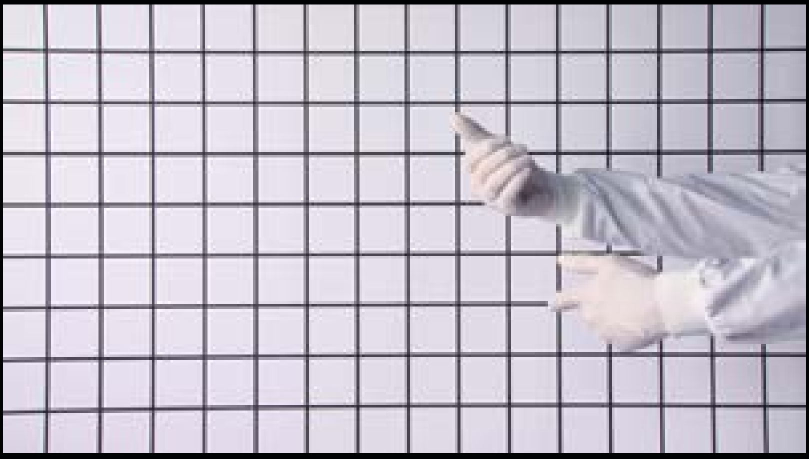
LABORATORY EPISTEMOLOGIES

A HANDS-ON PERSPECTIVE

JENNY BOULBOULLÉ



L A B O R A T O R Y * * *

E P I S T E M O L O G I E S

Experimental Futures

Technological Lives, Scientific Arts, Anthropological Voices

A series edited by

Michael M. J. Fischer and Joseph Dumit

LABORATORY EPISTEMOLOGIES

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JENNY BOULBOULLÉ

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For Robert, Noor, and Pim,
and my parents, Anja and Guido

CONTENTS

NOTE ON DESCARTES'S TEXTS AND THEIR TRANSLATION

The philosopher and experimenter René Descartes (1596–1650) wrote his treatises and corresponded in Latin and in French. His masterwork, *Meditations on First Philosophy*, was first published in Latin in 1641 but soon translated into French and issued during his lifetime with his approval. See "Works by René Descartes" in the bibliography for the editions of Descartes's treatises and letters cited in this book and the modern English-language translations consulted. The citation system is explained here.

For Descartes's works and correspondence, I generally cite the standard modern edition: René Descartes, *Oeuvres de Descartes*, 11vols., edited by Charles Adam and Paul Tannery (Paris: Vrin, 1996 [1896–1901]), abbreviated as at I–XI. Citations show the shortened title of Descartes's work with the appropriate volume number of at, as in this example: Descartes, *Les méditations métaphysiques,* at IX. Page numbers appear at the end in all citations. at is accessible online at History of Philosophy: Texts Online, http://philosophyfaculty.ucsd.edu/faculty/ctolley/texts/descartes.html.

When I cite directly from the first print editions of individual works by Descartes, I give the shortened title of the work, followed by the year of publication, as in this example: Descartes, *Les méditations métaphysiques* (1647). Select first editions are accessible online at Corpus Descartes: Édition en ligne des oeuvres et de la correspondence de Descartes, https://www.unicaen.fr/puc/sources/prodescartes/presentation.html.

For all English-language translations of Descartes's writings, I have whenever possible consulted existing translations. As needed, I have adapted and modified them to keep them as close as possible to the original French texts. I relied primarily on: René Descartes, *The Philosophical Writings of Descartes*, 2 vols., translated by John Cottingham, Robert Stoothoff, and Dugald Murdoch (Cambridge: Cambridge University Press, 1985), abbreviated as csm 1–2; and René Descartes, *The Philosophical Writings of Descartes*, Vol. 3, *The Correspondence*, translated by John Cottingham, Robert Stoothoff, Dugald Murdoch, and Anthony Kenny (Cambridge: Cambridge University Press, 1991), abbreviated as csmk. Citations show the short title of Descartes's work or details of the correspondence, followed by the appropriate volume number, as in these examples: Descartes, *Meditation on First Philosophy*, csm 2; Descartes, letter to Mersenne, June 1632, csmk.

Other translations I consulted are: René Descartes, *Discourse on Method, Optics, Geometry, and Meteorology*, translated and edited by Paul J. Olscamp, (Indianapolis, IN: Bobbs-Merrill, 1976); and René Descartes, *The World and Other Writings*, translated and edited by Stephen Gaukroger (Cambridge: Cambridge University Press, 1998). These are cited as in this example: *Optics*, in Descartes, *Discourse on Method*.

* * *

One of the most critical passages of Descartes's *Meditations on First Philosophy* for the present book is his detailed account of a "wax *experience*," described in the Second Meditation. The relevant pages from the first French edition of the work, *Les méditations métaphysique* (1647), 26–27, follow here (see also figs. 1.2 and 1.3).

bride, afin que venant cy-apres à la retirer doucement & à propos, nous le puissions plus facilement regler & conduire.

Commençons par la consideration des choses les plus communes, & que nous croyons comprendre le plus distinctement, à sçauoir les corps que nous touchons & que nous voyons. Ie n'entens pas parler des corps en general, car ces notions generales sont d'ordinaire plus confuses, mais de quelqu'vn en particulier. Prenons pour exemple ce morceau de cire qui vient d'estre tiré de la ruche, il n'a pas encore perdu la douceur du miel qu'il contenoit, il retient encore quelque chose de l'odeur des fleurs dont il a esté recueilly; sa couleur, sa figure, sa grandeur, sont apparentes: il est dur, il est froid, on le touche, & si vous le frappez, il rendra quelque son. Enfin toutes les choses qui peuuent distinctement faire connoistre vn corps, se rencontrent en celuy-cy.

Mais voicy que cependant que ie parle on l'aproche du feu, ce qui y restoit de saueur s'exale, l'odeur s'euanoüit, sa couleur se change, sa figure se perd, sa grandeur augmente, il deuient liquide, il s'échauffe, à peine le peut-on toucher, & quoy qu'on le frappe il ne rendra plus aucun son: La mesme cire demeure-t'elle aprés ce changement? Il faut auoüer qu'elle demeure, & personne ne le peut nier. Qu'est-ce donc que l'on connoissoit en ce morceau de cire auec tant de distinction? Certes ce ne peut estre rien de tout ce que i'y ay remarqué par l'entremise des sens, puis que toutes les choses qui tomboient sous le goust, ou l'odorat, ou la veuë, ou l'attouchement, ou l'ouye se trouuent changées, & cependant la mesme cire demeure. Peut-estre estoit-ce ce que ie pense maintenant, à sçauoir que la cire n'estoit pas, ny cette douceur du miel, ny cette agreable odeur des fleurs, ny cette blancheur, ny cette figure, ny ce son, mais seulement vn corps qui vn peu auparauant me paroissoit sous ces formes, & qui maintenant se fait remarquer sous d'autres. Mais qu'est-ce precisément parlant que i'imagine, lors que ie la conçoy en cette sorte? Considerons-le attentiuement, & éloignant toutes les choses qui n'appartiennent point à la cire, voyons ce qui reste. Certes il ne demeure rien que quelque chose d'estendu, de flexible & de muable: Or qu'est-ce que cela flexible & muable? n'est-ce pas que i'imagine que cette cire estant ronde est capable de deuenir quarrée, & de passer du quarré en vne figure triangulaire? non certes ce n'est pas cela, puis que ie la conçoy capable de receuoir vne infinité de semblables changemens, & ie ne sçaurois neantmoins parcourir cette infinité par mon imagination, & par consequent cette conception que i'ay de la cire ne s'accomplit pas par la faculté d'imaginer.

