proc. R. Soc.* A **400** 97
[20] Kirkpatrick S, Gelatt C D and Vecchi M P 1983 Optimization by simulated annealing *Science* **220** 671
[21] Deutsch D and Jozsa R 1992 Rapid solution of problems by quantum computation *Proc. R. Soc.* A **439** 553
[22] Simon D 1994 Proc. 35th Annu. Symp. Found. Comput. Sci. (IEEE Comput. Soc. Press) pp 116–23
[23] Shor P 1994 Proc. 35th Annu. Symp. Found. Comput. Sci. (IEEE Comput. Soc. Press) pp 124–34
[24] Kitaev A Y 1995 Quantum measurements and the Abelian Stabilizer Problem ArXiv: quant-ph/9511026
[25] Grover L K 1996 *Proc. 28th Annual ACM Symp. Theory Comput.—STOC'96* (New York: ACM Press) pp 212–9
[26] Brassard G, Hoyer P, Mosca M and Tapp A 2000 Quantum amplitude amplification and estimation ArXiv: 0005055 [quant-ph]
[27] Das A and Chakrabarti B K 2008 Colloquium: quantum annealing and analog quantum computation *Rev. Mod. Phys.* **80** 1061
[28] Tang E 2019 *Proc. 51st Annu. ACM SIGACT Symp. Theory Comput* (New York: ACM) pp 217–28
[29] Wootters W K and Zurek W H 1982 A single quantum cannot be cloned *Nature* **299** 802
[30] Shor P W 1995 Scheme for reducing decoherence in quantum computer memory *Phys. Rev.* A **52** R2493

[31] Steane A M 1996 Error correcting codes in quantum theory *Phys. Rev. Lett.* **77** 793
[32] Shor P W 1996 Fault-tolerant quantum computation ArXiv: quant-ph/9605011
[33] DiVincenzo D P 2000 The physical implementation of quantum computation *Fortschr. Phys.* **48** 771
[34] McMichael R D https://nist.gov/programs-projects/diamond-nv-center-magnetometry (Accessed 19 July 2021)
[35] Wang J *et al* 2018 Multidimensional quantum entanglement with large-scale integrated optics *Science* **360** 285
[36] Ladd T D, Jelezko F, Laflamme R, Nakamura Y, Monroe C and O'Brien J L 2010 Quantum computers *Nature* **464** 45
[37] Cirac J I and Zoller P 1995 Quantum computations with cold trapped ions *Phys. Rev. Lett.* **74** 4091
[38] Shnirman A, Schoen G and Hermon Z 1997 Quantum manipulations of small Josephson junctions *Phys. Rev. Lett.* **79** 2371
[39] Jaksch D, Cirac J I, Zoller P, Rolston S L, Coˆte´ R and Lukin M D 2000 Fast quantum gates for neutral atoms *Phys. Rev. Lett.* **85** 2208
[40] Loss D and DiVincenzo D P 1998 Quantum computation with quantum dots *Phys. Rev.* A **57** 120
[41] Nizovtsev A P 2005 A quantum computer based on NV centers in diamond: optically detected nutations of single electron and nuclear spins *Opt. Spectrosc.* **99** 233
[42] Knill E, Laflamme R and Milburn G J 2001 A scheme for efficient quantum computation with linear optics *Nature* **409** 46
[43] Gershenfeld N A and Chuang I L 1997 Bulk spin-resonance quantum computation *Science* **275** 350
[44] Kane B E 1998 A silicon-based nuclear spin quantum computer *Nature* **393** 133
[45] Kitaev A 2003 Fault-tolerant quantum computation by anyons *Ann. Phys. (N. Y).* **303** 2
[46] Brooke J 1999 Quantum annealing of a disordered magnet *Science* **284** 779
[47] Raussendorf R and Briegel H J 2001 A one-way quantum computer *Phys. Rev. Lett.* **86** 5188
[48] Born M and Jordan P 1925 Zur quantenmechanik *Z. Phys.* **34** 858–88
[49] Benioff P 1980 The computer as a physical system: a microscopic quantum mechanical hamiltonian model of computers as represented by turing machines *J. Stat. Phys.* **22** 563–91
[50] Feynman R P 1985 Quantum mechanical computers *Optics News* **11** 11–20
[51] Yuri M 1980 *Vychislimoe i nevychislimoe [Computable and Uncomputable]* (original in Russian: Soviet Radio)
[52] Deutsch D 1985 Quantum theory, the Church—turing principle and the universal quantum computer *Proc. Royal Soc. Lond. Ser. A, Math. Phys. Sci.* **400** 97–117
[53] Lloyd S 1996 Universal quantum simulators *Science* **273** 1073–8
[54] Deutsch D and Jozsa R 1992 Rapid solution of problems by quantum computation *Proc. Royal Soc. Lond. Ser. A, Math. Phys. Sci.* **439** 553–8
[55] Simon D R 1997 On the power of quantum computation *SIAM J. Comput.* **26** 1474–83
[56] Shor P W 1997 Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer *SIAM J. Comput.* **26** 1484–509
[57] Grover L K 1996 A fast quantum mechanical algorithm for database search Proc. of the 28th Annual ACM Symp. on Theory of Computing pp 212–9

[58] Bennett C H, Bernstein E, Brassard G and Vazirani U 1997 Strengths and weaknesses of quantum computing *SIAM J. Comput.* **26** 1510–23
[59] Aaronson S 2015 Read the fine print *Nat. Phys.* **11** 291–3
[60] Harrow A W, Hassidim A and Lloyd S 2009 Quantum algorithm for linear systems of equations *Phys. Rev. Lett.* **103** 150502
[61] Morales M E S, Tlyachev T and Biamonte J 2018 Variational learning of grover's quantum search algorithm *Phys. Rev.* A **98** 062333
[62] Farhi E, Goldstone J and Gutmann S 2014 A quantum approximate optimization algorithm arXiv:1411.4028
[63] Bravo-Prieto C, LaRose R, Cerezo M, Subasi Y, Cincio L and Coles P J 2020 Variational quantum linear solver arXiv:1909.05820
[64] Lubasch M, Joo J, Moinier P, Kiffner M and Jaksch D 2020 Variational quantum algorithms for nonlinear problems *Phys. Rev.* A **101** 010301
[65] Yung M-H, Casanova J, Mezzacapo A, McClean J, Lamata L, Aspuru-Guzik A and Solano E 2014 From transistor to trapped-ion computers for quantum chemistry *Sci. Rep.* **4** 3589
[66] Peruzzo A, McClean J, Shadbolt P, Yung M-H, Zhou X-Q, Love P J, Aspuru-Guzik A and O'brien J L 2014 A variational eigenvalue solver on a photonic quantum processor *Nat. Commun.* **5** 4213
[67] Biamonte J 2021 Universal variational quantum computation *Phys. Rev.* A **103** L030401
[68] Biamonte J D, Dorozhkin P and Zacharov I 2019 Keep quantum computing global and open *Nature* **573** 190–1
[69] Arute F *et al* 2019 Quantum supremacy using a programmable superconducting processor *Nature* **574** 505–10
[70] Zhong H-S *et al* 2020 Quantum computational advantage using photons *Science* **370** 1460–3
[71] Schumacher B 1995 Quantum coding *Phys. Rev.* A **51** 2738–47
[72] Bruzewicz C D, Chiaverini J, McConnell R and Sage J M 2019 Trapped-ion quantum computing: Progress and challenges *Appl. Phys. Rev.* **6** 021314
[73] Kok P, Munro W J, Nemoto K, Ralph T C, Dowling J P and Milburn G J 2007 Linear optical quantum computing with photonic qubits *Rev. Mod. Phys.* **79** 135–74
[74] Nielsen M A and Chuang I L 2009 *Quantum Computation and Quantum Information* (Cambridge University Press)
[75] Shor P W 1996 Fault-tolerant quantum computation Proc. of 37th Conf. on Foundations of Computer Science (IEEE Comput. Soc. Press)
[76] Shor P W 1995 Scheme for reducing decoherence in quantum computer memory *Phys. Rev.* A **52** R2493–6
[77] Georgescu I 2020 25 years of quantum error correction *Nat. Rev. Phys.* **2** 519 519
[78] Farhi E, Goldstone J, Gutmann S, Lapan J, Lundgren A and Preda D 2001 A quantum adiabatic evolution algorithm applied to random instances of an np-complete problem *Science* **292** 472–5
[79] Aharonov D, van Dam W, Kempe J, Landau Z, Lloyd S and Regev O 2008 Adiabatic quantum computation is equivalent to standard quantum computation *SIAM Rev.* **50** 755–87
[80] Childs A M 2009 Universal computation by quantum walk *Phys. Rev. Lett.* **102** 180501

