IOPscience iopscience.iop.org

This content has been downloaded from IOPscience. Please scroll down to see the full text.

Download details:

IP Address: 18.222.167.58
This content was downloaded on 03/05/2024 at 08:08

Please note that terms and conditions apply.

You may also like:

Single-shot work extraction in quantum thermodynamics revisited
Shang-Yung Wang

An introductory review of the resource theory approach to thermodynamics
Matteo Lostaglio

Catalysis of entanglement and other quantum resources
Chandan Datta, Tulja Varun Kondra, Marek Miller et al.

Quantum coherence in a quantum heat engine
Yun-Hao Shi, Hai-Long Shi, Xiao-Hui Wang et al.

Quantum Thermodynamics

An introduction to the thermodynamics of quantum information

Quantum Thermodynamics

An introduction to the thermodynamics of quantum information

Sebastian Deffner
University of Maryland, Baltimore County (UMBC), Baltimore, Maryland, USA

Steve Campbell
Trinity College, Dublin, Ireland

Morgan & Claypool Publishers

Copyright © 2019 Morgan & Claypool Publishers

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publisher, or as expressly permitted by law or under terms agreed with the appropriate rights organization. Multiple copying is permitted in accordance with the terms of licences issued by the Copyright Licensing Agency, the Copyright Clearance Centre and other reproduction rights organizations.

Rights & Permissions
To obtain permission to re-use copyrighted material from Morgan & Claypool Publishers, please contact info@morganclaypool.com.

ISBN 978-1-64327-658-8 (ebook)
ISBN 978-1-64327-655-7 (print)
ISBN 978-1-64327-656-4 (mobi)

DOI 10.1088/2053-2571/ab21c6

Version: 20190701

IOP Concise Physics
ISSN 2053-2571 (online)
ISSN 2054-7307 (print)

A Morgan & Claypool publication as part of IOP Concise Physics
Published by Morgan & Claypool Publishers, 1210 Fifth Avenue, Suite 250, San Rafael, CA, 94901, USA

IOP Publishing, Temple Circus, Temple Way, Bristol BS1 6HG, UK

Quidquid praecipies, esto brevis.
(Horaz, Ars poetica 335)

Contents

Preface

What is physics? According to standard definitions in encyclopedias *physics is a science that deals with matter and energy and their interactions*[1]. However, as physicists what is it that we actually do? At the most basic level, we formulate predictions for how inanimate objects behave in their natural surroundings. These predictions are based on our expectation that we extrapolate from observations of the *typical behavior*. If typical behavior is universally exhibited by many systems of the same 'family', then this typical behavior is phrased as a *law*.

Take for instance the infamous example of an apple falling from a tree. The same behavior is observed for any kind of fruit and any kind of tree—the fruit 'always' falls from the tree to the ground. Well, actually the same behavior is observed for any object that is let loose above the ground, namely everything will eventually fall towards the ground. It is this observation of *universal falling* that is encoded in the *law of gravity*.

Most theories in physics then seek to understand the nitty-gritty details, for which finer and more accurate observations are essential. Generally, we end up with more and more fine-grained descriptions of nature that are packed into more and more sophisticated laws. For instance, from classical mechanics over quantum mechanics to quantum field theory we obtain an ever more detailed prediction for how smaller and smaller systems behave.

Realizing this typical mindset of physical theories, it does not come as a big surprise that many students have such a hard time wrapping their minds around *thermodynamics*:

> *Thermodynamics is a phenomenological theory to describe the average behavior of heat and work.*

As a phenomenological theory, thermodynamics does not seek to formulate detailed predictions for the microscopic behavior of *some* physical systems, but rather it aims to provide the most universal framework to describe the typical behavior of *all* physical systems.

'Reflections on the motive power of fire'. The origins of thermodynamics trace back to the beginnings of the industrial revolution [6]. For the first time, mankind started developing artificial devices that contained so many moving parts that it became practically impossible to describe their behavior in full detail. Nevertheless, the first devices, steam engines, already proved to be remarkably useful and dramatically increased the effectiveness of productive efforts.

The founding father of thermodynamics is undoubtedly Sadi Carnot. After Napoleon had been exiled, France started importing advanced steam engines from Britain, which made Carnot realize how far France had fallen behind its adversary from across the channel. Quite remarkably, a small number of British engineers, who totally lacked any formal scientific education, had started to collect reliable data about the efficiency of many types of steam engines. However, it was not at all clear whether there was an optimal design and what the highest efficiency would be.

[1] This and similar definitions can be found, for instance, in Merriam-Webster.

Nicolas Léonard Sadi Carnot:

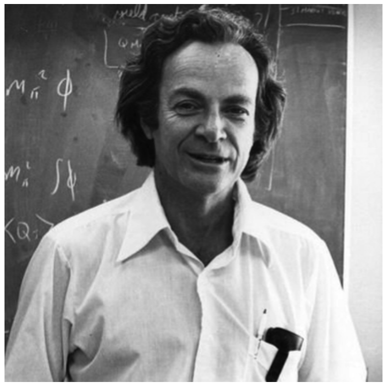
Everyone knows that heat can produce motion [2].