Qu'est-ce maintenant que cette extension? n'est-elle pas aussi inconnuë? Puis que dans la cire qui se fond elle augmente, & se trouue encore plus grande quand elle est entierement fonduë, & beaucoup plus encore quand la chaleur augmente dauantage; & ie ne con-

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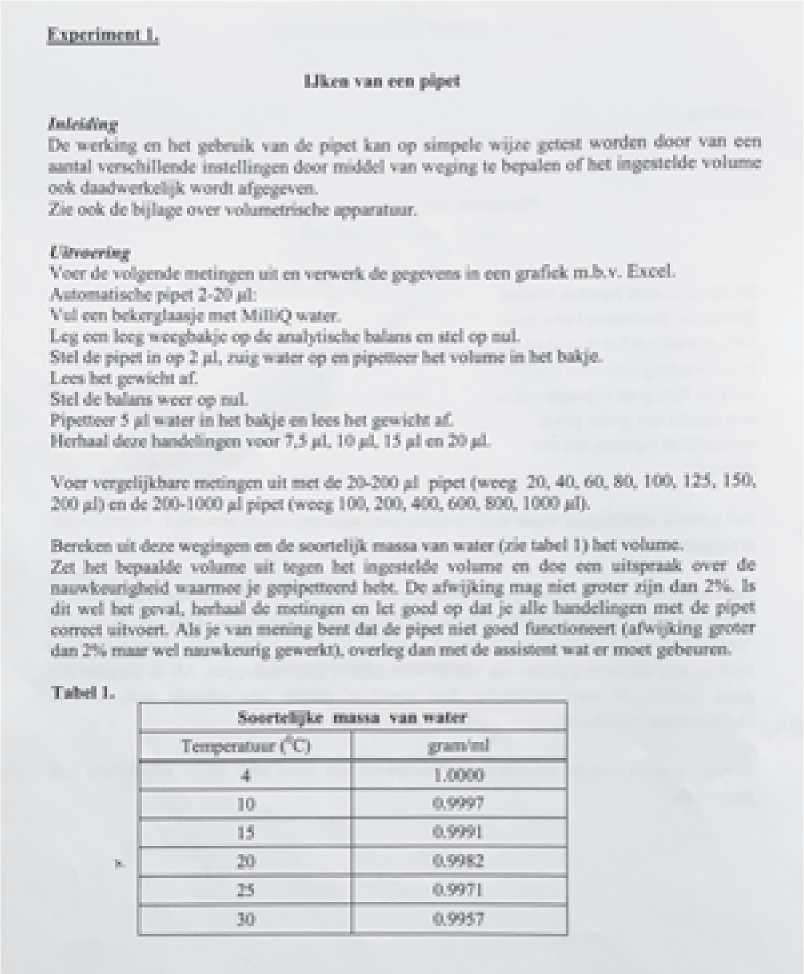
Introduction

A FEELING FOR THE LIFE SCIENCES

Looking back at my first day in a teaching laboratory for life sciences and chemistry students, I remember how unfamiliar it felt in the beginning to hold a pipette, to pick up the sterile tips without touching them, and to fill them without sucking up air bubbles. Microliter pipettes are delicate and expensive instruments adapted for exact measurements. They form an indispensable part of innumerable procedures in technoscientific research and production laboratories all over the world. Ensuring that these manually operated precision tools are used accurately and function properly is not trivial but is part and parcel of good laboratory practice in the life sciences. Today's automatic microliter pipettes are adapted for accuracy and exactness to measure and transfer volumes of liquids as small as 2 microliters (μl), swiftly with one hand—if calibrated correctly and handled



Experiment 1.

IJken van een pipet

Inleiding
De werking en het gebruik van de pipet kan op simpele wijze getest worden door van een aantal verschillende instellingen door middel van weging te bepalen of het ingestelde volume ook daadwerkelijk wordt afgegeven.
Zie ook de bijlage over volumetrische apparatuur.

Uitvoering
Voer de volgende metingen uit en verwerk de gegevens in een grafiek m.b.v. Excel.
Automatische pipet 2-20 µl:
Vul een bekerglaasje met MilliQ water.
Leg een leeg weegbakje op de analytische balans en stel op nul.
Stel de pipet in op 2 µl, zuig water op en pipetteer het volume in het bakje.
Lees het gewicht af.
Stel de balans weer op nul.
Pipetteer 5 µl water in het bakje en lees het gewicht af.
Herhaal deze handelingen voor 7,5 µl, 10 µl, 15 µl en 20 µl.

Voer vergelijkbare metingen uit met de 20-200 µl pipet (weeg 20, 40, 60, 80, 100, 125, 150, 200 µl) en de 200-1000 µl pipet (weeg 100, 200, 400, 600, 800, 1000 µl).

Bereken uit deze wegingen en de soortelijk massa van water (zie tabel 1) het volume.
Zet het bepaalde volume uit tegen het ingestelde volume en doe een uitspraak over de nauwkeurigheid waarmee je gepipetteerd hebt. De afwijking mag niet groter zijn dan 2%. Is dit wel het geval, herhaal de metingen en let goed op dat je alle handelingen met de pipet correct uitvoert. Als je van mening bent dat de pipet niet goed functioneert (afwijking groter dan 2% maar wel nauwkeurig gewerkt), overleg dan met de assistent wat er moet gebeuren.

Tabel 1.

Soortelijke massa van water	
Temperatuur (°C)	gram/ml
4	1.0000
10	0.9997
15	0.9991
20	0.9982
25	0.9971
30	0.9957

I.1 * “Experiment 1: IJken van een pipet” (translation, *opposite*). Instructions for biochemistry practicum, Gorlaeus Laboratories, Leiden University. From Erik Vijgenboom et al., “Handleiding Introductie & Biochemie Practicum I, Sept–Okt 2005,” p. 11.

properly and with care. Functioning, well-calibrated pipettes are, indeed, vital to life science laboratories’ routines. Perhaps not surprisingly, then, the first experiment I performed in the biochemistry practicum at Leiden University was the calibration of a microliter pipette (figure I.1).1 Indeed, it is no coincidence that we as novices spent our first day in the laboratory calibrating pipettes: setting measurements, fitting plastic tips onto pipettes, sucking up tiny amounts of fluids, transferring and releasing fluids into plas-

Experiment 1.