[81] Lovett N B, Cooper S, Everitt M, Trevers M and Kendon V 2010 Universal quantum computation using the discrete-time quantum walk *Phys. Rev.* A **81** 042330
[82] Van den Nest M, Miyake A, Dür W and Briegel H J 2006 Universal resources for measurement-based quantum computation *Phys. Rev. Lett.* **97** 150504
[83] Harrow A W and Montanaro A 2017 Quantum computational supremacy *Nature* **549** 203–9
[84] Preskill J 2018 Quantum computing in the nisq era and beyond *Quantum* **2** 79
[85] Waldrop M M 2016 The chips are down for Moore's law *Nature* **530** 144–7
[86] Biamonte J, Wittek P, Pancotti N, Rebentrost P, Wiebe N and Lloyd S 2017 Quantum machine learning *Nature* **549** 195–202
[87] Pande M and Mulay P 2020 Bibliometric survey of quantum machine learning *Sci. Technol. Libr.* **39** 369–82
[88] Seskir Z C and Aydinoglu A U 2021 The landscape of academic literature in quantum technologies *Int. J. Quantum Inform.* **19** 2150012
[89] van Eck N J and Waltman L 2009 Software survey: Vosviewer, a computer program for bibliometric mapping *Scientometrics* **84** 523–38
[90] Watkins G P and Knight F H 1922 Knight's risk, uncertainty and profit *Quart. J. Econ.* **36** 682
[91] DiVincenzo D P 2017 Scientists and citizens: getting to quantum technologies *Ethics Inform. Technol.* **19** 247–51
[92] Möller M and Vuik C 2017 On the impact of quantum computing technology on future developments in high-performance scientific computing *Ethics Inform. Technol.* **19** 253–69
[93] Coenen C and Grunwald A 2017 Responsible research and innovation (rri) in quantum technology *Ethics Inform. Technol.* **19** 277–94
[94] de Wolf R 2017 The potential impact of quantum computers on society *Ethics Inform. Technol.* **19** 271–6
[95] Johnson W S 1883 Electric tele-thermoscop *US Patent* 281,884
[96] Schütze A, Helwig N and Schneider T 2018 Sensors 4.0—smart sensors and measurement technology enable industry 4.0 *J. Sensors Sensor Syst.* **7** 359–71
[97] Bentley J P 1995 *Principles of Measurement Systems* (New York: Longman Publishing Group) 3rd edn
[98] Wilson J S 2005 *Sensor Technology Handbook* (Amsterdam: Elsevier)
[99] Taylor J R 1996 *An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements* (Mill Valley, CA: University Science Books)
[100] Fink J K 2012 *Polymeric Sensors and Actuators* (New York: Wiley)
[101] Simmons E E 1940 Material testing apparatus *US Patent* 2,350,972
[102] Ruge A C 1939 Strain gauge *US Patent* 2,350,972
[103] Wasley R J, Hoge K G and Cast J C 1969 Combined strain gauge—quartz crystal instrumented hopkinson split bar *Rev. Sci. Instrum.* **40** 889–94
[104] Barbour N and Schmidt G 2001 Inertial sensor technology trends *IEEE Sens. J.* **1** 332–9
[105] Narayanaswamy R and Wolfbeis O S 2004 *Optical Sensors* (Berlin: Springer)
[106] Santos J and Farahi F 2014 *Handbook of Optical Sensors* (Boca Raton, FL: CRC Press)
[107] Jain Y K, Alex T K and Kalakrishnan B 1980 Ultimate ir horizon sensor *IEEE Trans. Aerospace Electron. Syst.* **16** 233–8
[108] Casas J R and Cruz P J S 2003 Fiber optic sensors for bridge monitoring *J. Bridge Eng.* **8** 362–73

[109] García I, Zubia J, Durana G, Aldabaldetreku G, Illarramendi M A and Villatoro J 2015 Optical fiber sensors for aircraft structural health monitoring *Sensors (Switzerland)* **15** 15494–519
[110] Udd E and Spillman W B 2011 *Fiber Optic Sensors: An Introduction for Engineers and Scientists* 2nd edn (New York: Wiley)
[111] Lee B H, Kim Y H, Park K S, Eom J B, Kim M J, Rho B S and Choi H Y 2012 Interferometric fiber optic sensors *Sensors* **12** 2467–86
[112] Baldini F and Mignani A G 2002 Optical-fiber medical sensors *MRS Bull.* **27** 383–7
[113] Baltes H P and Popovic R S 1986 Integrated semiconductor magnetic field sensors *Proc. IEEE* **74** 1107–32
[114] Janata J 2009 *Principles of Chemical Sensors* (New York: Springer US)
[115] Bănică F-G 2012 *Chemical Sensors and Biosensors: Fundamentals and Applications* (New York: Wiley)
[116] Baron R and Saffell J 2017 Amperometric gas sensors as a low cost emerging technology platform for air quality monitoring applications: a review *ACS Sens.* **2** 1553–66
[117] Thévenot D R, Toth K, Durst R A and Wilson G S 2001 Electrochemical biosensors: Recommended definitions and classification *Biosens. Bioelectron.* **16** 121–31
[118] United Nations 2015 *Transforming Our World: The 2030 Agenda for Sustainable Development* (New York: United Nations)
[119] A European green deal–striving to be the first climate neutral continent 2021 (https://ec.europa.eu/info/strategy/priorities-2019–2024/european-green-deal_en)
[120] Ho C K, Robinson A, Miller D R and Davis M J 2005 Overview of sensors and needs for environmental monitoring *Sensors* **5** 4–37
[121] Lewis A and Edwards P 2016 Validate personal air-pollution sensors *Nature* **535** 29–31
[122] Barabde M and Danve S 2015 Real time water quality monitoring system *Int. J. Innov. Res. Comput. Commun. Eng.* **3** 5064–9
[123] Pasika S and Gandla S T 2020 Smart water quality monitoring system with cost-effective using iot *Heliyon* **6** E04096
[124] Groves P D 2015 Principles of gnss, inertial, and multisensor integrated navigation systems *IEEE Aerosp. Electron. Syst. Mag.* **30** 26–7
[125] Kessler D J, Johnson N L, Liou J-C and Matney M 2010 The kessler syndrome: Implications to future space operations *Adv. Astron. Sci.* **137** 61
[126] Wang Q, Zhu X, Ni Y, Gu L and Zhu H 2020 Blockchain for the IoT and industrial IoT: a review *Internet of Things* **10** 100081
[127] UN Online Index of Objects Launched into Outer Space (https://unoosa.org/oosa/osoindex/search-ng.jspx?lf_id=)
[128] 2020 Global Space Economy at a Glance (https://brycetech.com/reports)
[129] Measuring the Ecomomic Impact of the Space Sector, OECD Background Paper for the G20 Space Economy Leaders' Meeting, October 7, 2020
[130] Dependence of the European Economy on Space Infrastructures, Potential Impacts of Space Assets Loss, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, European Commission
[131] Akrami Y *et al* 2020 Planck 2018 results: overview and the cosmological legacy of Planck *Astron. Astrophys.* **641** A1
[132] Voyage 2050: Long-Term Planning of the ESA Science Programme. White Papers. (https://cosmos.esa.int/web/voyage-2050/white-papers)

