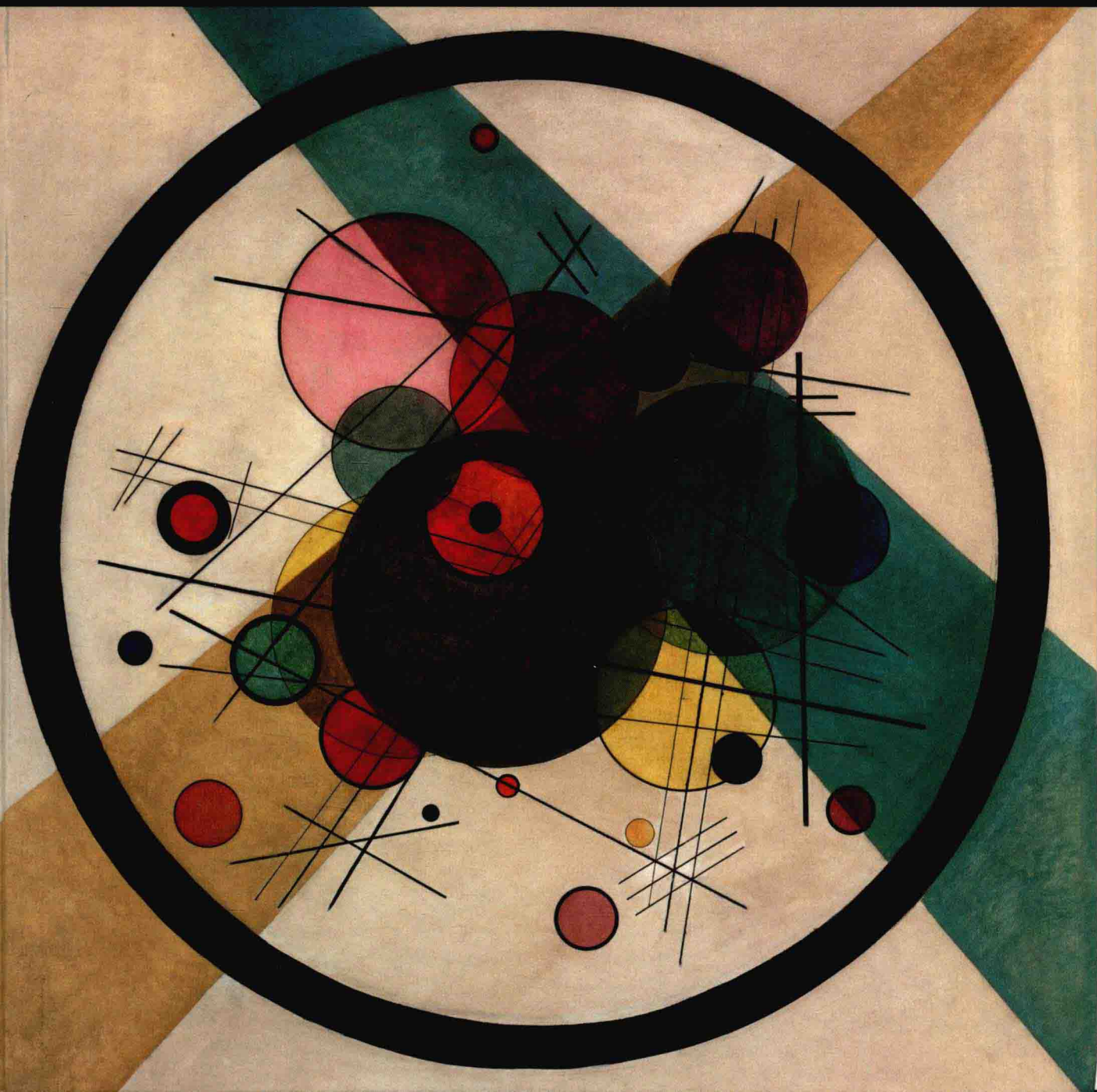


OPTICAL TWEEZERS

ES AND APPLICATIONS

Philip H. Jones, Onofrio M. Maragò
and Giovanni Volpe



Optical Tweezers

Principles and Applications

PHILIP H. JONES
ONOFRIO M. MARAGÒ
GIOVANNI VOLPE



CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org

Information on this title: www.cambridge.org/9781107051164

© Philip H. Jones, Onofrio M. Maragò and Giovanni Volpe 2015

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First published 2015

Printed in the United Kingdom by TJ International Ltd. Padstow Cornwall

A catalogue record for this publication is available from the British Library

ISBN 978-1-107-05116-4 Hardback

Additional resources for this publication at www.cambridge.org/9781107051164

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication, and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