Calibration of a Pipette

Introduction

The functioning and the use of the pipette can be tested in a simple manner. By means of a set of weight experiments, it can be determined whether the set volume is delivered indeed. . . .

Protocol

Perform the following measurements and process the data using Excel.
Automatic pipette 2–20 µl:
Fill a beaker with Milli-Q water.
Put an empty plastic medicine cup on the analytical balance and set to zero.
Set the pipette to 2 µl, draw water with the pipette, and pipette the volume into the plastic cup.
Record the weight.
Set the balance back to zero.
Pipette 5 µl water into the cup and record the weight.
Repeat this for 7.5 µl, 10 µl, 15 µl, and 20 µl.

Likewise, repeat the procedure with the 20–200 µl pipette (use 20, 40, 60, 80, 100, 125, 150, 200 µl) and the 200–1,000 µl pipette (use 100, 200, 400, 600, 800, 1,000 µl).

Calculate from the recorded weights and the relative density of water (see Table 1) the (average) weight volume. Plot the weight volume against the set volume and make a statement about the precision with which you pipetted. The deviation should not exceed 2 percent. If the deviation is larger, you should repeat the measurements. Pay close attention to handling the pipette correctly during all steps of the procedure. If you believe the pipette is not functioning properly (the deviation is larger than 2 percent, in spite of working correctly), discuss with the assistant the next step(s).[2]

Table 1

Specific Gravity of Water	
Temperature (°C)	**g/mL**
4	1.0000
10	0.9997
15	0.9991
20	0.9982
25	0.9971
30	0.9957

I.2 * Still from “How to Calibrate Pipettors,” YouTube, posted by benchflydotcom, October 23, 2009, https://www.youtube.com/watch?v=ImFy3tBC-8o&feature=youtu.be.

tic cups, weighing them with high-precision scales and minutely recording the weights, entering data into Excel tables, calculating average weights and statistical errors, and finally producing digital graphs and interpreting them.

In retrospect, our calibration experiment turned out to be much more than a repetitious, dull, and tedious mechanical procedure of weighing minuscule water droplets. In fact, calibrating an everyday lab tool on our first day introduced us to indispensable skills needed for successful experimentation. Moreover, when pipettes are used conscientiously—in conjunction with disposable sterile plastic tips—experienced pipettors can handle tiny amounts of liquids with hardly any risk of contamination. Numerous online instructions and how-to videos on the proper use and maintenance of pipettes show that good pipetting is not only a basic skill but also a matter of ongoing concern in contemporary laboratories (figure I.2).

Life sciences research and instruction sites are devoted to the study of life processes on cellular and molecular levels—mostly invisible to the naked eye. In retrospect, measuring microscopic amounts of transparent and odorless fluids epitomized my experience of doing molecular biological experiments. Only rarely could I perceive the life processes that we were investigating with my ordinary senses—that is, by sight or touch—though we definitely smelled the specific odor of the *Escherichia coli* bacteria that naturally inhabit our lower intestines. Most of the life-forms we worked with were cultivated in the lab; as such, we would not generally be able to encounter these "model organisms" in nature, outside the confines of the laboratory. Most important, I learned that it is crucial in a life science lab to handle barely visible amounts of media, living and nonliving, and that it was critical to avoid any unnecessary physical disturbance of these media and particularly to not bring them directly, or indirectly, into contact with any surfaces or parts of my body. Proper handling of manual precision tools is hereby of vital importance.

In hindsight, our calibration experiment can perhaps best be described as a complex process of "enskillment," "skilled practice," and cultivation of specific "bodily techniques" that involves a training of manual as well as cognitive abilities—minds and hands.[3] In practice, our calibration experiment made visible the entangled activities of manual benchwork, material engagement, observational documentation, and statistical data processing. Calibration understood *as practice* makes us attentive to the interdependency of mind, hand, instruments, and materials in scientific experimentation. Moreover, performing the experiment made plain that calibration is an *embodied* practice that fine-tunes body-instrument interactions and fosters a mindful engagement with materials for scientific analysis.[4]

Hands-On Knowledge Making in the Life Sciences

The initializing calibration experiment turned out to be programmatic for the book that you now hold in your hands. This seemingly simple experiment brings us right to the core of what this book is about: developing a better understanding of apparently mundane, yet on closer view complex, knowledge-making practices in the life sciences that remain resistant to categorical distinctions between mind and hand. What is at issue is the very idea that we can envision a neat dividing line between the cognitive and the manual in doing life sciences.

Instead, I argue that we can best describe the work of life scientists in instruction and research laboratories with a continuum approach that does not privilege mind over hand and rationalization over material engagement. However, while life science handbooks are full of scientific descriptions of complex life processes, they lack any descriptions of the complexities of benchwork or idiosyncrasies of bodily work in microbiological labs that underpin the wealth of information that life science students have to get into their heads—and the bits they have to be able to reproduce by hand. Paradoxically, the manual knowledge that comes with skilled practice—and forms an integral part of lab-based learning and experimental research in the life sciences—appears to have been written out of life science handbooks. And not only out of books: manual training and research are done in the lab but, generally, are not topics of discussion in life science lecture halls and research meetings. In this book, I put the manual center stage. To better understand how it functions as an integral part of knowledge making in the life sciences, I investigate hands-on laboratory practices from an ethnographic, historical, and philosophical perspective. I argue that the manual should be acknowledged not only as a fundamental part of daily life science research but also as a vital feature of epistemologies concerned with life processes on cellular and molecular levels—that is, the theoretical discourses of *how* we can gain knowledge of life processes on (sub)cellular levels. As knowledge makers, we should be able not only to manually produce knowledge but also to talk about and understand—culturally, historically, and philosophically—*how we make knowledge*. In this sense, this book functions as a how-to book for life sciences research, that is, as *a manual* for making *the manual* explicit in experimental life sciences.

Fundamentally, this is an epistemological question that requires recalibration from a hands-on perspective. This book thus situates reflections on today's experimental life sciences within broader debates on knowledge making in history and philosophy of science. It provides a *long durée* philosophical perspective with a radical rereading of a key source text in epistemology: at its heart lies an invitation to read René Descartes's (1596–1650) famous *Meditations* against the grain of an outdated but persistent Cartesianism that has traditionally located capacities of knowing in our minds, not our hands. Based on participatory hands-on experiences in molecular biology, I offer a critical reading of laboratory ethnographies that fundamentally recalibrates anti-Cartesian discourses in science studies.

Recalibrations

Learning to work accurately with a micropipette and becoming habituated to proper handling of pipettes and tips takes a while. It is a skill that is learned through continuous practice. Moreover, becoming attuned to a manual precision tool is a reciprocal process that affects both instrument and operator.