[133] Voyage 2050 Sets Sail: ESA Chooses Future, ESA—Voyage 2050 Sets Sail: ESA Chooses Future Science Mission Themes
[134] Exploration Mission-1 Map, NASA (https://nasa.gov/image-feature/exploration-mission-1-map)
[135] Moonlight: Connecting Earth with the Moon (https://esa.int/Applications/Telecommunications_Integrated_Applications/Lunar_satellites)
[136] Allen C *et al* 2012 Challenges of a Mars simple return mission from the samples' perspective—contamination, preservation, and planetary protection *Concepts and Approaches for Mars Exploration* June 12–14, 2012, Houston, Texas
[137] Moon Village, A Vision for Global Cooperation and Space 4.0 (https://esa.int/About_Us/Ministerial_Council_2016/Moon_Village)
[138] *Melissa, Micro Ecological Life Support System Alternative* (https://melissafoundation.org/page/melissa-pilot-plant)
[139] Protection of Frequencies for Radioastronomical Measurements in the Shielded Zone of the Moon, RECOMMENDATION ITU-R RA.479–5, ITU Radiocommunication Assembly
[140] Barhels M 2019 *Radio Telescope Unfurls 3 Antennas Beyond the Far Side of the Moon* 2 December (https://space.com/radio-telescope-beyond-moon-far-side-antennas-deploy.html)
[141] Global Exploration Roadmap, Supplement Augsut 2020, Lunar Surface Exploration Scenario Update, ISECG, August 2020 (https://globalspaceexploration.org/wp-content/uploads/2020/08/GER_2020_supplement.pdf)
[142] *The Global Risk Report 2021* 16th edn (http://www3.weforum.org/docs/WEF_The_Global_Risks_Report_2021.pdf)
[143] *UCS (Union of Concerned Scientists) Satellite Database*, Jan 2019 (https://ucsusa.org/nuclear-weapons/space-weapons/satellite-database?_ga=2.21168895.576778038.1554626468-1092692463.1554216706#.XDZDs2l7ksc)
[144] *ESA Budget 2021* (https://esa.int/Newsroom/ESA_budget_2021)
[145] *Essential Climate Variables, World Metereological Organisation* (https://public.wmo.int/en/programmes/global-climate-observing-system/essential-climate-variables)
[146] *EU Climate Strategies & Targets, 2050 Long-Term Strategy* (https://ec.europa.eu/clima/policies/strategies/2050_en)
[147] *The European Green Deal, Communication from the Commission to the European Parliament, The Euroepan Council, The Council, The European Economica and Social Committee and the Committee of the Regions* (https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1596443911913&uri=CELEX:52019DC0640#document2)
[148] *A Brief Outlook on Future Copernicus Missions* (https://sentinels.copernicus.eu/web/sentinel/missions/copernicus-expansion-missions)
[149] *Contracts Awarded for Development of Six New Copernicus Missions* (https://esa.int/Applications/Observing_the_Earth/Copernicus/Contracts_awarded_for_development_of_six_new_Copernicus_missions)
[150] *ESA Earth Explorers: Understanding Our Planet* (https://esa.int/Applications/Observing_the_Earth/Future_EO/Earth_Explorers/About_Earth_Explorers2)
[151] *ESA and NASA Join Forces To Understand Climate Change* (https://esa.int/Applications/Observing_the_Earth/ESA_and_NASA_join_forces_to_understand_climate_change)
[152] Avila-Rodriguez J-A *et al* 2006 The MBOC modulation: the final touch to the galileo frequency and signal plan *Proc. of the Int. Technical Meeting of the Institute of Navigation (Fort Worth, TX, 25–28 September)* ION-GNSS 2006

[153] *Galileo's Contribution to COSPAS-SARSAT Programme* (https://ec.europa.eu/growth/sectors/space/galileo/sar_en)
[154] Galileo High-Accuracy Services 2020 *Information Note* GSA (https://gsc-europa.eu/sites/default/files/sites/all/files/Galileo_HAS_Info_Note.pdf)
[155] *Assuring Authentication for all, European Global Navigation Satellite Systems Agency, GSA* (https://gsc-europa.eu/news/assuring-authentication-for-all)
[156] Schuldt T *et al* 2021 Optical clock technologies for global navigation satellite systems *GPS Solutions* **25** 83
[157] Navigation system based on neutrino detection, US. Patent, US 8,849,565 B1, 2014
[158] The Current State of Space Debris (https://esa.int/Safety_Security/Space_Debris/The_current_state_of_space_debris)
[159] Space Surveillance Network (SSN), U.S. Army, Navy and Air Force (http://au.af.mil/au/awc/awcgate/usspc-fs/space.htm)
[160] Krag H *et al* 2017 A 1 cm space debris impact onto the Sentinel-1A Solar Array *Acta Astronaut.* **137** 434–43
[161] Kessler D *et al* 1978 Collision frequency of artificial satellites: the creation of a debris belt *J. Geophys. Res.* **83** 2637–46
[162] *IADC Space Debris Mitigation Guidelines*, IADC-02-01 Revision 1 September 2007
[163] *ESA Purchases World-First Debris Removal Mission from Start-up* (https://esa.int/Safety_Security/ESA_purchases_world-first_debris_removal_mission_from_start-up)
[164] *Planetary Defence* (www.esa.int/Safety_Security/Hera/Planetary_defence)
[165] *ESA Sfatey & Security Missions: Plans for the Future* (www.esa.int/Safety_Security/Plans_for_the_future)
[166] Euroconsult December 2019 *The Space Economy Report 2019*
[167] Crane K W *et al* 2020 *Measuring the Space Economy: Estimating the Value of Economic Activities in and for Space* (Science &Technology Policy Institute)
[168] *The Future of the European Space Sector How to Leverage Europe's Technological Leadership and Boost Investments for Space Ventures* (European Investment Bank, 2019)
[169] Geohistorical data website https://geohistoricaldata.org
[170] Fujita M, Krugman P R and Venables A J 2001 *The Spatial Economy: Cities, Regions, and International Trade* (Cambridge, MA: MIT Press)
[171] Barthelemy M 2016 *The Structure and Dynamics of Cities* (Cambridge: Cambridge University Press)
[172] Batty M 2013 *The New Science of Cities* (Cambridge, MA: MIT Press)
[173] O'Sullivan D and Manson S M 2015 Do physicists have geography envy? and what can geographers learn from it? *Ann. Assoc. Am. Geogr.* **105** 704–22
[174] Auerbach F 1913 Das gesetz der bevölkerungskonzentration *Petermanns Geogr. Mitt.* **59** 74–6
[175] Zipf G K 1949 *Human Behavior and the Principle of Least Effort* (Reading, MA: Addison-Wesley)
[176] Cottineau C 2017 Metazipf. a dynamic meta-analysis of city size distributions *PLoS One* **12** e0183919
[177] Verbavatz V and Barthelemy M 2020 The growth equation of cities *Nature* **587** 397–401
[178] Batty M 2006 Rank clocks *Nature* **444** 592–6
[179] Seto K C, Fragkias M, Güneralp B and Reilly M K 2011 A meta-analysis of global urban land expansion *PLoS One* **6** e23777

[180] Seto K C, Güneralp B and Hutyra L R 2012 Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools *Proc. Natl Acad. Sci.* **109** 16083–8
[181] Atlas of urban expansion 2024 http://atlasofurbanexpansion.org
[182] Barbosa H, Barthelemy M, Ghoshal G, James C R, Lenormand M, Louail T, Menezes R, Ramasco J J, Simini F and Tomasini M 2018 Human mobility: models and applications *Phys. Rep.* **734** 1 74
[183] Newman P W G and Kenworthy J R 1989 Gasoline consumption and cities: a comparison of us cities with a global survey *J. Am. Plan. Assoc.* **55** 24–37
[184] Creutzig F, Baiocchi G, Bierkandt R, Pichler P-P and Seto K C 2015 Global typology of urban energy use and potentials for an urbanization mitigation wedge *Proc. Natl Acad. Sci.* **112** 6283–8
[185] Verbavatz V and Barthelemy M 2019 Critical factors for mitigating car traffic in cities *PLoS One* **14** e0219559
[186] Fujita M and Ogawa H 1982 Multiple equilibria and structural transition of non-monocentric urban configurations *Reg. Sci. Urban Econ.* **12** 161–96
[187] Louf R and Barthelemy M 2013 Modeling the polycentric transition of cities *Phys. Rev. Lett.* **111** 198702
[188] Louf R and Barthelemy M 2014 How congestion shapes cities: from mobility patterns to scaling *Sci. Rep.* **4** 5561
[189] Branston D 1976 Link capacity functions: a review *Transp. Res.* **10** 223–36
[190] TomTom International BV (2008–2017) TomTom Traffic Index
[191] OECD 2016 The OECD Metropolitan Areas Database visualized through the Metropolitan eXplorer
[192] Duranton G and Turner M A 2011 The fundamental law of road congestion: evidence from us cities *Am. Econ. Rev.* **101** 2616–52
[193] Moran D, Kanemoto K, Jiborn M, Wood R, Többen J and Seto K C 2018 Carbon footprints of 13000 cities *Environ. Res. Lett.* **13** 064041
[194] Lighthill M J and Whitham G B 1955 On kinematic waves ii. a theory of traffic flow on long crowded roads *Proc. Royal Soc. Lond. Ser. A. Math. Phys. Sci.* **229** 317–45
[195] Nagel K and Schreckenberg M 1992 A cellular automaton model for freeway traffic *J. Phys.* I **2** 2221–9
[196] Blandin S, Argote J, Bayen A M and Work D B 2013 Phase transition model of non-stationary traffic flow: definition, properties and solution method *Transp. Res.* B **52** 55
[197] Gartner N H, Messer C J and Rathi A 2002 Traffic flow theory—a state-of-the-art report: revised monograph on traffic flow theory https://rosap.ntl.bts.gov/view/dot/35775
[198] Nagel K and Paczuski M 1995 Emergent traffic jams *Phys. Rev.* E **51** 2909
[199] Sugiyama Y, Fukui M, Kikuchi M, Hasebe K, Nakayama A, Nishinari K, Tadaki S-ichi and Yukawa S 2008 Traffic jams without bottlenecks—experimental evidence for the physical mechanism of the formation of a jam *New J. Phys.* **10** 033001
[200] Tadaki S-ichi, Kikuchi M, Fukui M, Nakayama A, Nishinari K, Shibata A, Sugiyama Y, Yosida T and Yukawa S 2013 Phase transition in traffic jam experiment on a circuit *New J. Phys.* **15** 103034
[201] Tadaki S-ichi, Kikuchi M, Nakayama A, Shibata A, Sugiyama Y and Yukawa S 2016 Characterizing and distinguishing free and jammed traffic flows from the distribution and correlation of experimental speed data *New J. Phys.* **18** 083022