Carnot had been trained in the latest developments in physics and chemistry, and it was he who recognized that steam engines need to be understood in terms of their energy balance. Thus, optimizing steam engines was not only a matter of improving the expansion and compression of steam, but actually needed an understanding of the relationship between work and heat [2].

Sadly, Carnot's work [2] was largely ignored by the scientific community until the railroad engineer Émile Clapeyron quoted and generalized Carnot's results. Eventually 30 years later, it was Rudolph Clausius, who put Carnot's insight into a solid mathematical framework [3], which is the same mathematical theory that we still use today—thermodynamics.

Thus, thermodynamics is not only unique among the theories in physics with respect to its mindset, but also with respect to its beginnings. No other theory is so intimately connected with someone never holding an academic position—Sadi Carnot. Formulating the original ideas was thus largely motivated by practical questions and not purely by scientific curiosity. This might explain why more than any other theory, thermodynamics is a framework to describe the typical and universal behavior of any physical system.

Richard P Feynman:



Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy [4].

Quantum computing—Feynman's dream come true. A remarkable quote from Carnot's work [2] is the following:

> *The study of these engines is of the greatest interest, their importance is enormous, their use is continually increasing, and they seem destined to produce a great revolution in the civilized world.*

If we replaced the word 'engines' with 'quantum computers', Carnot's sentence would fit nicely into the announcements of the various 'quantum initiatives' around the globe [7].

Ever since Feynman's proposal in the early 1980s [4] quantum computing has been a promise that could initiate a technological revolution. Over the last couple of years big corporations, such as Microsoft, IBM and Google, as well as smaller start-ups, such as D-Wave or Rigetti, have started to present more and more intricate technologies that promise to eventually lead to the development of a practically useful quantum computer.

Rather curiously, we are in a very similar situation to that which Carnot found in the beginning of the 19th century. Novel technologies are being developed by crafty engineers that are much too complicated to be described in full microscopic detail. Nevertheless, the question that we are really after is how to operate these technologies optimally in the sense that the least amount of resources, such as work and information, are wasted into the environment.

As physicists we know exactly which theory will prevail in the attempt to describe what is going on, since it is the only theory that is universal enough to be useful when faced with new challenges—thermodynamics. However, this time the natural variables can no longer be volume, temperature, and pressure, which are characteristic for steam engines. Rather, in *Quantum Thermodynamics* the first task has to be to identify the new *canonical variables*, and then write the dictionary for how to translate between the universal thermodynamic framework and practically useful statements for the optimization of quantum technologies.

Purpose and target audience of this book. The purpose of this book is to provide a concise introduction to the conceptual building blocks of quantum thermodynamics and their application in the description of quantum systems that process information. Large parts of this book arose from our lecture notes that we had put together for graduate classes in statistical physics or for workshops and summer schools dedicated to quantum thermodynamics. When teaching the various topics of quantum thermodynamics we always felt a bit unsatisfied as no single book contained a comprehensive overview of all the topics we deemed essential. Earlier monographs have become a bit outdated, such as *Quantum Thermodynamics* by our colleagues Gemmer, Michel, and Mahler [5], or are simply not written as a textbook suited for teaching, such as *Thermodynamics in the Quantum Regime* which was edited by Binder *et al* [1].

Thus, we took it upon ourselves to write a text that we will be using for advanced special topics classes in our graduate program. Considering graduate statistical physics and quantum mechanics as prerequisites the topics of the present book can be covered over the course of a semester. However, as always when designing a new course it is simply not possible to cover everything that would be interesting. Thus, we needed to make some tough choices and we hope that our colleagues will forgive us if they feel their work should have been a more prominent part of this text.

Longum iter est per praecepta, breve et efficax per exempla.
(Seneca Junior, 6th letter)

Sebastian Deffner
Baltimore, Maryland, USA

Steve Campbell
Dublin, Ireland

References

[1] Binder F, Correa L A, Gogolin C, Anders J and Adesso G (ed) 2018 *Thermodynamics in the Quantum Regime. Fundamental Theories of Physics* (Berlin: Springer)

[2] Carnot S 1824 *Réflexions Sur La Puissance Motrice De Feu Et Sur Les Machines Propres à Développer Cette Puissance* (Paris: Bachelier)

[3] Clausius R 1854 Über eine veränderte Form des zweiten Hauptsatzes der mechanischen Wärmetheorien *Ann. Phys. Chem.* **93** 481

[4] Feynman R P 1982 Simulating physics with computers *Int. J. Theor. Phys.* **21** 467

[5] Gemmer J, Michel M and Mahler G 2009 *Quantum Thermodynamics* (Berlin: Springer)

[6] Kondepudi D and Prigogine I 1998 *Modern Thermodynamics* (New York: Wiley)

[7] Sanders B C 2017 *How to Build a Quantum Computer* (Bristol: IOP Publishing)

Acknowledgments

Sebastian Deffner—Every academic strives to live up to his mentors. In my case, this is an almost inconceivable challenge, since I have been very fortunate to have learned from the best. In particular, I would like to thank my *Doktorvater* and friend, Eric Lutz, for making me his first student. Without his vision and foresight I would never have started to work in quantum thermodynamics. I will also forever be indebted to Chris Jarzynski for putting up with me during my early postdoctoral phase. His kindness and unwavering support paired with his unmatched understanding of thermodynamics allowed me to grow into the physicist I am today. Finally, I will never forget the lessons I was taught by Wojciech H Zurek. Being one of the most influential theoretical physicists he opened my eyes to the insurmountable variety of questions that can be addressed with the tools of quantum thermodynamics. His dedication to and his joy in unlocking the mysteries of the Universe, while at the same time remaining grounded in what really counts in life, remind me almost every day why I became a theoretical physicist and what kind of man I want to be.