During our first-year calibration experiment, no information was given on how to proceed in case an inaccuracy of our tested pipette would have been established, nor were we given access to calibration tools to make such adjustments ourselves. I suppose our teachers and tutors generally assumed that any significant deviations in the accuracy of the instrument were more likely due to our poor performances during the process of calibration than to dysfunction of our tested pipette. Most likely, our first-day experiment was just as much geared toward calibrating the bodily skills of us novices as toward calibrating our new tools. In retrospect, I like to think of this first day of weighing water droplets with my bench partner, a first-year chemistry student, as an initiation rite into the art of pipetting with an automatic microliter pipette—an indispensable skill in experimental life sciences research. The *Oxford English Dictionary* defines *pipettor* (= *pipetter*, n.) as an instrument that allows for automated operation of one or more pipettes.5 Yet *pipettor* cannot refer only to a machine that can automatically operate several pipettes. *Pipettor* is grammatically and etymologically analogous to terms like *instructor*, *lecturer*, or *practitioner*. In all these examples the suffix *-er* or *-or* is added to the stem of a verb. The endings *-er* and *-or* historically served to designate persons according to their profession or occupation: someone who experiments becomes an *experimenter*. Derivatives from action verbs are also called agent nouns. Agent nouns, like *instructor*, *teacher*, and *vlogger*, are nowadays used to denote not only human but also material agents, or even instruments. *Pipettor* is such a multivalent term, which can in fact denote both—an instrument (i.e., a material agent) and the operator of an instrument (i.e., a human agent who operates a pipette). This semantic ambivalence aptly conveys the intimate relationship of instrument and instrument operator that is key to good scientific benchwork. So we might wonder what it was that was calibrated during our first-day experiment—the pipettes or us, the instrument users? Perhaps, we can best say that the calibration of a *pipettor* teaches us—albeit implicitly—a lesson in the reciprocal and fine-tuned body-instrument actions of laboratory work and that the semantic ambiguity of *pipettor* testifies to the intimately entangled user-instrument relations and skillful mind/hand/tool/material interactions in scientific practices.

What motivated me to write this book was experiencing how knowledge making in life science labs requires as much training in dexterity and care as cognitive capacities for operating with biological concepts in the abstract realms of genes, proteins, molecules, deoxyribonucleic acid (dna) codes, and Mendel's laws. Yet, when interning with life scientists in the molecular genetics laboratories of the Leiden Institute of Chemistry, I wondered why successful careers in the life sciences are rarely acclaimed for the expertise that researchers gained during years-long or even lifelong training in highly skilled hands-on practices. The aim of this book is to write researchers' hands and bodies back into the sciences of life and to make them explicit in theories of scientific knowledge production. The book draws on historical and ethnographic accounts of past and present hands-on practices to explicate the role of the manual and embodied practices in knowledge-formation processes since the rise of the experimental life sciences in the seventeenth century.

Becoming a Life Scientist

> You let the material tell you where to go, and it tells you at every step what the next has to be because you are integrating with an overall brand new pattern in your mind. You are not following an old one; you are convinced of a new one.
>
> Barbara McClintock, quoted in Evelyn Fox Keller, *A Feeling for the Organism*

The biography *A Feeling for the Organism* traces the academic career of Barbara McClintock (1902–1992), a plant biologist and a pioneer in the field of cytogenetics in the context of the emergent life sciences.[6] The conversations on which the publication is based are a testimony to an encounter between two extraordinary women of science. The interviewee, McClintock, was the first woman to receive an unshared Nobel Prize in Physiology and Medicine (1983). The interviewer, Evelyn Fox Keller (1936–2023), was an eminent scholar known for her important oeuvre on gender and science and the history and philosophy of the life sciences that shape our understanding of genetics and molecular biology.[7] Keller interviewed not only McClintock but also McClintock's peers and former students, to give voice to a researcher whose work on plant genetics has long remained in the shadow of more prominent male-dominated narratives of the rapidly unfolding "molecular revolution" in twentieth-century biology. Keller's portrayal of McClintock and her lifelong research on innumerable minute details of genetic organization in plants and fungi shows how this life scientist, who could see what others could not see, contributed to the rise of a "new biology" that came to focus on genetics and cellular and molecular processes.[8] Yet, McClintock's groundbreaking research on mobile genetic elements in maize was strikingly slow to win acclaim from her peers. When her biography was published in 1983—the same year that she would receive the highest possible scientific recognition for the research she conducted in the 1940s—the biologist had reached the eminent age of eighty-two.

In one of the interviews, McClintock recalls how she became fascinated with biological research, first as a student and later as a scientist specializing in plant genetics. When Keller probed her about the capacities that made her into an outstanding scientist, the biologist expressed her wish to be "free of the body." "The body," she told her biographer, "was something you dragged around." To her, it was not something that enabled her to experience and perceive what interested her but something that stood in the way, a burden that appeared to hold her back from fulfilling her scientific ambition. As she explained: "I always wished that I could be an objective observer, and not be what is known as 'me' to other people." Her own "bodily me" was first and foremost an impediment that others mistakenly associated her with and which she preferred to ignore.[9]

Keller chronicles McClintock's ambivalent feelings about her body throughout her academic career. When the biologist talks about her passion for learning and how she enjoyed writing an exam in her favorite subject while still a high school student, she recalls how she experienced her own body as something irritating and annoyingly irrelevant, yet persistently present: "I think it had to do with the body being a nuisance. What was going on, what I saw, what I was thinking about, and what I enjoyed seeing and hearing was so much more important."[10] McClintock intimates a longing for a transparent body that could not block her view and would not get in the way of all the more important things she wanted to explore and understand. This wish appears at once sensible and puzzling in light of her own research on our bodies' innermost life processes, which we share with other living organisms. Her biographer presents these recollections as moments of special concentration, highlighting McClintock's remarkable ability to be fully absorbed in learning and later in research: they provide a glimpse "of the characteristics that would be so important in defining her as a scientist."[11] We see here how McClintock's extraordinary "feeling for the organism" is framed as a disembodied affair. What marks her out as a successful scientist is her capacity to forget her "bodily me"—or, as she puts it, an ability to make sense of a living being despite the nuisance of having a body that appears to obscure rather than illuminate the clarity of her exceptional vision of a body's innermost life processes.

In the course of the first half of the twentieth century, biology and the field of classical Mendelian genetics saw a rapid transformation when the concept of the gene became more and more materially defined, culminating in the mid-twentieth century in Oswald Avery's identification of dna as the bearer of genetic information and its reconceptualization as the "master molecule of life."[12] Mendel's fuzzy concept of a gene had now become a *molecular object*, a term used by James Watson, one of the three male laureates who won the Nobel Prize in 1962 for providing a molecular structure for dna.[13] Noticeably, as Mark Lawler posted in *The Conservation* on April 24, 2018, these researchers' female collaborator, Rosalind Franklin, has never received the proper recognition for her scientific contribution to these groundbreaking publications.[14] Franklin (1920–1958), whose work on experimental visualizations of dna molecules with X-ray diffraction photography was instrumental in discovering the double helix structure of deoxyribonucleic acid in the 1950s, never made it onto the list of Nobel Prize nominees in the 1960s, as the prize is not awarded posthumously.[15] Despite her untimely, early death, this fact may still raise questions about gender biases in scientific committees and also might suggest that a scientist's skilled and innovative mastery of new imaging technologies did not speak as much to the imagination of the Nobel Prize Committee as did the idea of a marvelous "meeting of minds" that was later promoted by Watson and Crick.[16] As we will see, this emphasis on ingenious minds was omnipresent and went hand in hand with a conspicuous disregard for the virtuoso experimental handiwork involved in writing the history of the life sciences in twentieth-century laboratories.

