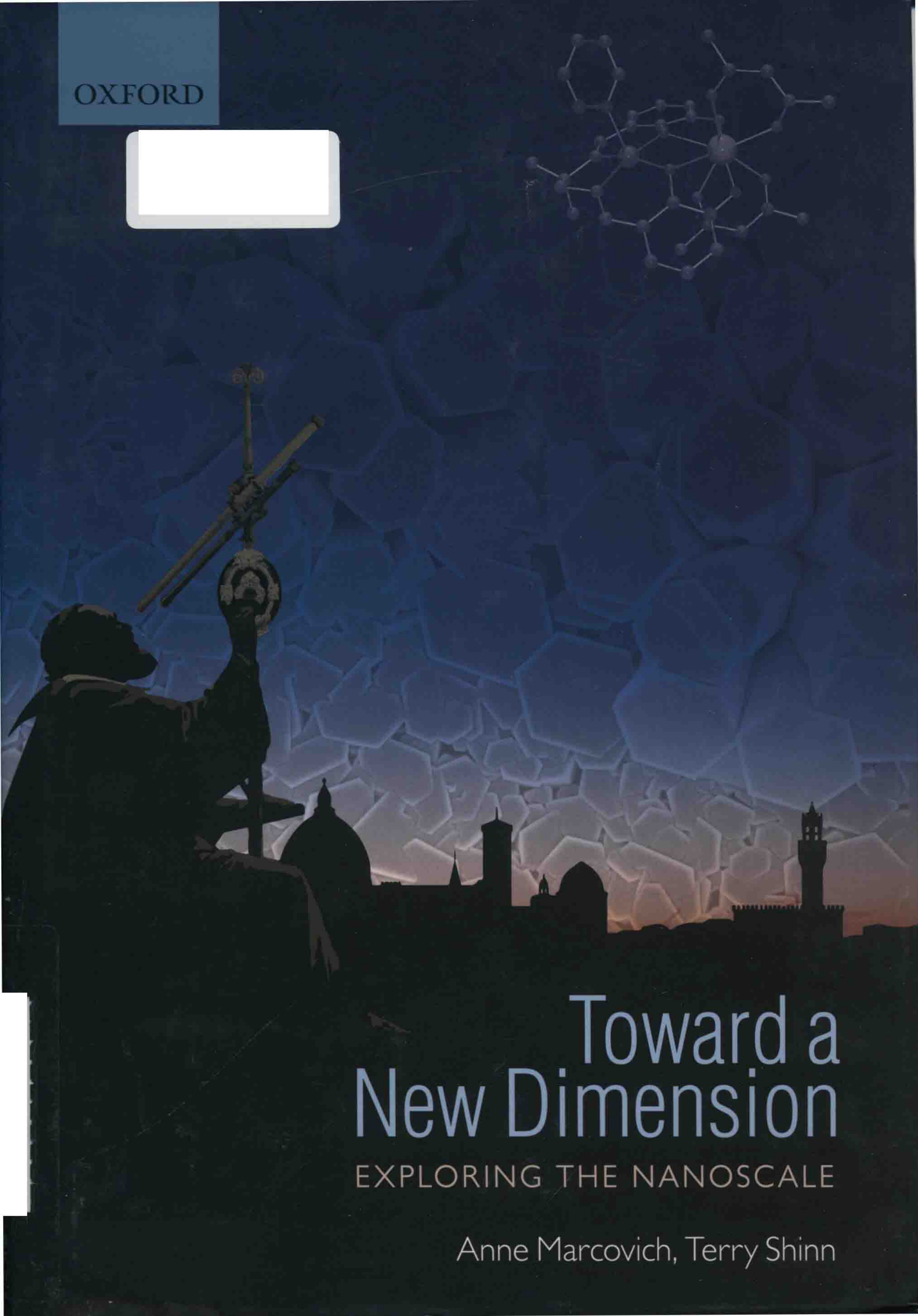

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Toward a New Dimension

EXPLORING THE NANOSCALE

Anne Marcovich, Terry Shinn

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OXFORD
UNIVERSITY PRESS

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Great Clarendon Street, Oxford, OX2 6DP,
United Kingdom

Oxford University Press is a department of the University of Oxford.
It furthers the University's objective of excellence in research, scholarship,
and education by publishing worldwide. Oxford is a registered trade mark of
Oxford University Press in the UK and in certain other countries

First Edition published in 2014

Impression: 1

Published in the United States of America by Oxford University Press
198 Madison Avenue, New York, NY 10016, United States of America

British Library Cataloguing in Publication Data
Data available

Library of Congress Control Number: 2014931557

ISBN 978–0–19–871461–3

Printed in Great Britain by
Clays Ltd, St Ives plc

TOWARD A NEW DIMENSION

For Paul Forman—a loyal and wise friend and exceptional scholar and colleague.
– Terry Shinn