Optical Tweezers

Combining state-of-the-art research with a strong pedagogical approach, this text provides a detailed and complete guide to the theory, practice and applications of optical tweezers. In-depth derivation of the theory of optical trapping and numerical modelling of optical forces are supported by a complete step-by-step design and construction guide for building optical tweezers, with detailed tutorials on collecting and analysing data. Also included are comprehensive reviews of optical tweezers research in fields ranging from cell biology to quantum physics.

Featuring numerous exercises and problems throughout, this is an ideal self-contained learning package for advanced lecture and laboratory courses and an invaluable guide to practitioners wanting to enter the field of optical manipulation.

The text is supplemented by the website www.opticaltweezers.org, a forum for discussion and a source of additional material including free-to-download, customisable, research-grade software (OTS) for calculation of optical forces, digital video microscopy, optical tweezers calibration and holographic optical tweezers.

Philip H. Jones is a Reader in Physics at University College London, where he leads the Optical Tweezers research group.

Onofrio M. Maragò is a Researcher at the Istituto per i Processi Chimico-Fisici (CNR-IPCF) in Messina, Italy, where he leads the Optical Trapping research group.

Giovanni Volpe is an Assistant Professor at Bilkent University, where he is head of the Soft Matter Lab.

To Annie, Becky, Andrew, Antonella, Carmen and Joana
For their love and patience

Preface

Since the first demonstration of optical tweezers approximately 30 years ago, they have become widespread both as a subject of research in their own right and as an enabling tool in fields as diverse as molecular biology, statistical physics, materials science and quantum physics. Currently the number of active research groups worldwide is in the hundreds – and counting. Furthermore, with the advent of commercially available optical tweezers and low-cost lab kits, optical tweezers experiments can now be found as a common instructional tool in advanced undergraduate and graduate laboratories. This broad interest gives rise to a pressing need for a reference textbook covering the principles and applications of optical tweezers. We began our journey of writing this book with the aim of filling this gap. Therefore we sought to write a textbook with a strong pedagogic approach to both the theory and practice of optical manipulation, supplemented by an overview of the current state of the art in optical manipulation research, and supported by exercises and problems. Eventually, this book saw the light of day.

This book comprises three parts. Part I covers the theory of optical tweezing, providing intuitive and rigorous explanations of the physics behind optical trapping and manipulation, an introduction to the numerical methods most commonly employed in the study of optical forces and torques, and a detailed explanation of the dynamics of optically trapped particles. Part II focuses on the experimental practice of optical manipulation, including both the implementation of a working optical tweezers set-up – complete with detailed step-by-step advice on its construction, on troubleshooting and on the acquisition and analysis of data – and instructions on how to develop more advanced optical manipulation techniques. Parts I and II both include numerous exercises to illustrate the concepts, ideas and techniques discussed, and each chapter ends with problems to solve as a starting point for further investigations. Finally, Part III provides an overview of some of the most exciting applications that optical tweezers have found in various fields, from the study of biological systems to the investigation of the quantum limit for trapped mesoscale objects. Furthermore, we have enhanced this book with an extensive supplementary material, available online for download from the book website at www.opticaltweezers.org. This includes, in particular, the comprehensive OTS – the Optical Tweezers Software toolbox, which we encourage readers to download, use and develop further.