The first half of the twentieth century saw a growing interest in genetics and the mechanisms of inheritance among physicists, who brought, in the words of the famous theoretical physicist Max Delbrück (1906–1981), a "new intellectual approach to biology."[17] McClintock's work on maize genetics must be seen in the context of a larger shift in focus from multicellular plants and animals to quickly reproducing single-celled microorganisms and minuscule bacterial viruses—too small to see under a light microscope—as preferred objects for gene studies. A new biology was on the rise that aimed at bringing life phenomena back to the most basic mechanisms and to study these as much as possible in isolation from nature's diversity, complexity, and the time-consuming cultivation dependent on annual seasons. The bold reductionism that arrived in 1945 along with Delbrück at Cold Spring Harbor Laboratory, on Long Island, New York, "was steeped in a tradition that seeks understanding in simplicity rather than complexity."[18] For the "new biologists" this quest for simplicity entailed—"naturally," so to speak—a search for the smallest living organism that could provide the simplest possible system for the study of fundamental life processes.[19] In a lecture delivered in 1946, Delbrück introduced the rhetorical figure of an "imaginary physicist" equipped with the powerful vision needed to solve the secret of life with an irresistibly reductionist model: a bacterial virus that was hailed as the smallest and simplest organism for the study of life's basic mechanisms.[20] Delbrück envisioned this as follows: "We will do a few experiments at different temperatures, in different media, with different viruses, and we will know. Perhaps we may have to break into the bacteria at intermediate stages between infection and lysis. Anyhow, the experiments can only take a few hours each, so the whole problem cannot take long to solve."[21]

In the brilliant mind of the imaginary physicist, the laborious lab life of experimental biologists and biochemists is reduced to a task that can be solved within a matter of hours. Somewhat chastened by his own experimental experience, Delbrück curbed this boldly optimistic time estimate, acknowledging in the same lecture that it might take more time—and trained hands—to conduct the laboratory experiments.[22] But the main message of Delbrück's carefully crafted recollections remains unaltered: to meet the challenges of a new biology, what was needed most was a new generation of brilliant minds who commit themselves to understanding the basic mechanisms of life. In Delbrück's fast-paced vision, there is no room for manual know-how and skilled expertise acquired in years-long hands-on training at the laboratory bench or in fields of plants. What remains unvoiced in his narrative is any kind of material and technical mastery in working with organic and biochemical material realities. Delbrück's well-known disdain for biochemistry's messiness is apparent in his airy, disembodied vision of an imaginary physicist.[23] For the bright-minded new life scientists the practical and material challenges of daily experimental laboratory life and its demands for bodily know-how, technical skills, and material literacy are—ideally—of no major concern. For the theoretical physicist Delbrück, the new science of life was essentially a matter of minds, not hands. Yet, at the same time, McClintock attended to her maize crops at the Cold Spring Harbor Laboratory and immersed herself in plant experiments that ultimately would challenge the appealing simplicity of reductionist approaches to the study of (sub)cellular life processes.

"The mind's eye" became the hallmark of a rapidly evolving and highly successful "molecularization" of genetics and later of biology, medicine, and life.[24] Keller's historical account illustrates how an intellectually biased reductionism goes hand in hand with a theoretical attitude vis-à-vis the pursuit of scientific knowledge that profoundly marginalizes forms of manual know-how and makes redundant a biologist's hard-won intimate acquaintance with living organisms and the material literacy that comes with years-long bench training. The preeminence of a Cartesian mind-body dualism in this discourse is not coincidental but was deeply ingrained in the rising new science of genetics: "The theory of the gene was quintessentially mechanistic and the methodology of genetics inherently quantitative; geneticists were entranced with the power of numbers."[25] It was partly in opposition to such a disembodied and bloodless understanding of life processes that McClintock and other cytologists came to define their own practice and approach in the mid-twentieth century.

In 1964, a decade after Crick and Watson's groundbreaking publication in *Nature* on the dna molecule structure that so profoundly contributed to the transformation of twentieth-century biological sciences, giving rise to the new field of molecular genetics, the First Chromosome Conference was convened in Oxford.[26] Some thirty years after the publication of C. D. Darlington's seminal *Recent Advances in Cytology*, which was hailed by his peers for introducing the chemists' and physicists' reductionist and unifying attitude into the biological sciences, the British cytologist opened the conference with a noticeable cautionary note.[27] Darlington voiced a shared concern among cytologists about the limitations of the approach of the chemist, who reduces the chromosome to the model of a chemical structure, and that of the mathematical geneticist, who formalizes the genetic constituents of the chromosome in mechanical models.[28] Looking back on the rapid developments of the preceding ten years and their shift of focus toward biochemical formalizations and molecular model constructions, Darlington reminded his audience: "We must applaud the success achieved by our colleagues on the basis of these assumptions [the theoretically deduced properties of chromosomes and their genetic constituents]. But they see the chromosomes through the mind's eye. We, who believe we see actual chromosomes through the microscope, must explain what we have seen, and point out that it is not always what our friends expect. For us, neither the chemical code, nor the linkage map of the chromosome, nor the genes embodied in it, are enough."[29]

Darlington's speech expressed a critique of a "mind's eye" approach that "shifted attention away from the organism as a whole" and led to a deeply problematic divide between the mechanistic and quantitative explanations of geneticists, on the one hand, and the qualitative science of cytologists, embryologists, and developmental biologists, on the other.[30] The latter, including McClintock, remained much more intimately engaged with biological materialities, and many shared the belief that the particular realities of bio matter ought to undergird a robust heredity theory and provide the material basis for the conceptual entities of more quantitative approaches.[31] Keller emphasizes that McClintock's work in cytogenetics required "physical, active participation with the material itself."[32] The recalcitrant nature of McClintock's experimental research on plant genetics in maize—a complex, higher organism demanding a particular kind of enduring and season-dependent attendance—apparently did not fit very well into the brisk pace of the "new intellectual approach to biology."[33]

Skilled Vision

I found that the more I worked with them [the chromosomes of *Neurospora*, a red mold on bread] the bigger and bigger [they] got, and when I really was working with them I wasn't outside, I was down there. I was part of the system. I was right down there with them, and everything got big. I even was able to see the internal part of the chromosomes—actually everything was there. It surprised me because I actually felt as if I were right down there and these were my friends.