[202] Biham O, Middleton A A and Levine D 1992 Self-organization and a dynamical transition in traffic-flow models *Phys. Rev.* A **46** R6124
[203] Cuesta J A, Martnez F C, Molera J M and Sánchez A 1993 Phase transitions in two-dimensional traffic-flow models *Phys. Rev.* E **48** R4175
[204] Echenique P, Gómez-Gardenes J and Moreno Y 2005 Dynamics of jamming transitions in complex networks *EPL (Europhys. Lett.)* **71** 325
[205] Carmona H A, de Noronha A W T, Moreira A A, Araújo N A M and Andrade J S 2020 Cracking urban mobility *Phys. Rev. Res.* **2** 043132
[206] Lampo A, Borge-Holthoefer J, Gómez S and Solé-Ribalta A 2021 Multiple abrupt phase transitions in urban transport congestion *Phys. Rev. Res.* **3** 013267
[207] Bellocchi L and Geroliminis N 2020 Unraveling reaction-diffusion-like dynamics in urban congestion propagation: Insights from a large-scale road network *Sci. Rep.* **10** 1–11
[208] Jiang Y, Kang R, Li D, Guo S and Havlin S 2017 Spatio-temporal propagation of traffic jams in urban traffic networks *arXiv preprint* arXiv:1705.08269
[209] Saberi M, Hamedmoghadam H, Ashfaq M, Hosseini S A, Gu Z, Shafiei S, Nair D J, Dixit V, Gardner L and Waller S T *et al* 2020 A simple contagion process describes spreading of traffic jams in urban networks *Nat. Commun.* **11** 1–9
[210] Li D, Fu B, Wang Y, Lu G, Berezin Y, Stanley H E and Havlin S 2015 Percolation transition in dynamical traffic network with evolving critical bottlenecks *Proc. Natl Acad. Sci.* **112** 669–72
[211] Kadanoff L P 2000 *Statistical Physics: Statics, Dynamics and Renormalization* (Singapore: World Scientific)
[212] Taillanter E and Barthelemy M 2021 Empirical evidence for a jamming transition in urban traffic *J. R. Soc. Interface* **18** 20210391
[213] Louail T, Lenormand M, Cantu Ros O G, Picornell M, Herranz R, Frias-Martinez E, Ramasco J J and Barthelemy M 2014 From mobile phone data to the spatial structure of cities *Sci. Rep.* **4** 1–12
[214] Ratti C, Frenchman D, Pulselli R M and Williams S 2006 Mobile landscapes: using location data from cell phones for urban analysis *Environ. Plan. B: Plan. Design* **33** 727–48
[215] Chang S, Pierson E, Koh P W, Gerardin J, Redbird B, Grusky D and Leskovec J 2021 Mobility network models of Covid-19 explain inequities and inform reopening *Nature* **589** 82–7
[216] Ganin A A, Kitsak M, Marchese D, Keisler J M, Seager T and Linkov I 2017 Resilience and efficiency in transportation networks *Sci. Adv.* **3** e1701079
[217] Wang W, Yang S, Stanley H E and Gao J 2019 Local floods induce large-scale abrupt failures of road networks *Nat. Commun.* **10** 1–11
[218] Buldyrev S V, Parshani R, Paul G, Stanley H E and Havlin S 2010 Catastrophic cascade of failures in interdependent networks *Nature* **464** 1025–8
[219] Sanders L, Pumain D, Mathian H, Guérin-Pace F and Bura S 1997 Simpop: a multiagent system for the study of urbanism *Environ. Plan. B: Plan. Design* **24** 287–305
[220] Aldous D and Barthelemy M 2019 Optimal geometry of transportation networks *Phys. Rev.* E **99** 052303

Chapter 8

[1] OECD 2019 *The OECD Learning Compass 2030* (http://oecd.org/education/2030-project/teaching-and-learning/learning/)

[2] Phys 21: Preparing Physics Students for 21st-Century Careers 2016 *A Report by the Joint Task Force on Undergraduate Physics Programs* (American Physical Society) (https://aps.org/programs/education/undergrad/jtupp.cfm)
[3] McLoughlin E, Butler D, Kaya S and Costello E 2020 STEM education in schools: what can we learn from the research? *ATS STEM Report #1* (Ireland: Dublin City University)
[4] Munfaridah N, Avraamidou L and Goedhart M 2021 The use of multiple representations in undergraduate physics education: what do we know and where do we go from here? *EURASIA J. Math., Sci. Technol. Educ.* **17** em1934
[5] Bao L and Koenig K 2019 Physics education research for 21st century learning *Discip. Interdiscip. Sci. Educ. Res.* **1**(2)
[6] Dewey J 1938 *Logic: The Theory of Inquiry* (New York: Holt, Rinehart and Winston)
[7] Lazonder A W and Harmsen R 2016 Meta-analysis of inquiry-based learning: effects of guidance *Rev. Educ. Res.* **86** 681–718
[8] Papadouris N and Constantinou C P 2018 Formative assessment in physics teaching and learning *The Role of Laboratory Work in Improving Physics Teaching and Learning* (Nature Switzerland AG: Springer)
[9] OECD 2021 *Positive, High-achieving Students? What Schools and Teachers Can Do, TALIS* (Paris: OECD Publishing)
[10] Gonsalves A J, Danielsson A and Pettersson H 2016 Masculinities and experimental practices in physics: the view from three case studies *Phys. Rev. Phys. Educ. Res.* **12** 020120
[11] Hodapp T and Hazari Z 2015 Women in physics: why so few? American Physical Society news *The Back Page, November* (https://aps.org/publications/apsnews/201511/backpage.cfm)
[12] Hazari Z, Brewe E, Goertzen R M and Hodapp T 2017 The importance of high school physics teachers for female students' physics identity and persistence *Phys. Teach.* **55** 96–9
[13] STEP UP 4 Women (https://engage.aps.org/stepup/home)
[14] Why Not Physics? A Snapshot of Girl's Uptake at A-level 2018 *An Institute of Physics Report* (https://iop.org/sites/default/files/2018-10/why-not-physics.pdf)
[15] Gender Stereotypes and their Effect on Young People 2019 *An Institute of Physics Report* (https://iop.org/sites/default/files/2019-07/IGB-gender-stereotypes.pdf)
[16] European Strategy Group 2020 *Update on Particle Physics*
[17] Michelini M 2021 Innovation of curriculum and frontiers of fundamental physics in secondary school: research-based proposals *Fundamental Physics and Physics Education Research* (Berlin: Springer) pp 101–16
[18] Building America's STEM Workforce: Eliminating Barriers and Unlocking Advantages 2021 *A Report by the American Physical Society Office of Government Affairs* (https://aps.org/policy/analysis/upload/Building-America-STEM-workforce.pdf)
[19] 2018 *The Role of Laboratory Work in Improving Physics Teaching and Learning* ed D Sokołowska and M Michelini (Nature Switzerland AG: Springer)
[20] Chang S L and Ley K 2006 A learning strategy to compensate for cognitive overload in online learning: learner use of printed online materials *J. Interact. Online Learn.* **5** 104–17
[21] Singer L M and Alexander P A 2017 Reading on paper and digitally: what the past decades of empirical research reveal *Rev. Educ. Res.* **87** 1007–41
[22] Nicholas V 2015 Mobile learning for online practical science modules in higher education *Mobile Learning and STEM: Case Studies in Practice* ed H Crompton and J Traxler (Abingdon: Routledge) pp 234–43