For Jonathan, Esther, and Judith Elbaz—for their solidarity throughout this long project and for their love.
– Anne Marcovich

PREFACE

The research and writing of this book constitute one piece of our long-standing reflection about the theme of transformation in contemporary scientific research. It is commonly acknowledged that science has changed considerably over the course of the last century. In turning our gaze to research on the nanoscale, we asked what does the birth and growth of nanoscience tell us about the evolution of research? At the opening of this study, we were confronted by two contradictory answers to our questions about the transformative character of nanoresearch: "no, with nano there is nothing new under the Sun," and "yes, in nano, scientific investigation is being modified in many important ways." In view of these responses, nanoscale research appeared to be a privileged window to explore the confluence of the old and the new. The scientists' answers referred to the fact that science's theoretical foundations had not been seriously recast during the last decades, but that research practice and epistemology have become in important respects significantly different. Nanoscale research is a child of material, technological, and epistemological novelties. But at the same time, aspects of reasoning dominant during the nineteenth century, that had declined across much of the twentieth century, have suddenly and surprisingly been rekindled in combination with emerging technologies and accompanying experimental practices.

The epistemological arrow that historically slaved research questions to the materials available in nature has been reversed in nanoscale scientific investigation. This has opened the path for new ways of thinking and doing. Indeed since the 1980s, nanoscale research has been capable of synthesizing pre-designed materials, atom by atom and molecule by molecule, making it possible for experimenters to exactingly tailor the material objects to which they direct their questions. This constitutes a decisive historical turning point. Nanoscale research is the landscape of material control. Inside nano, an entirely new specialty has emerged that is devoted to the design, synthesis, and fabrication of preconceived objects.

Nanoscale research is inextricably linked to the genesis of a new species of metrological instrumentation. A category of instruments termed scanning probe microscopy lies at the heart of this material revolution. Such instrumentation can study (see) single molecules and atoms and can also shift them about and even attach them one to another, at will. A second recently introduced category of devices, "computational instrumentation," often known as "numerical simulation," has pervaded the research universe since the 1990s; but nowhere more so than in the area of nanoscale studies. Simulation based investigation has in several cases designed and explored nanostructured materials even prior to their concrete materialization. The relationship between metrological and computational experimentation in the nano field constitutes a deeply ingrained combinatorial that is central to nano culture. Scanning probe microscopy and numerical simulation both express information about the structure of nanoscale objects in terms of visual images. They simultaneously provide a synthetic and local picture of phenomena. For example, by sharpening pictorial contrasts of structure and by introducing differentiating color schemes into research images, practitioners painstakingly generate a cartography and corresponding comprehension of often nuanced nanoscale properties and processes. Of utmost importance, images operate as a common language between metrologists and simulators, thus promoting complementarity. They are indeed an epistemological cornerstone of nanoscience.

The function of images is tightly connected with questions of form. Images as drawings and also photographs were for a long time—throughout the nineteenth century and even before—important in science prior to nano. This was certainly the case with reference to things geographic, geological, botanic, zoological, anatomical, crystallographic, etc. It is essential to grasp that the pivotal position of form in nano explicitly constitutes a kind of renaissance of an earlier historical era. The morphology of objects and sometimes of their behavior is a key question in nanoscale research, thus giving a renewed importance to the traditional epistemological parameter of form. Through the new instrumentation of imaging, form has recovered its earlier importance that during much of the twentieth century had subsequently often been supplanted by mathematical formalism or statistical representations.

Taken together, images and form reinject an epistemology of descriptivism which was central to much pre-twentieth-century science. Descriptivism is a way of seeing the world, reflecting about it, ascribing relationships and explanation, and finally communicating about the world. In nano, description focuses on the highly local and particular. Nanometric landscapes are worthy of description in and of themselves, and not least of all for their local features. The combinatorial of description and local privileges the unique as opposed to the highly general. It is partly for this reason that theory and models are not the main expectation of nanoscientists.

Since the end of the nineteenth century, the microscopic universe, the worlds of molecules and atoms, was principally long described and explained in terms of statistical probability—the indeterminacy approach. This is certainly the case with the Schrödinger equation and the like. Scientists were restricted to determining the probability of an event. However, with the advent of nanoscale scientific research, with its battery of novel instrumentation and materials, under specified conditions it is now common practice to identify the position of a single molecule and even to study the morphology of its surface, as Galileo studied the landscape of the moon gazing through his telescope some four hundred years ago. Molecules and atoms are now understood in terms of a determinist epistemology, as opposed to a stochastic, probabilistic epistemology. The very action of molecular and atomic control constitutes the materialization of determinism.