Barbara McClintock, quoted in Evelyn Fox Keller, *A Feeling for the Organism*

The cell's innermost secrets don't reveal themselves to a bright mind in the blink of an eye. Seeing and making sense of what one sees on a microscopic and submicroscopic level is a laborious process. Skillful hands-on work with materials, living and nonliving, played a crucial part in McClintock's experimental exploration of life processes. If we listen closely to the oral accounts documented in her biography, we hear how the biologist gave voice to embodied experiences of doing her research.[34] In McClintock's experiential account, the scale of the chromosomes is reenvisioned in relation to her own body: the visual encounter is narrated as an embodied experience in which she can relate spatially and even socially to the invisibly and intangibly small subjects of inquiry that, in her own perception, "got big" and became "her friends."[35] Such a friendship cannot be built within mere hours but grows over time. Her biographer notes that in the process of embodied and materially engaged knowledge-making practices, "the objects of her study become subjects in their own right."[36] And she calls attention to the fact that her "intimate knowledge" was "made possible by years of close association with the organism she studies."[37] Keller learns during their conversations that a "motivated observer develops faculties that a casual spectator may never be aware of," and that it takes years of intimate engagement to bring forth the "heightening powers of discernment" that McClintock was known for among her peers.[38]

Indeed, McClintock's mastery of observational tools and experimental techniques was legendary.[39] Among the peers who acknowledged McClintock's "skilled vision" was the biochemist Rollin Hotchkiss (1911–2004), a "brilliant, analytical mind" who gained fame for determining the genetic material in bacteria and is remembered today for his pioneering work on the isolation and characterization of new antibiotics from soil bacteria.[40] Hotchkiss remembers McClintock as an "expert microscopist" and calls to mind that she was admired for her "masterful control" of dye and staining techniques and her cunning use of biochemical tools for her cytological studies of chromosome structures and behavior.[41]

Many of the processes McClintock studied were too small to be observed with the microscope but could be inferred from related, observable features or studied with analytical tools from biochemistry. She recalled that when she started to work with George Beadle at Stanford University on the cytology of the mold *Neurospora*, she "couldn't see anything well with the light microscope," but, as Keller points out, she could draw on her many years of experience in experimental observation.[42] This enabled McClintock, as Beadle put it, to do "more to clean up the cytology of *Neurospora* than all other cytological geneticists had done in all previous time on all forms of mold."[43]

Her biographer coins the term *virtuoso technique* to describe the ways with which McClintock attained an intimate knowledge of the chromosomal behavior of the organisms she worked with.[44] Scattered through the biography, we find mention of McClintock's hands-on expertise: her improvements of techniques of staining plant cells, and her careful and meticulous preparations of samples.[45] "Everything," Keller writes, "depends on the care and ingenuity with which cells are fixed and stained on the slides"—which is done by hand, of course.[46] The knowing touch and gaze with which McClintock could assess the quality of the crops in the cornfields marked her out. Throughout her scientific career, she continued to engage in the "most laborious parts of her investigations herself, leaving none of the labor, however onerous or routine, to others"; such a hands-on attitude is not exceptional but expected in making a career in science. As Keller put it, "In this she did as almost all beginning scientists."[47]

A former student recalled how long it took her to learn the art of looking that McClintock practiced. Evelyn Witkin, then a student at Cold Spring Harbor and later the holder of the Barbara McClintock Chair at Rutgers University, described how rewarding it was to become apprenticed in the skilled vision of this cytogeneticist: "Just looking over her shoulder, looking at the spots, you could visualize what was going on—she made you see it." Under McClintock's supervision, Witkin learned to discern chromosomal movements and structural changes that McClintock studied intensively in her laboratory until Witkin herself "became competent at reading the patterns so well, that she, too, could 'actually see genes turning on and off at definite times.'"[48]

Keller also interviewed the influential cytogeneticist Marcus Rhoades (1903–1991), who recalled a conversation with McClintock in which he marveled at her capacity to "look at a cell under the microscope and see so much!" To this, McClintock replied, "Well, you know, when I look at a cell, I get down in that cell and look around."[49] Looking into the depth of the corn cells to understand how cellular and chromosomal processes on a (sub)microscopic scale relate to observable traits in the full-grown plants demands "due attentiveness."[50] McClintock's "special blend of observational and cognitive skills" and her "heightened powers of discernment" allowed her to get in touch with life on a scale that for many of us would be unimaginably small.[51] Although many of the indirect methods of observation she worked with later became common practice in life science labs for the experimental study of cellular and molecular processes, McClintock was in particular remembered for being the only one who could "learn quite so many of the cell's secrets simply by close observation."[52] On closer inspection, *simply* is perhaps not the right word to account for the skilled vision of this seasoned biologist who could make sense of the "wealth of new patterns of color and texture in the tissues of the maturing plants that could be seen with the naked eye" and through the microscope.[53] Based on observations through a "cytological window" of how the genome functioned, the groundbreaking findings did not come easily but required an "extensive training of the eye."[54] In due course, McClintock acquired an extraordinary material literacy and observational competency that did not simply spring to the brilliant mind of a smart scientist but came with many years of diligent hands-on experience.

Knowledge Cultures

I would say that the best part of working here [at Cold Spring Harbor Laboratory] is being a small part of all the research that goes on here. Even though it's a small part of that research, it's still probably the most important part because you can't understand DNA in plants if you don't have any plants.

Tim Mulligan, "Uplands Farm"

Corn genetics is hard work.

Evelyn Fox Keller, *A Feeling for the Organism*

The experimental life sciences call for sensitive and sensible finger work as well as bright and well-trained minds, but the hands-on skills that are involved in the life sciences' cultures of knowledge often go unnoticed. This is quite surprising, given that life scientists undergo years-long hands-on training at the bench. Through bench training they learn how what they do with their hands relates to complex theoretical understandings and cognitive operations. This is obvious to experimental scientists, but the constitutive role of manual expertise in the experimentalization of life processes has rarely been acknowledged as part of scientific achievements.