[23] Thoms L-J and Girwidz R 2017 Virtual and remote experiments for radiometric and photometric measurements *Eur. J. Phys.* **38** 1–24
[24] Global Hands-on Universe 2020 *Global Hands-on Universe Projects* (https://handsonuniverse.org/projects/) (Accessed 4 May 2021)
[25] Mazur E 1991 *Peer Instruction: A Users' Manual* (Englewood, NJ: Prentice-Hall)
[26] Jordan S 2013 E-assessment: past, present and future *New Dir. Teach. Phys. Sci.* **9** 87–106
[27] Hatherly P A, Jordan S E and Cayless A 2009 Interactive screen experiments: innovative virtual laboratories for distance learners *Eur. J. Phys.* **30** 751–62
[28] Faulconer E and Gruss A B 2018 A review to weigh the pros and cons of online, remote, and distance science laboratory experiences *Int. Rev. Res. Open Distrib. Learn.* **19** 155–68
[29] Dintsios N, Artemi S and Polatoglou H 2018 Acceptance of remote experiments in secondary students *Int. J. Online Eng.* **14** 4–18
[30] Matthews D 2021 COVID triggers remote-experiment revolution at labs across Europe *Times High. Educ.* (https://timeshighereducation.com/news/covid-triggers-remote-experiment-revolution-labs-across-europe) (Accessed 5 February 2021)
[31] Pan R, Sinha S, Kaski K and Jari Saramäki J 2012 The evolution of interdisciplinarity in physics research *Sci. Rep.* **2** 551
[32] Pluchino A, Burgio G, Rapisarda A, Biondo A E, Pulvirenti A, Ferro A and Giorgino T 2019 Exploring the role of interdisciplinarity in physics: success, talent and luck *PLoS One* **14** e0218793
[33] Darbellay F, Moody Z, Sedooka A and Steffen G 2014 Interdisciplinary research boosted by serendipity *Creat. Res. J.* **26** 1–10
[34] National Academy of Sciences, and National Academy of Engineering 2005 *Facilitating Interdisciplinary Research* (The National Academies Press)
[35] Klein J T 2014 Interdisciplinarity and transdisciplinarity: keyword meanings for collaboration science and translational medicine *J. Transl. Med. Epidemiol.* **2** 1024
[36] Darbellay F 2015 Rethinking inter- and transdisciplinarity: Undisciplined knowledge and the emergence of a new thought style *Futures* **65** 163–74
[37] Wernli D and Darbellay F 2016 *Interdisciplinarity and the 21st Century Research-Intensive University* Position paper (The League of European Research Universities (LERU))
[38] Klein J T 2012 Research integration, a comparative knowledge base *Case Studies in Interdisciplinary Research* ed A Repko, W Newell and R Szostak (Thousand Oaks, CA: Sage) pp 283–98
[39] Klein J T 2009 *Creating Interdisciplinary Campus Cultures: A Model for Strength and Sustainability* (New York: Wiley)
[40] Fiore S M 2008 Interdisciplinarity as teamwork: how the science of teams can inform team science *Small Group Res.* **39** 251–77
[41] Wuchty S, Jones B F and Uzzi B 2007 The increasing dominance of teams in production of knowledge *Science* **316** 1036–9
[42] Uzzi B, Mukherjee S, Stringer M and Jones B 2013 Atypical combinations and scientific impact *Science* **342** 468–72
[43] Brown R R, Deletic A and Wong T H F 2015 Interdisciplinarity: how to catalyse collaboration *Nature* **525** 315–7
[44] Stokols D 2014 Training the next generation of transdisciplinarians *Enhancing Communication et Collaboration in Interdisciplinary Research* ed M O'Rourke, S Crowley, S D Eigenbrode et and J D Wulfhorst (Thousand Oaks, CA: Sage) pp 56–81

[45] Darbellay F 2017 From monomyth to interdisciplinary creative polymathy: the researcher with a thousand faces *Special Issue: The Hero's Journey. A Tribute to Joseph Campbell and his 30th Anniversary of Death. The Journal of Genius and Eminence* 45–54
[46] Repko A and Szostak R 2016 *Interdisciplinary Research Process and Theory* (Thousand Oaks, CA: Sage)
[47] Hirsch Hadorn G, Hoffmann-Riem H, Biber-Klemm S, Grossenbacher-Mansuy W, Joye D, Pohl C, Wiesmann U and Zemp E (ed) 2008 *Handbook of Transdisciplinary Research* (Berlin: Springer)
[48] Frodeman R, Klein J T and Pacheco R C S (ed) 2017 *The Oxford Handbook of Interdisciplinarity* 2nd edn (Oxford: Oxford University Press)
[49] Fam D and O'Rourke M (ed) 2020 *Interdisciplinary and Transdisciplinary Failures* (Routledge)
[50] Duderstadt J J 2000 New roles for the 21st-century university *Issues Sci. Technol.* **16** 37–44
[51] https://21stcenturylab.lincoln.ac.uk/
[52] Bush V 1945 *Science—The Endless Frontier. A Report to the President* (Washington, DC: United States Government Printing Office)
[53] Edgerton D 2004 The linear model did not exist *The Science-Industry Nexus: History, Policy, Implications* ed K Grandin, N Worms and S Widmalm (Sagamore Beach, MA: Science History Publications) pp 31–57
[54] Godin B 2006 The linear model of innovation: the historical construction of an analytical framework *Sci., Technol. Human Values* **31** 639–67
[55] Jasanoff S 2003 Technologies of humility: citizen participation in governing science *Minerva* **41** 223–44
[56] Rogers E M 1962 *Diffusion of Innovations* (New York: Free Press of Glencoe)
[57] Merton R 1973 The normative structure of science ed N Storer *The Sociology of Science* (Chicage, IL: University of Chicago Press) pp 267–78
[58] National Research Council 1983 *Risk Assessment in the Federal Government: Managing the Process* (Washington, DC: National Academies Press)
[59] Perrow C 1984 *Normal Accidents: Living with High-Risk Technologies* (Princeton, NJ: Princeton University Press)
[60] Beck U 1992 *The Risk Society. Towards a New Modernity* (London: Sage)
[61] Macnaghten P and Urry J 1998 *Contested Natures* (London: Sage)
[62] Jasanoff S 2016 *The Ethics of Invention: Technology and the Human Future* (New York: W. W. Norton and Co.)
[63] Gibbons M, Limoges C, Nowotny H, Schwartzman S, Scott P and Trow M 1994 *The New Production of Knowledge: The Dynamics of Science and Research in Contemporary Societies* (London: Sage)
[64] Funtowicz S and Ravetz J 1993 Science for the post-normal age *Futures* **25** 739–55
[65] Irvine J and Martin B 1984 *Foresight in Science: Picking the Winners* (London: Pinter)
[66] Etzkowitz H and Leydesdorff L 2000 The dynamics of innovation: from national systems and 'Mode 2' to a triple helix of university-industry-government relations *Res. Policy* **29** 109–23
[67] Nowotny H, Scott P and Gibbons M 2001 *Re-Thinking Science. Knowledge and the Public in an Age of Uncertainty* (Cambridge: Polity Press)
[68] Hessels L and van Lente H 2008 Re-thinking new knowledge production: a literature review and a research agenda *Res. Policy* **37** 740–60