The reader can see, therefore, that the nanoscale scientific enterprise rejuvenates many older intellectual traditions as they are re-introduced through new instrumentation and material control. We thus no longer frame the issue of transformations of contemporary scientific research in terms of *"no, there is nothing new under the Sun,"* versus *"yes, scientific investigation is being renewed in many important ways,"* but now we reason in terms of subtle combinatorials between the perpetuation of nineteenth-century epistemology and late twentieth-century materials and instrument evolution. It is this peculiar balance that allows us to effectively address the question of complex change in contemporary scientific research.

The issue of the significance of what has emerged in the course of recent scientific investigation, refers not only to matters of instrumentation, research-objects, and epistemology, but also extends to the question of the organization and institutions of research. The debate between the discipline based structuring of science versus interdisciplinarity continues to rage. Proponents of the disciplinary organization of work insist that original investigation must be tightly defined and that it occurs best in a disciplinary matrix. By contrast, pro-interdisciplinary advocates insist on cognitive complexity, heterogeneity, and fluidity, and they claim that innovative progress is not consistent with a disciplinary frame. Our investigation of nanoscience points in the direction of disciplinary structures, but that are reshaped in the context of contemporary cognitive practices which often entail well-defined, temporary collaborations of practitioners from different stable, established disciplinary domains. At the birth of nanoscale research, some practitioners predicted that the field would ultimately emerge as a new, autonomous scientific discipline. In contrast and more recently, many observers have argued that nano is totally fragmented, where each specialty possesses its specific nano routines.

Our study of nanoscale scientific research instead suggests that a "transversalist" perspective of nanoscience, and perhaps beyond nano (for many other areas of science), may offer a more perspicacious and balanced vision. As seen from our proposed transversalist perspective, nanoscale practitioners, whatever their home field, can work inside the framework of their homeland discipline while simultaneously speaking across their respective borderland to colleagues working in other fields. Boundaries and circumscribed circulation are here compatible. We refer to this species of organizational, institutional, cognitive configuration as the "new disciplinarity." Here, the maintenance of strong disciplinary boundaries does not preclude a practitioner standing on their disciplinary borderland and shouting across the boundary wall to colleagues who too work in their home disciplines and who also shout over the separating wall! If our assessment is correct, then the concept and activities of transversality, as vehicled in the new disciplinarity, are slated to become a component in the transformational processes of contemporary science—still another possible message gleaned from exploring the nanoscale.

ACKNOWLEDGEMENTS

We wish to thank the scholars who generously read our manuscript and provided commentary in the capacity of colleagues or reviewers: Bernadette Bensaud-Vincent (University of Paris I Sorbonne, Maria Caramez-Carlotto (University of Sao Paulo), Johannes Lenhard (Bielefeld University), Cyrus Moody (Rice University), Alfred Nordmann (Darmstadt University), Arnaud de Saint-Martin (Centre National de la Recherche Scientifique, Paris). Among the many scientists who we interviewed during our research, we are particularly indebted to: Tristan Cren, Roger Grousson, Bernard Jusserand, Claudine Noguera, Bernard Perrin, Valia Voliotis (Institut des Nanosciences, Paris), Gerald Dujardin, Philippe Minard, (University of Orsay, France), Uzi Landman (Georgia Institute of Technology), Paul Rothemund (Caltech University), Ned Seeman (New York University), Shimon Weiss (University of UCLA). We also thank Alexandra Frenod (Groupe d'Etude des Methodes de l'Analyse Sociologique de la Sorbonne, Centre National de la Recherche Scientifique) and Nora Scott for their alert editing of our manuscript. We are also indebted to Matthieu Renard, the art graphist who designed the book cover. Finally, it has been a pleasure to deal with Sonke Adlung and Jessica White at Oxford University Press who have constantly proven efficient and kind in the birth of the present volume.

LIST OF ABBREVIATIONS

AFM	atomic force microscope
CLSM	confocal laser scanning microscope
CVD	chemical vapor deposition
DFT	density functional theory
ESQC	elastic scattering quantum chemistry
FESEM	field-emission scanning electron microscopy
FRET	Förster resonance electron transfer or fluorescent resonance electron transfer
FTIR	Fourier transform infra-red spectroscopy
LEED	Low energy electron diffraction
MBE	molecular beam epitaxy
NEMS	nanoelectromechanical systems
NFOM	near field optical microscopy
NNI	nanotechnology initiative
NMR	nuclear magnetic resonance
NSR	nanoscale research
NST	nanoscience and technology
OES	optical emission spectroscopy
PCR	polymerase chain reaction
PES	photo-electron spectroscopy
QD	quantum dots
SAMs	self-assembling monolayers
SEM	scanning electron microscope
SPM	scanning probe microscopy
STM	scanning tunneling microscope
STS	scanning tunneling spectroscopy
TEM	transmission electron microscope
VR	virtual reality
XPS	X-ray photo-electron microscopy