In 1983 the Nobel Prize Committee praised McClintock for her experimental work "carried out with great ingenuity and intellectual stringency."[55] The committee portrayed McClintock as a solitary genius "working completely on her own" while "her observations received very little attention" from her contemporaries.[56] Indeed, it took her a lifetime to have her academic peers "realize the generality and significance of her findings."[57] The committee lauded McClintock for "carrying out experiments of great sophistication" and for her "immense perseverance and skill."[58] At the same time, the committee described her work at the award ceremony as especially "encouraging" because it "shows that great discoveries can still be made with simple tools."[59] Similarly, the Nobel Prize organization claimed in its press release that maize, the model organism to which McClintock dedicated almost her entire career, has the great advantage that its individual chromosomes "are easily studied" and mutations "easily observed."[60] McClintock's groundbreaking achievements were presented by the prize committee as the feat of an extraordinary scientific mind, while her experimental handiwork with plants and tools was made to appear surprisingly "simple" and "easy." Implicit in the committee's laudation is a dismissive gesture toward manual labor and the embodied practice of trained observation. In addition, conspicuously absent are any references to the biologist's extraordinarily skilled expertise in cultivating, handling, and examining the corn plants that were vital to her research on cytogenetics. The account, though, that McClintock imparted to her biographer sheds a different light on her work with maize: "Over and over again, she tells us one must have the time to look, the patience to 'hear what the material has to say to you,' the openness to 'let it come to you.'"[61] Keller's oral history of McClintock's extraordinary attentive capacity might suggest that McClintock had a particular gift or inborn talent. She quotes McClintock's own words: "Above all, one *must have* 'a feeling for the organism.'"[62] However, if we listen closely to McClintock's oral account, we get a glimpse of the ways in which McClintock *developed* such a capacity through on-the-spot observation and a caring engagement with the plants over long periods of time. Motivated by the drive to genuinely get to know another organism, the biologist wanted to understand

> how it grows, understand its parts, understand when something is going wrong with it. [An organism] isn't just a piece of plastic, it's something that is constantly being affected by the environment, constantly showing attributes or disabilities in its growth. You have to be aware of all that. . . . You need to know those plants well enough so that if anything changes . . . you [can] look at the plant and right away you know what this damage you see is from—something that scraped across it or something that bit it or something that the wind did.[63]

One needs to develop an awareness for every individual plant, she explains to her interviewer: "No two plants are alike. They are all different, and as a consequence, you have to know that difference."[64] The commitment this work demands is not only immensely time- and labor-intensive but also—in her words—deeply rewarding: "I start with the seedling, and I don't want to leave it. I don't feel I really know the story if I don't watch the plant all the way along. So I know every plant in the field. I know them intimately, and I find it a real pleasure to know them."[65]

Keller here reaches the intriguing conclusion that McClintock's "intimate knowledge, made possible by years of close association with the organism, is a prerequisite for her extraordinary perspicacity."[66] The observational skills that formed the basis of McClintock's scientific discoveries were honed through many years of committed and caring work with maize plants. In addition, her scientific peers acknowledged the "unique virtuosity" that she had developed in practice.[67] Rollins A. Emerson (1873–1947), who was instrumental in promoting the maize plant as a major research tool for genetic studies, described her as "the best trained and most able person in this country on the cytology of maize genetics."[68] Recently, these intimate aspects of her work attracted more attention in academia.[69]

The Nobel Prize Committee also omitted any mention of collaborative work with corn farmers that we can assume must have been part of McClintock's daily work. It is a widely held assumption that her work has long remained unnoticed because "her results were reported in publications that were not widely read, such as the annual report of the institute where she worked and in special newsletters exchanged by plant breeders working with maize."[70] Yet the fact that she published for a community of plant breeders also shows the relevance of expert communities for her own research that have mostly remained unacknowledged or ignored by academia and scientific institutions. McClintock not only supervised researchers but also closely engaged with farming staff and convinced the committee to hire a farm manager she had mentored. In her heyday at Cold Spring Harbor, McClintock used to have her own acres and was known to do everything herself. She continued to work at Uplands Farm, the agricultural field station that the Cold Spring Harbor Laboratory maintains for its plant research group, in the last years of her career.[71] Tim Mulligan, the farm manager, recalls how McClintock, who had persuaded the hiring committee to give him his first job at Uplands Farm, taught him how to drive the tractor to properly plow a maize field when he was managing his first crop in 1989:

> When you turn the soil over you create furrows and you are supposed to level them out in the field and I was not doing this correctly with my equipment. As a researcher doing crosses, you walk constantly, maybe there are twenty plants in a row and you have 200 rows to cross, so to make it easier the field has to be flat with no stones. So here I am turning this thing out that I guess was pretty terrible and she said, "You know you have to do a better job." She talked and told me how to drive the tractor and she gave me my marching orders. I turned out a much better field that next time. They were kidding me about this because she had short legs and she always liked her field to be flat and immaculate.[72]

The knowledge that Barbara McClintock harvested from her corn plants depended on her extraordinary capacity to link the highly abstract language of genetics to her hands-on work in the cornfields and in her lab. Another of McClintock's mentees, the biochemist and later Nobel laureate Elizabeth Blackburn (born in 1948), recalls her first encounter and provides a vivid impression of the intrinsically entangled practices of intellectual discourse and material engagement that characterized McClintock's research practice: "She just absolutely enchanted and enraptured me, because she immediately got deeply into a scientific discussion. She had all her ears of corn all around. She was showing us all the different stocks."[73] McClintock's "mind's eye" was profoundly shaped by manual engagement with the organisms she studied. Blackburn recalls a conversation they had on odd experimental results in 1977 in which McClintock encouraged her "to go with your intuition, really trust what you see."[74] Blackburn explains, "[When] I had told her about my unexpected findings with the rDNA end sequences, she urged me to trust my intuition about my scientific research results. This advice was surprising to me then, because intuitive thinking was not something that at the time I allowed myself to admit might be a valid aspect of being a biology researcher. I think her advice recognizes an important and sometimes overlooked aspect of the intellectual processes that underlie scientific research, and for me it had a liberating aspect to it."[75]

The intuition that McClintock refers to here had been cultivated over years of working intimately with maize both in and outside the lab. McClintock's acute perceptiveness did not derive from mental effort but instead was a certainty that grows from knowing by hand how plant genetics work. Her "seeing" is not the gaze of an uninvolved observer but the skilled vision of a caring practitioner who comes to know the object of study through intimate embodied and sensory engagement. To be in touch with plant life is a highly sensitive experience:

> Animals can walk around, but plants have to stay still to do the same things, with ingenious mechanisms. . . . Plants are extraordinary. For instance, . . . if you pinch a leaf of a plant you set off electric pulses. You can't touch a plant without setting off an electric pulse. . . . There is no question that plants have [all] kinds of sensitivities. They do a lot of responding to their environment. They can do almost anything you can think of. But just because they sit there, anybody walking down the road considers them just a plastic area to look at, [as if] they are not really alive.[76]