Finally, we wish to thank all the colleagues and friends who have contributed to the writing of this book with their advice, input and encouragement. In particular, our special thanks go to Giuseppe Pesce for his help in writing Chapters 8, 9 and 11, Rosalba Saija for her constant advice on scattering theory and computational issues covered in Chapters 5 and 6, Agnese Callegari and S. Masoumeh Mousavi for their help in developing the OTS toolbox, Giorgio Volpe for his help in writing Chapter 7, and Juan José (Juanjo) Sáenz for

his critical reading of several chapters. We have also received a lot of help and assistance from Ferdinando Borghese, Maria Grazia Donato, Barbara Fazio, Marco Grasso, Pietro Gucciardi, Antonella Iatí, Alessia Irrera, Fatemeh Kalantarifard, Alessandro Magazzù and Mite Mijalkov. We have greatly profited from discussions with Ennio Arimondo, Paolo Denti, Roberto Di Leonardo, Andrea C. Ferrari, Chris Foot, Simon Hanna, Alper Kiraz, Isabel Llorente Garcia, Oliver Morsch, Antonio Alvaro Ranha Neves, Ferruccio Renzoni, Maurizio Righini, Antonio Sasso, Salvatore Savasta, Stephen Simpson and Cirino Vasi. We would also like to acknowledge the students and postdoctoral researchers in our laboratories, whose hard work has permitted us to spare the time needed to write this book. It goes without saying that we claim full ownership of any remaining errors.

Phil Jones
Onofrio Maragò
Giovanni Volpe

Contents

<i>Preface</i>	<i>page xv</i>
1 Introduction	1
1.1 A brief history of optical manipulation	2
1.2 Crash course on optical tweezers	4
1.3 Optical trapping regimes	6
1.4 Other micromanipulation techniques	8
1.5 Scope of this book	10
1.6 How to read this book	11
1.7 OTS - the Optical Tweezers Software	12
References	13
 Part I Theory	 17
2 Ray optics	19
2.1 Optical rays	20
2.2 Optical forces	24
2.3 Scattering and gradient forces	26
2.4 Counter-propagating beam optical trap	29
2.5 Optical tweezers	31
2.6 Filling factor and numerical aperture	34
2.7 Non-uniform beams	36
2.8 Non-spherical objects and the windmill effect	37
Problems	40
References	41
 3 Dipole approximation	 42
3.1 The electric dipole in electrostatics	43
3.2 Polarizability and the Clausius–Mossotti relation	45
3.3 The electric dipole in an oscillating electric field	50
3.4 Radiative reaction correction to the polarizability	52
3.5 Cross-sections	54
3.6 The optical theorem	56
3.7 Optical forces	58
3.7.1 Gradient force	61

3.7.2 Scattering force	63
3.7.3 Spin–curl force	64
3.8 Atomic polarisability	65
3.9 Plasmonic particles	67
3.10 Optical binding	70
Problems	73
References	75
4 Optical beams and focusing	76
4.1 Propagating electromagnetic waves	77
4.2 Angular spectrum representation	79
4.3 From near field to far field	81
4.4 Paraxial approximation	83
4.4.1 Gaussian beams	83
4.4.2 Hermite–Gaussian beams	85
4.4.3 Laguerre–Gaussian beams	87
4.4.4 Non-diffracting beams	89
4.4.5 Cylindrical vector beams	92
4.5 Focusing	92
4.6 Optical forces near focus	97
4.7 Focusing near interfaces	100
4.7.1 Aberrations	102
4.7.2 Evanescent focusing	102
Problems	104
References	105
5 Electromagnetic theory	106
5.1 Conservation laws and the Maxwell stress tensor	107
5.1.1 Angular momentum of light	111
5.2 Light scattering	116
5.2.1 Solution of the Helmholtz equation	116
5.2.2 The scattering problem	123
5.2.3 Multipole expansion	126
5.2.4 Transition matrix	131
5.2.5 Mie scattering	132
5.3 Optical force and torque	137
5.3.1 Optical force	137
5.3.2 Optical torque	139
5.4 Optical force from a plane wave	139
5.5 Transfer of spin angular momentum to a sphere	143
5.6 Optical force in an optical tweezers	146
5.6.1 Orbital angular momentum	149
Problems	151
References	152