I would also like to thank my dear friends and collaborators, who helped me hone my thinking and whose work contributed to this book. In particular, I am grateful to Marcus Bonança, Bartłomeij Gardas, Frederico Brito, Haitao Quan, and Obinna Abah. I am looking forward to all the exciting research we will be tackling in the years to come.

Finally, I would like to thank my family, my parents, Alfred and Isabella, and my brother, Christoph, for accepting me for who I am and reminding me to never give up on my dreams. Last but not least, I am lacking words to express the importance of my partner in crime, my closest confidante, and mother of my children, Catherine. Thank you for always reminding me to keep fighting, for making me a better man, and for never giving up on me.

Maximillian and Alexander, like everything I do, this is for you!

Steve Campbell—I have been fortunate to have enjoyed a menagerie of collaborators over my relatively short research career so far. They all, in their own way, have contributed to how my interests have developed over the years which ultimately led to this work, and for this I am forever grateful. I am particularly indebted to those friends whose work formed the basis for some parts of this book: Marco Genoni, Gian Luca Giorgi, John Goold, Giacomo Guarnieri, Simon Pigeon, Maria Popovic, and Bassano Vacchini. I am also eternally grateful to Tony Apollaro, Barış Çakmak, Gabriele De Chiara, Mossy Fogarty, and Massimo Palma for the many years of stimulating discussions, punctuated with great refreshments, may they long continue.

I am lucky to have gained much of my scientific training from two world-leading physicists, Mauro Paternostro and Thomas Busch. The lessons learned from their expert guidance is woven throughout this book. I feel privileged to have benefitted from their friendship for so many years.

My parents, Larry and Shirley, and brother, Jaymz, I am thankful for all they continue to do for me. Finally, to my loves Flora and Qubit (the cat). Your support and encouragement to undertake and complete this book is the only reason I made it through. For putting up with the life of an early career academic trying to find his place, I owe you everything.

Author biographies

Sebastian Deffner

Dr Sebastian Deffner received his doctorate from the University of Augsburg in 2011 under the supervision of Eric Lutz. From 2011 to 2014 he was a Research Associate in the group of Chris Jarzynski at the University of Maryland, College Park and from 2011 to 2016 he was a Director's Funded Postdoctoral Fellow with Wojciech H Zurek at the Los Alamos National Laboratory. Since 2016 he has been on the faculty of the Department of Physics at the University of Maryland, Baltimore County (UMBC), where he leads the quantum thermodynamics group.

Dr Deffner's contributions to quantum thermodynamics have been recognized through the Early Career Award 2016 from IOP's *New Journal of Physics*, and he was also awarded the Leon Heller Postdoctoral Publication Prize from the Los Alamos National Laboratory in 2016.

To date, Dr Deffner has been reviewing for more than ten international funding agencies and more than thirty high-ranking journals. For these efforts he was named Outstanding Reviewer for *New Journal of Physics* in 2016, Outstanding Reviewer for *Annals of Physics* in 2016, and in 2017 he was named APS Outstanding Referee. Since 2017 Dr Deffner has been a member of the international editorial board for IOP's *Journal of Physics Communications*, and since 2019 he has been on the editorial advisory board of *Journal of Nonequilibrium Thermodynamics*.

As a theoretical physicist, Dr Deffner employs tools from statistical physics, open quantum dynamics, quantum information theory, quantum optics, quantum field theory, condensed matter theory, and optimal control theory to investigate the nonequilibrium properties of nanosystems operating far from thermal equilibrium.

Steve Campbell

After a PhD in Queens University Belfast in 2011 under the supervision of Mauro Paternostro, Dr Steve Campbell moved to University College Cork to work with Thomas Busch in 2012. He spent 2013 at the Okinawa Institute of Science and Technology Graduate University in Japan. Returning to Belfast, he spent 2014 through to 2016 at his *alma mater* Queens University. In 2017 he was awarded a fellowship from the INFN Sezione di Milano and worked with Bassano Vacchini. From February 2019 he has been appointed as Senior Research Fellow at Trinity College Dublin through the award of a Science Foundation Ireland Starting Investigators Research Grant.

Dr Campbell is interested in exploring the role which fundamental bounds, such as the quantum speed limit, play in characterizing and designing thermodynamically efficient control protocols for complex quantum systems. He works on a variety of topics including open quantum systems, critical spin systems and phase transitions, metrology, and coherent control.