[69] Brooks S *et al* 2009 *Silver Bullets, Grand Challenges and the New Philanthropy* (Brighton: STEPS Working Paper 24, STEPS Centre)
[70] Ludwig D, Pols A and Macnaghten P 2018 *Organisational Review and Outlooks* (Wageningen University and Research)
[71] Jump P 2014 No Regrets, says outgoing EPSRC Chief David Delpy: 'Thick Skin' helped research council boss take the flak for controversial shaping capability measures *Times High. Educ.* April 17, 2014
[72] Flink T and Kaldewey D 2018 The new production of legitimacy: STI policy discourses beyond the contract metaphor *Res. Policy* **47** 14–22
[73] Calvert J 2013 Systems biology: big science and grand challenges *BioSocieties* **8** 466–79
[74] National Council on Bioethics 2012 *Emerging Biotechnologies: Technology, Choice and the Public Good* (London: Nuffield Council on Bioethics)
[75] Jasanoff S and Simmet H 2017 No funeral bells: public reason in a 'Post-Truth' world *Soc. Stud. Sci.* **47** 751–70
[76] Jasanoff S 1990 *The Fifth Branch: Science Advisers as Policymakers* (Cambridge, MA: Harvard University Press)
[77] Jasanoff S (ed) 2004 *States of Knowledge: The Co-Production of Science and the Social Order* (New York: Routledge)
[78] Miller C 2004 Climate science and the making of a global social order *States of Knowledge: The Co-Production of Science and the Social Order* ed S Jasanoff (New York: Routledge) pp 247–85
[79] Owens S 2015 *Knowledge, Policy, and Expertise: The UK Royal Commission on Environmental Pollution 1970–2011* (Oxford: Oxford University Press)
[80] Rose N 2006 *The Politics of Life Itself: Biomedicine, Power, and Subjectivity in the Twenty-First Century* (Princeton, NJ: Princeton University Press)
[81] Stirling A 2008 Opening Up' and 'Closing Down': power, participation, and pluralism in the social appraisal of technology *Sci., Technol. Human Values* **23** 262–94
[82] Stirling A 2014 *Emancipating Transformations: From Controlling 'the transition' to Culturing Plural Radical Progress* (Brighton, UK: STEPS Working paper 64, STEPS Centre)
[83] European Commission 2007 *The European Research Area: New Perspectives* (Luxembourg: Green paper 04.04.2007. Text with EEA relevance, COM161, EUR 22840 EN. Office for Official Publications of the European Communities)
[84] Irwin A 2006 The politics of talk: coming to terms with the 'new' scientific governance *Soc. Stud. Sci.* **36** 299–330
[85] Macnaghten P 2010 Researching technoscientific concerns in the making: narrative structures, public responses and emerging nanotechnologies *Environ. Plan.* A **41** 23–37
[86] Macnaghten P and Chilvers J 2014 The future of science governance: publics, policies, practices *Environ. Plan. C: Govern. Policy* **32** 530–48
[87] Chilvers J and Kearnes M (ed) 2016 *Remaking Participation: Science, Environment and Emergent Publics* (London: Routledge)
[88] European Commission 2013 *Fact Sheet: Science with and for Society in Horizon 2020*
[89] Zwart H, Landeweerd L and van Rooij A 2014 Adapt or perish? Assessing the recent shift in the european research funding arena from 'ELSA' to 'RRI' *Life Sci., Soc. Policy* **10** 11

[90] von Schomberg R 2013 A vision of responsible research and innovation *Responsible Innovation: Managing the Responsible Emergence of Science and Innovation in Society* ed R Owen, J Bessant and M Heintz (London: Wiley) pp 51–74
[91] Adam B and Groves G 2011 Futures tended: care and future-oriented responsibility *Bull. Sci., Technol. Soc.* **31** 17–27
[92] Grinbaum A and Groves C 2013 What is 'Responsible' about responsible innovation? Understanding the ethical issues *Responsible Innovation: Managing the Responsible Emergence of Science and Innovation in Society* ed R Owen, J Bessant and M Heintz (London: Wiley) pp 119–42
[93] Collingridge D 1980 *The Social Control of Technology* (Milton Keynes: Open University Press)
[94] Hajer M 2003 Policy without polity? Policy analysis and the institutional void *Policy Sci.* **36** 175–95
[95] Douglas H 2003 The moral responsibilities of scientists (tensions between autonomy and responsibility) *Am. Philos. Q.* **40** 59–68
[96] Owen R, Macnaghten P and Stilgoe J 2012 Responsible research and innovation: from science in society to science for society, with society *Sci. Public Policy* **39** 751–60
[97] Stilgoe J, Owen R and Macnaghten P 2013 Developing a framework of responsible innovation *Rese. Policy* **42** 1568–80
[98] Grove-White R, Macnaghten P, Mayer S and Wynne B 1997 *Uncertain World: Genetically Modified Organisms, Food and Public Attitudes in Britain* (Lancaster: Centre for the Study of Environmental Change)
[99] Macnaghten P 2004 Animals in their nature: a case study of public attitudes on animals, genetic modification and 'nature' *Sociology* **38** 533–51
[100] Macnaghten P and Szerszynski B 2013 Living the global social experiment: an analysis of public discourse on geoengineering and its implications for governance *Global Environ. Change* **23** 465–74
[101] Macnaghten P, Davies S and Kearnes M 2019 Understanding public responses to emerging technologies: a narrative approach *J. Environ. Plann. Policy* **21** 504–18
[102] Williams L, Macnaghten P, Davies R and Curtis S 2017 Framing fracking: exploring public responses to hydraulic fracturing in the UK *Public Understand. Sci.* **26** 89–104
[103] EPSRC 2013 *Framework for Responsible Innovation* (Swindon: EPSRC)
[104] Owen R 2014 The UK Engineering and Physical Sciences Research Council's commitment to a framework for responsible innovation *J. Respons. Innov.* **1** 113–7
[105] Murphy J, Parry S and Walls J 2016 The EPSRC's policy of responsible innovation from a trading zones perspective *Minerva* **54** 151–74
[106] Finkel A 2018 What kind of society do we want to be? Keynote address by Australian Government Chief Scientist *Human Rights Commission 'Human Rights and Technology' Conf. (Four Seasons Hotel, Sydney)*
[107] Scientists, keep an open line of communication with the public *Nat. Med.* **26** 1495–5 01 10 2020
[108] Lewenstein B 2015 Informal science: a resource and online community for informal learning projects, research, and evaluation. Retrieved 14 January 2020 from http://informalscience.org/research/wiki/Public-Engagement
[109] Bell P, Lewenstein B, Shouse A W and Feder M A *et al* 2009 *Learning Science in Informal Environments: People, Places, and Pursuits* vol 140 (Washington, DC: National Academies Press)

[110] http://visit.cern/universe-of-particles
[111] http://physicsmatters.physics.mcgill.ca/lectures/
[112] http://www.bbc.co.uk/programmes/b04v5vjz
[113] http://en.wikipedia.org/wiki/A_Brief_History_of_Time
[114] http://quantumdelta.nl/welcome-to-living-lab-quantum-and-society/
[115] http://www.zooniverse.org/projects/achmorrison/steelpan-vibrations
[116] Miller S 2001 Public understanding of science at the crossroads *Public Understand. Sci.* **10** 115–20
[117] Schäfer M S 2014 *Vom Elfenbeinturm in die Gesellschaft: Wissenschaftskommunikation im Wandel* (Zürich: Universität Zürich)
[118] Irwin A 2006 The politics of talk: coming to terms with the 'new' scientific governance *Soc. Stud. Sci.* **36** 299–320
[119] Haste 2005 *Connecting science: what we know and what we don't know about science and society* Department of Psychology, University of Bath
[120] https://www.natureindex.com/news-blog/how-to-crowdfund-your-research-science-experiment-grant
[121] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment data/file/905466/public-attitudes-to-science-2019.pdf
[122] NCCPE—National Coordinating Centre for Public Engagement 2012 The engaged university: a manifesto for public engagement.
[123] NCCPE—National Coordinating Centre for Public Engagement 2010 How public engagement helps to maximize the flow of knowledge and learning between HEIs and society.
[124] UUK 2010 Universities: Engaging with Local Communities, Retrieved on 15 January 2020 from https://www.universitiesuk.ac.uk/policy-and-analysis/reports/Documents/2010/universities-engaging-with-local-communities.pdf
[125] Robinson F, Zass-Ogilvie I and Hudson R 2012 *How Can Universities Support Disadvantaged Communities* (Joseph Rowntree Foundation)
[126] Oreskes N 2019 *Why Trust Science?* (Princeton, NJ: Princeton University Press)
[127] Lakomỳ M, Hlavová R and Machackova H 2019 Open science and the science-society relationship *Society* **56** 246–55
[128] Cavalier D, Hoffman C H P and Cooper C B 2020 *The Field Guide to Citizen Science: How You Can Contribute to Scientific Research and Make a Difference* (Timber Press Incorporated)
[129] Wellcome Trust 2006 *Science Communication*
[130] Burchell K, Franklin S and Holden K 2009 *Public culture as professional science: final report of the SCoPE project (Scientists on public engagement: from communication to deliberation?)* London School of Economics and Political Science, London
[131] Jensen P, Rouquier J-B, Kreimer P and Croissant Y 2008 Scientists who engage with society perform better academically *Sci. Public Policy* **35** 527–41
[132] Martinez-Conde S 2016 Has contemporary academia outgrown the Carl Sagan effect? *J. Neurosci.* **36** 2077–82
[133] Trench B 2012 Vital and vulnerable: science communication as a university subject *Science Communication in the World* (Berlin: Springer) pp 241–57
[134] Bubela T *et al* 2009 Science communication reconsidered *Nat. Biotechnol.* **27** 514–8
[135] Gorman M J 2020 *Idea Colliders: The Future of Science Museums* (Cambridge, MA: MIT Press)