6 Computational methods	154
6.1 T-matrix	155
6.1.1 Optical force	156
6.1.2 Optical torque	158
6.1.3 Amplitudes of a focused beam	160
6.1.4 Translation theorem	162
6.1.5 Rotation theorem	165
6.1.6 Clebsch–Gordan coefficients	168
6.2 Metal spheres sustaining longitudinal fields	170
6.3 Radially symmetric spheres	172
6.4 Clusters of spheres	174
6.4.1 Aggregates of spheres	174
6.4.2 Inclusions	176
6.4.3 Convergence	178
6.5 Discrete dipole approximation	179
6.6 Finite-difference time domain	180
6.7 Hybrid techniques	183
Problems	183
References	185
7 Brownian motion	188
7.1 The physical picture	189
7.2 Mathematical models	191
7.2.1 Random walk	192
7.2.2 Langevin equation	194
7.2.3 Free diffusion equation	195
7.2.4 Fokker–Planck equation	197
7.3 Fluctuation–dissipation theorem, potential and equilibrium distribution	197
7.4 Brownian dynamics simulations	199
7.4.1 White noise	200
7.4.2 Optically trapped particle	202
7.5 Inertial regime	205
7.6 Diffusion gradients	207
7.7 Viscoelastic media	211
7.8 Non-spherical particles and diffusion matrices	212
7.8.1 Free diffusion	213
7.8.2 External forces	215
Problems	216
References	217
Part II Practice	219
8 Building an optical tweezers	221
8.1 The right location	222
8.2 Inverted microscope construction	222

8.2.1 Objectives	226
8.2.2 Illumination schemes	232
8.3 Sample preparation	236
8.4 Optical beam alignment	239
8.4.1 Lasers	244
8.4.2 Lenses	246
8.4.3 Mirrors	248
8.4.4 Filters	248
8.4.5 Polarisation control	249
8.5 Optical trapping and manipulation	250
8.5.1 Steerable optical tweezers	251
8.6 Alternative set-ups	253
Problems	253
References	253
9 Data acquisition and optical tweezers calibration	255
9.1 Digital video microscopy	256
9.1.1 Digital cameras	261
9.2 Interferometry	262
9.2.1 Photodetectors	271
9.2.2 Acquisition hardware	273
9.3 Calibration techniques: An overview	273
9.4 Potential analysis	274
9.5 Equipartition method	276
9.6 Mean squared displacement analysis	278
9.7 Autocorrelation analysis	280
9.7.1 Crosstalk analysis and reduction	280
9.8 Power spectrum analysis	283
9.8.1 Analytical least square fitting	286
9.8.2 Hydrodynamic corrections	288
9.8.3 Noise tests	290
9.9 Drag force method	291
Problems	293
References	294
10 Photonic force microscope	296
10.1 Scanning probe techniques	297
10.2 Photonic torque microscope	300
10.3 Force measurement near surfaces	307
10.3.1 Equilibrium distribution method	308
10.3.2 Drift method	309
10.4 Relevance of non-conservative effects	311
10.5 Direct force measurement	312
Problems	316
References	317

11 Wavefront engineering and holographic optical tweezers	319
11.1 Basic working principle	320
11.2 Computer-generated holograms	324
11.2.1 Single steerable trap	325
11.2.2 Random mask encoding	327
11.2.3 Superposition of gratings and lenses	328
11.2.4 Gerchberg–Saxton algorithm	329
11.2.5 Adaptive–additive algorithm	331
11.2.6 Direct search algorithms	332
11.3 Higher-order beams and orbital angular momentum	332
11.4 Continuous optical potentials	334
11.5 Set-up implementation	335
11.5.1 Spatial light modulators	338
11.6 Alternative approaches	340
11.6.1 Time-shared optical traps	340
11.6.2 Generalised phase contrast	341
Problems	342
References	343
12 Advanced techniques	345
12.1 Spectroscopic optical tweezers	346
12.1.1 Fluorescence tweezers	347
12.1.2 Photoluminescence tweezers	349
12.1.3 Raman tweezers	349
12.2 Optical potentials	350
12.2.1 Periodic and quasi-periodic potentials	350
12.2.2 Random potentials and speckle tweezers	351
12.3 Counter-propagating traps and optical fibre traps	353
12.3.1 Optical stretcher	354
12.3.2 Longitudinal optical binding	355
12.4 Evanescent wave traps	356
12.4.1 Evanescent tweezers	356
12.4.2 Waveguides	357
12.4.3 Optical binding	358
12.4.4 Plasmonic traps	359
12.5 Feedback traps	361
12.6 Haptic optical tweezers	362
References	365
Part III Applications	369
13 Single-molecule biophysics	371
13.1 DNA mechanics: Stretching	372
13.2 DNA mechanics: Thermal fluctuations	374
13.3 DNA mechanics: Torsional properties	376