CONTENTS

Introduction

Is the world of nano not in some ways akin to Galileo turning his telescope inward toward the nano universe? Galileo observed the landscape of the Moon and the satellites of Jupiter. Has nano not also "looked with the eye" onto the topography of single molecules and the geography of atomic constellation? On the other hand, Galileo, Copernicus, and Kepler could not conceive of rearranging the configuration and material of the Sun's planetary system in order to test and thus to better grasp the laws of nature. Yet nano can for its part modify or even create materials in such a way that scientists introduce artificial conditions by designing and fabricating molecule-scale universes for dreamed-of experimental study of objects that do not exist in nature. Through design, control, and observation on the scale of single molecules and atoms, nano replaces, or at least complements, the dominant long-standing probabilistic quantum perception of the micro universe with a deterministic epistemology of objects as stable forms; and with it, it correspondingly introduces an alternative neo-descriptivist paradigm.

In the land of nano-investigation, where the dimensions of objects neighbors a billionth of a meter, science has discovered that physical properties are determined strongly by size and form. Here the learning derived from the century-old exploration of "bulk materials," whose dimensions range between a few hundred nanometers and infinity, are no longer relevant. Are the introduction, evolution, and substance of this new way of observing, doing, and thinking not worthy of historical, epistemological, and sociological attention?

The orientation of this book contrasts with the direction of much contemporary scholarship, which examines scientific research in terms of the public understanding of science, government research policy, innovation, communication, and the evolution of the institution of science in post-modern culture. Our study instead focuses on intra-cognitive elements: we investigate the place of instrumentation and materials in the origins and structuring of nanoscale research (or NSR) and explore questions of epistemology with reference to form, image, descriptivism, and determinism. The intra-cognitive side of science is investigated as opposed to an alternative path which examines its extra-cognitive dimensions. In short, this book stands at the crossroads of the history of ideas in contemporary science and its sociology.

The rapid expansion and considerable cognitive achievements of research on nanodimension objects spring from two factors: (1) the ability to observe and analyze the surface features of single molecules and their position; (2) the power to control their spatial relations. The originality of nanoscale research and its distinction from other fields of science revolve around this tandem. The connection between single molecules and control notably endows nanoscale research with a measure of transversality of scientific relevance. Single-molecule observation and atom-by-atom and molecular-based designed, made-to-order materials are today central to the growth of contemporary knowledge in both the physical sciences and the life sciences. This transversality of nanoscale investigation runs counter to the received view that nano constitutes an acutely fragmented field. On a different register, the physical characteristics of matter have traditionally defined and restricted the questions that can be formulated in a research project. In the case of nano-investigations, however, the relationship between material and question is reversed. Why is this? The power to design and build novel materials signifies that questions can now fuel materials rather than being slaves to them. This is a foremost contribution of science nano style.

In nanoscale research, the observational empowerment acquired through the invention of the scanning tunneling microscope, or STM (1981), and of its cousin the atomic force microscope, or AFM (1985), has now made it possible for the first time in the annals of research to explore single molecules, to study an individual molecule's surface features and internal structure. These instruments also enable nanopractitioners to identify the location of an atom, to observe the sometimes complex and surprising geometry of interfacing or locking. In addition to the possibility of dealing with single objects, in nanoscale research, the capacity to design and to synthesize an expanding variety of man-made, artificial materials are also synonymous with nanoscale science. Materials include fullerenes, and in particular carbon nanotubes, and equally decisive, although perhaps less well known, low-dimensional materials such as nanowires, nanowells, and quantum dots. The crucial point here is that these novel materials and instruments now open the way to an unprecedented dialog between the articulation of research questions and what we term "materials by design." Note that objects of nanometric dimensions exhibit properties or behaviors absent or different from bulk materials. Bulk materials are particles whose dimensions exceed one micron, and their surface is small compared with their volume. In nano objects, large surface-to-mass ratios transform physical characteristics.

Recall that a nanometer measures one billionth of a meter; this is equivalent to one ten thousandth of the diameter of a human hair! Precise control at this scale is now routine. Control is situated at the intersection of instrumentation and material. For example, devices like the scanning tunneling microscope enable the manipulation of atoms so precisely that words can be spelled out using clusters of individual atoms to form letters. This was demonstrated in 1989, in a famous article by Donald Eigler in which he wrote the abbreviation IBM with 35 xenon atoms. This feat astounded scientists the world over and alerted them to the latent promise of nanoscale research. Such exact manipulation is now common practice; it is regularly mobilized to create defined molecular and atomic architectures that are the foundation of unprecedented materials, and it underpins