[136] Darbellay F, Moody Z and Lubart T 2017 *Creativity, Design Thinking and Interdisciplinarity* (Berlin: Springer)
[137] https://ec.europa.eu/commission/commissioners/2019–2024/gabriel_en
[138] Reference framework for assessing the scientific and socio-economic impact of research infrastructures: https://www.oecd-ilibrary.org/science-and-technology/reference-framework-for-assessing-the-scientific-and-socio-economic-impact-of-research-infrastructures_3ffee43b-en
[139] Impact pathways: https://ri-paths-tool.eu/en/impact-pathways
[140] https://www.eso.org/public/announcements/ann21002/
[141] https://home.cern/about/what-we-do/our-impact#:~:text=CERN%20brings%20nations%20together%20and,such%20as%20health%20and%20environment
[142] IPCC 2021 *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed V Masson-Delmotte *et al* (Cambridge: Cambridge University Press)
[143] Wartofsky M W 2012 *Models: Representation and the Scientific Understanding* vol 48 (Cham: Springer Science & Business Media)
[144] Vicsek T 2002 Complexity: the bigger picture *Nature* **418** 131–1
[145] Nichols T 2017 *The Death of Expertise: The Campaign Against Established Knowledge and Why It Matters* (Oxford: Oxford University Press)
[146] Lenton T M, Rockström J, Gaffney O, Rahmstorf S, Richardson K, Steffen W and Schellnhuber H J 2019 *Climate Tipping Points—Too Risky To Bet Against* (Nature Publishing Group)
[147] https://www.weforum.org/reports/the-global-risks-report-2020
[148] Allen T, Murray K A, Zambrana-Torrelio C, Morse S S, Rondinini C, Di Marco M, Breit N, Olival K J and Daszak P 2017 Global hotspots and correlates of emerging zoonotic diseases *Nat. Commun.* **8** 1–10
[149] Steffen W, Broadgate W, Deutsch L, Gaffney O and Ludwig C 2015 The trajectory of the Anthropocene: the great acceleration *Anthropocene Rev.* **2** 81–98
[150] Weart S 2013 Rise of interdisciplinary research on climate *Proc. Natl Acad. Sci.* **110** 3657–64
[151] Brulle R J and Norgaard K M 2019 Avoiding cultural trauma: climate change and social inertia *Environ. Polit.* **28** 886–908
[152] Swim J, Clayton S, Doherty T, Gifford R, Howard G, Reser J, Stern P and Weber E 2009 *Psychology and Global Climate Change: Addressing a Multi-Faceted Phenomenon and Set of Challenges. A Report by the American Psychological Association's Task Force on the Interface Between Psychology and Global Climate Change* (Washington, DC: American Psychological Association)
[153] Hansen J, Sato M and Ruedy R 2012 Perception of climate change *Proc. Natl Acad. Sci.* **109** E2415–23
[154] Martin B and Richards E 1995 Scientific knowledge, controversy, and public decision-making *Handbook of Science and Technology Studies* **506** 26
[155] Crow D A and Boykoff M T 2014 *Culture, Politics and Climate Change: How Information Shapes Our Common Future* (Routledge)
[156] Bowater L and Yeoman K 2012 *Science Communication: A Practical Guide for Scientists* (New York: Wiley)

[157] Sinatra R, Deville P, Szell M, Wang D and Barabási A-L 2015 A century of physics *Nat. Phys.* **11** 791–6
[158] Burns T W, O'Connor D J and Stocklmayer S M 2003 Science communication: a contemporary definition *Public Understand. Sci.* **12** 183–202
[159] http://www.oecd.org/sti/science-technology-innovation-outlook/Science-advice-COVID/
[160] Freudenburg W R, Gramling R and Davidson D J 2008 Scientific certainty argumentation methods (SCAMs): science and the politics of doubt *Sociol. Inq.* **78** 2–38
[161] E. M. A. O. National Academies of Sciences 2017 *Communicating Science Effectively: A Research Agenda* (National Academies Press)
[162] Kappel K and Holmen S J 2019 Why science communication, and does it work? A taxonomy of science communication aims and a survey of the empirical evidence *Front. Commun.* **4** 55
[163] Caulfield T 2020 Pseudoscience and COVID-19-we've had enough already *Nature (Lond.)* 27 Apr
[164] Boucher D 2016 Movie review: there's a vast cowspiracy about climate change *The Equation Blog*
[165] Le Quéré C, Jackson R B, Jones M W, Smith A J P, Abernethy S, Andrew R M, De-Gol A J, Willis D R, Shan Y and Canadell J Gothers 2020 Temporary reduction in daily global CO_2 emissions during the COVID-19 forced confinement *Nat. Clim. Change* **10** 647–53
[166] Pérez-González L 2020 Is climate science taking over the science?' A corpus-based study of competing stances on bias, dogma and expertise in the blogosphere *Human. Soc. Sci. Commun.* **7** 1–16
[167] Kreps S E and Kriner D L 2020 Model uncertainty, political contestation, and public trust in science: evidence from the COVID-19 pandemic *Sci. Adv.* **6** eabd4563
[168] Rödder S, Franzen M and Weingart P 2011 The sciences' media connection–public communication and its repercussionsvol 28 (Cham: Springer Science & Business Media)
[169] Peters H P 2013 Gap between science and media revisited: Scientists as public communicators *Proc. Natl Acad. Sci.* **110** 14102–9
[170] Lundby K 2014 *Mediatization of Communication*vol 21 (Walter de Gruyter GmbH & Co KG)
[171] Kahneman D, Lovallo D and Sibony O 2011 Before you make that big decision *Harv. Bus. Rev.* **89** 50–60
[172] Pahl S, Sheppard S, Boomsma C and Groves C 2014 Perceptions of time in relation to climate change *Wiley Interdiscip. Rev. Clim. Change* **5** 375–88
[173] Fuentes R, Galeotti M, Lanza A and Manzano B 2020 COVID-19 and climate change: a tale of two global problems *Sustainability* **12** 8560
[174] O'Brien K 2016 *Climate Change Adaptation and Social Transformation* (International Encyclopedia of Geography: People, the Earth, Environment and Technology: People, the Earth, Environment and Technology) pp 1–8
[175] https://partner.sciencenorway.no/climate-change-covid19-crisis/the-world-with-viruses-the-corona-crisis-shows-that-rapid-change-is-possible/1666488
[176] Saitz R and Schwitzer G 2020 Communicating science in the time of a pandemic *JAMA* **324** 443–4
[177] Gross M 2020 Communicating science in a crisis *Curr. Biol.* **30** R737–9