13.4 Motor proteins	379
13.5 Further reading	382
References	383
14 Cell biology	385
14.1 Cellular adhesion forces	386
14.2 Adhesion and structure of bacterial pili	388
14.3 Directed neuronal growth	389
14.4 Further reading	392
References	393
15 Spectroscopy	395
15.1 Absorption and photoluminescence spectroscopy	396
15.2 Raman spectroscopy	398
15.3 Coherent anti-Stokes Raman spectroscopy	402
15.4 Rayleigh spectroscopy and surface-enhanced Raman spectroscopy	402
15.5 Further reading	404
References	405
16 Optofluidics and lab-on-a-chip	409
16.1 Optical sorting	410
16.2 Monolithic integration	412
16.3 Photonic crystal cavities	414
16.4 Micromachines	415
16.5 Further reading	417
References	418
17 Colloid science	422
17.1 Hydrodynamic interactions	423
17.2 Electrostatic interactions	425
17.3 Depletion interactions	426
17.4 Further reading	430
References	430
18 Microchemistry	433
18.1 Liquid droplets	434
18.2 Vesicle and membrane manipulation	435
18.3 Vesicle fusion	438
18.4 Further reading	439
References	439
19 Aerosol science	441
19.1 Optical tweezers in the gas phase	442
19.2 Trapping and guiding	443

19.3 Photophoretic trapping and guiding	444
19.4 Further reading	445
References	446
20 Statistical physics	448
20.1 Colloids as a model system for statistical physics	449
20.2 Kramers rates	449
20.3 Stochastic resonance	451
20.4 Spurious drift in diffusion gradients	452
20.5 Colloidal crystals and quasicrystals	455
20.6 Random potentials and anomalous diffusion	455
20.7 Further reading	459
References	459
21 Nanothermodynamics	462
21.1 Violation of the second law	463
21.2 The Jarzynski equality	464
21.3 Information-to-energy conversion	465
21.4 Micrometre-sized heat engine	465
21.5 Further reading	467
References	468
22 Plasmonics	470
22.1 Plasmonic nanoparticles	471
22.2 Plasmonic substrates	474
22.3 Plasmonic apertures	477
22.4 Further reading	479
References	480
23 Nanostructures	484
23.1 Metal nanoparticles	485
23.2 Semiconductor nanostructures	486
23.3 Optical force lithography and placement	490
23.4 Prospects for nanotweezers	492
23.5 Further reading	492
References	493
24 Laser cooling and trapping of atoms	498
24.1 Laser cooling and optical molasses	499
24.2 Atom trapping	504
24.3 Optical dipole traps for cold atoms	506
24.4 The path to quantum degeneracy	507
24.5 Bose–Einstein condensation	508
24.6 Evaporative cooling and Bose–Einstein condensation in dipole traps	513

24.7 Holographic optical traps for cold atoms	514
24.8 Optical lattices	514
24.9 Further reading	518
References	518
25 Towards the quantum regime at the mesoscale	524
25.1 Cavity optomechanics: The classical picture	525
25.2 Cavity optomechanics: The quantum picture	527
25.3 Laser cooling of levitated particles	528
25.4 Feedback cooling schemes	529
25.5 Below the Doppler limit	531
References	534
<i>Index</i>	537