[178] Popper K 1970 The moral responsibility of the scientist *Induction, Physics and Ethics: Proceedings and Discussions of the 1968 Saltzburg Colloquium in the Philosophy of Science* ed P Weingartner and G Zecha (D. Reidel, Publ. Company) pp 329–36
[179] Gustafsson B, Rydén L, Tibell G and Wallensteen P 1984 Focus on: the uppsala code of ethics for science *J. Peace Res.* **21** 311–6
[180] Rydén L 1990 *Etik för forskare* (in Swedish) *UHÄ FoU Report* **1990** 1
[181] https://en.wikipedia.org/wiki/List_of_scientific_misconduct_incidents (Accessed March 1, 2021)
[182] Asplund K 2021 *Fuskarna* (in Swedish), fri tanke, Stockholm
[183] Fanelli D 2009 How many scientists fabricate or falsify research? A systematic review and meta-analyis of survey data *PLoS One* **4** e:5738
[184] For example, Kennedy A 2019 A short history of academic plagiarism, https://www.quetext.com/blog/short-history-academic-plagiarism (Accessed May 29, 2021)
[185] Garfield E 2002 Demand citation vigilance *The Scientist* **16** 6
[186] Mulligan A 2004 Is the peer review in crisis? *Perspectives in Publishing* (Elsevier) (https://elsevier.com/__data/assets/pdf_file/0003/93675/PerspPubl2.pdf) (Accessed 10 May 2021)
[187] Schubert T 2011 Empirical observations on new public management to increase efficiency in public research—Boon or bane? *J. Res. Policy* **38** 1225–38
[188] Gustafsson B 2014 Om forskningsmarknaden och forskningens retorik (in Swedish) *Vetenskapsretorik: Hur vetenskapen övertygar och övertalar* ed B Lindberg (Act. Reg. Soc. Scient, Litt. Goth., Interdiciplinaria)vol 13 pp 115–32
[189] Hasselberg Y 2012 Demand or discretion? The market model applied to science and its core values and institutions *Ethics Sci. Environ. Politics* **12** 35–51
[190] Ioannidis J P A 2005 Why most published research findings are false *PLoS Med.* **2** e124
[191] Ziliak S T and McCloskey D N 2008 *The Cult of Statistical Significance: How the Standard Error Costs Us Jobs, Justice and Lives* (The University of Michigan Press)
[192] Baker M 2016 1,500 scientists lift the lid on reproducibility *Nature* **533** 452–4
[193] https://www.go-fair.org/fair-principles/ (Accessed May 16, 2021)
[194] https://opensource.org (Accessed May 16, 2021)
[195] Gustafsson B 2004 *Origin and Evolution of the Elements, Carnegie Observatories Centennial Symposia* ed A McWilliam and M Rauch (Cambridge: Cambridge University Press) p 102
[196] Ioannidis J P A and Trikalinos T A 2005 Early extreme contradictory estimates may appear in published research: the Proteus phenomenon in molecular genetics research and randomised trials . *J. Clin. Epidemiol.* **58** 543–9
[197] ICMJE: http://www.icmje.org/recommendations/browse/roles-and-responsibilities/defining-the-role-of-authors-and-contributors.html (Accessed April 29, 2021)
[198] Helgesson G, Juth N and Schneider J *et al* 2018 Misuse of coauthorship in medical theses in Sweden *J. Empir. Res. Human Res. Ethics* **13** 402–11
[199] Teixeira da Silva J A and Dobránszki J 2016 Multiple authorship in scientific manuscripts: ethical challenges, ghost and guest/gift authorship, and the cultural/disciplinary perspective *Sci. Eng. Ethics* **22** 1457–72
[200] Douglas H E 2009 *Science, Policy and the Value-Free Ideal* (University of Pittsburgh Press)
[201] Hvistendal M 2013 China's publication bazaar *Science* **342** 1035
[202] https://en.wikipedia.org/wiki/Archaeoraptor (Accessed May 19, 2021)
[203] Resnik D B and Shamoo A E 2011 The Singapore statement on research integrity *Account Res.* **18** 71–5

[204] Anderson M S 2018 Shifting perspectives on research integrity *J. Empir. Res. Human Res. Ethics* **13** 459–60
[205] *The European Code of Conduct for Research Integrity*, https://allea.org/code-of-conduct/ (Accessed May 16, 2021)
[206] Sternwedel J D 2014 Life after misconduct: promoting rehabilitation while minimizing damage , *J. Microbiol. Biol. Educ.* **15** 177–80
[207] Fang F C and Casadevall A 2015 Competitive science: is competition ruining science? *Infect. Immun.* **83** 1229–33
[208] Merton R K 1957 Priorities in scientific discovery: a chapter in the sociology of science *Am. Sociol. Rev.* **22** 635–59
[209] Anderson M S, Ronning E A and De Vries R *et al* 2007 The perverse effects of competition on scientists work and relationships *Sci. Eng. Ethics* **13** 437–61
[210] Casadevall A and Fang F C 2012 Reforming science: methodological and cultural reforms *Am. Soc. Microbiol, Infect. Immun.* **80** 891–6
[211] Adamo S A 2013 Attrition of women in the biological sciences: workload, motherhood, and other explanations revisited *BioScience* **63** 43–8
[212] Amabile T M 1998 How to kill creativity *Harv. Bus. Rev.* **76** 76–87 cited in [190]
[213] Amabile T M 1996 *Creativity in Context* (Boulder, CO: Westview Press) cited in [190]
[214] Casadevall A and Fang F C 2012 Reforming science: structural reforms *Am. Soc. Microbiol., Infect. Immun.* **80** 897–901
[215] Scherk J and Schwarz J H 1974 Dual models for nonhadrons *Nucl. Phys.* **B81** 118
Polchinski J 1998 *String Theory* vol 2 (Cambridge: Cambridge University Press)
[216] Smolin L 2006 *The Trouble with Physics* (Houghton Mifflin)
[217] Quevedo F 2019 Is string phenomenology an oxymoron? *Why Trust a Theory?* ed R Dardashti, R Dawid and K Thebault (Cambridge: Cambridge University Press) e-print:161201589
[218] Guth A 1981 The inflationary universe: a possible solution to the horizon and flatness problems *Phys. Rev.* **D23** 347–56
[219] Ijjas A, Steinhardt P A and Loeb A 2014 Inflationary schism *Phys. Lett.* B **736** 142–6
[220] Linde A D 1986 Eternally existing self-reproducing chaotic inflationary universe *Phys. Lett.* B **175** 395
[221] Ellis G and Silk J 2014 Defend the integrity of physics *Nature* **516** 321–3
[222] Dawid R 2013 *String Theory and the Scientific Method* (Cambridge: Cambridge University Press)
[223] Witten E 1995 String theory dynamics in various dimensions, hep-th/9503124 *Nucl. Phys.* **B443** 85–126
Maldacena J 1999 The large N limits of superconformal field theories and supergravity *Int. J. Theor. Phys.* **38** 1113–33
[224] Weinberg S 1992 *Dreams of a Final Theory* (Vintage)
[225] Witten E 1996 Reflections on the fate of spacetime *Physics Meets Philosophy at the Planck Scale* ed C Callender and N Huggett (Cambridge: Cambridge University Press)
[226] Well illustrated overview by Maria Teodora Stanescu Black Holes and Gravitational Waves, 2018: https://www.mpifr-bonn.mpg.de/4171741/Maria_Stanescu.pdf
[227] https://www.iter.org

[228] Kinoshita Y *et al* 2014 Diagnosis of intraocular lesions using vitreous humor and intraocular perfusion fluid cytology: experience with 83 cases: intraocular cytology of the globe *Diagn. Cytopathol.* **43** 353–9
[229] Meadows D, Meadows D, Randers J and Behrens W 1972 *The Limits to Growth. A Report for the Club of Rome's Project on the Predicament of Mankind* (New York: Universe Books)
[230] Turner G 2008 *A comparison of Limits to Growth with thirty years of reality* (Canberra: CSIRO Working Papers)
[231] Rockström J and Steffen W *et al* 2009 Planetary boundaries: exploring the safe operating space for humanity *Ecol. Soc.* **14** 32
[232] Steffen W, Richardson K and Rockström J *et al* 2015 Planetary boundaries: guiding human development on a changing planet *Science* **347** 736–47
[233] Steffen W, Crutzen P J and McNeill J R 2007 The anthropocene: are humans now overwhelming the great forces of nature *Ambio* **36** 614–21
[234] Steffen W and Broadgate W *et al* 2015 The trajectory of the anthropocene *Anthropocene Rev.* **2** 81–98
[235] von Weizsäcker E U and Wijkman A 2018 *Come On! Capitalism, Short-terminsm, Population and the Destruction of the Planet* (New York: Springer)
[236] Rapley J 2004 *Globalization and Inequality. Neoliberalism's Downward Spiral* (Boulder, CO: Lynne Rienner Publ)
[237] Cartwright M 2012 Yin and Yang. Definition. Ancient History Encyclopedia https://www.worldhistory.org/Yin_and_Yang/
[238] Frithjof C 1975 *The Tao of Physics. An Exploration of the Parallels Between Modern Physics an Eastern Mysticism* (Boulder: Shambhala)
[239] Riane E 1987 *The Chalice and the Blade* (San Francisco, CA: Harper Collins)
[240] Riane E 2007 *The Real Wealth of Nations: Creating a Caring Economics* (San Francisco, C: Berrett-Koehler)
[241] Wilkinson R and Picket K 2009 *The Spirit Level. Why Greater Equality Makes Societies Stronger* (New York: Bloomsbury)