Hands-on expertise and care are of vital importance to experimental life sciences, and not only in plant cytogenetics. Conducting experiments with model organisms and cell cultures in today's molecular biology laboratories depends on highly skilled manual training and expertise in culturing and maintaining model organisms in the lab. Knowledgeable hands-on work is constitutive for these epistemic cultures. However, Keller's discussion of McClintock's research practices also remains indebted to a theory-laden, immaterial, and disembodied history of science.[77] References to McClintock's skillful ways of engaging with the materialities of her experimental daily practices are scarce and scattered throughout her biography, and a more substantial discussion of her "virtuoso technique" and hands-on engagements with organic materials and tools is mainly lacking. Keller's epistemological analyses of McClintock's research practice tend to quickly turn from experiential accounts to the immaterial realm of "qualitative and quantitative reasoning," and multisensory embodied practices are reduced to the domain of the visual.[78] Any forms of nonpropositional, embodied, or material ways of knowing are readily delegated to nonworldly realms of "mysticism."[79] The fine motoric and material practice of close microscopic inspection is described as requiring "an extensive training of the eye," but eventually, we need to turn inward toward essentially "internal visions" to understand how this outstanding scientist makes cytogenetic knowledge.[80] Also, here the mind's eye takes over when the embodied act of seeing becomes knowing: "For her the eyes of the body were the eyes of the mind."[81] In this description, Keller echoes the famous assertion "I become a transparent eye-ball; I am nothing; I see all" by the American transcendentalist Ralph Waldo Emerson.[82] Keller interprets McClintock's attentive absorption as a way to transcend her "bodily me": McClintock apparently found a way to overcome her wish to be freed of her body, and it is precisely this capacity that defines her as a successful scientist.[83]

Hence, the specialized and embodied acts of seeing of the trained cytologist and expert microscopist are turned into an essentially disembodied, mental activity or cognitive achievement: Keller portrays the Nobel Prize–winning biologist here, too, primarily as a knowing mind that eclipses the image of the hands-on experimenter who can only see "what others can't see" through an embodied practice of careful attention and a laborious process of skillful manual operations and preparations. In Keller's narrative the mental and the manual are hierarchically ordered: in the act of knowing, the mental takes primacy over the body, and the latter recedes into the background. The epistemic bias for the mind at the cost of the body has a long history that dates back to the ancient philosophies of Plato and Aristotle. Its importance for modern Western thinking was reaffirmed with René Descartes's influential account of the knowing subject (the Cartesian cogito) that has absolute epistemic agency and is categorically distinguished from objects and bodies. Interestingly, Keller makes an effort to conceptualize McClintock's fully absorbed self not in terms of a Cartesian "knowing mind" that is self-consciously affirmed through the act of reasoning. In her attempt to circumvent contestable subject-object and mind-body dichotomies, Keller interprets this "loss of self" not as an affirmation of a modern knowing I, but as the disappearance of a self-conscious subject in a "state of subjective fusion with the object of knowledge."[84] For Keller, a self-forgetting absorption and an extraordinary feeling for the organism are defining characteristics of Barbara McClintock's research experiences, which cannot be told in terms of a rational subject alone. However, despite Keller's attempt to push beyond a Cartesian mind-body dualism, we see that her descriptions remain indebted to a language and epistemic discourse that readily gravitates toward the knowing mind and easily loses sight of the manual and material.

The Disembodied Knower

The contested yet persistent image of knowers as "thinkers without hands" underpins the modern rationalistic and positivistic ideal of an uninvolved observer who can view natural processes under controlled conditions but without human intervention or manipulation. This ideal of noninterventionist yet controlled observation chimes conspicuously well with McClintock's desideratum of a transparent body that could not block her vision and would go unnoticed by others. The biologist's recollections conjure up a contested model of a disembodied observer, a knower with virtually no hands and an all-pervasive gaze who seeks knowledge through detached observation and pure contemplation. McClintock's wish to get rid of her body to become the scientific persona she wishes to be feeds into long-standing debates in arts, sciences, and philosophy on the interrelation between praxis and theory, doing and knowing, material practices and immaterial concepts, laboring bodies and knowing minds, dating back to the ancient philosophies of Plato and Aristotle. The disembodied knower model is today commonly linked with René Descartes's epistemology that postulates a knowing subject as an immaterial entity that is distinguished from the material worlds of bodies and objects. The so-called Cartesian mind-body distinction has decisively shaped our thinking in the Western world on how cognition works and how (scientific) knowledge making is conceptualized and theorized. It is also intimately linked to an ongoing cultural discourse about the role of the human body in knowledge formation.

In art historical and aesthetic discourses, the disembodied knower model has its counterpart in the image of a "painter with no hands." The paradox of a Renaissance master painter as a man of ideas with no need for laboriously trained hands, hands-on knowledge of paint making, or pens and brushes to materialize his ideas proves illuminating for a better understanding of the problematic model of a bodiless maker of knowledge in scientific discourse. Renaissance scholars have shown how artists promoted drawing (*disegno*) as a superior artistic form. The celebration of *disegno* "as a purely abstract and mental moment in creation" was motivated by the wish to ascertain the intellectual nature of artistic production and to shift attention away from artists' and artisans' manual labor.[85] This mental turn in art theory aimed to elevate the status of painting from a mechanical art (*techne*) to one of the liberal arts (*arti liberali*), while at the same time obscuring the fact that Renaissance artists gained their artistic mastery in years-long hands-on workshop training.[86] The conceptualization of *disegno* as a mental achievement contributed to the devaluation of manual labor in visual arts discourse. For instance, due to a persistent tendency to consider Renaissance painting as a matter of the intellect, in-depth inquiries into the role of the hand in creating artworks had long remained understudied.[87]

The long tradition of devaluating manual aspects of art making was particularly celebrated in the Enlightenment era by the German poet and art critic Gotthold Ephraim Lessing, who introduced the famous trope of a "Raphael with no hands" in his play *Emilia Galotti* (1772). In a dialogue, the court painter Conti laments how much gets lost between the eye and hand of an artist in the act of painting; he asks his prince rhetorically: "Or do you think, Prince, that Raphael would not have been the greatest genie in painting, if he would have had the bad fortune to be born without hands?"[88] The reference to the famous Italian Renaissance painter Raffaello Sanzio da Urbino (1483–1520) as an artistic genius—even without hands—suggests that we can make a hierarchical distinction between the work of the mind and that of the hand in the process of artistic creation. Lessing's Raphael-without-hands conveys the idea that great art is first and foremost a mental achievement; it is a product of the artist's mind, whereas the handicraft involved in making the work of art should not be considered as a genuine part of the creative process and aesthetic value of the artwork. This alleged opposition between artists' mental and manual work has been challenged in art theory and practice, and there exists a long tradition in art scholarship of debating the impossibility of categorical distinctions between manual and material investments in and the intellectual content of artworks. The persistent occlusion of manual work and material engagement as constitutive elements of artistic meaning has been met with much criticism, and scholars have emphasized instead that handmade artifacts manifest the unique results of intractable collaborations between minds and hands, at least for art production up to the nineteenth century.[89] Similarly, scholars have started to criticize a long tradition in history and philosophy of science that tends to frame the early modern period in Western Europe and the rise of modern experimental sciences in terms of "autonomous ideas and disembodied mentalities."[90] This tendency manifested itself in a historiographical tradition that construed the Scientific Revolution in seventeenth-century Europe as a primarily conceptual revolution to be written in terms of mental operations with comparatively little attention to bodily issues or the innovative material and manual ways of *making* scientific knowledge that this era witnessed.[91] In the last century, beginning in the 1990s, we have observed a shift in perspective in history and philosophy of science from realms of ideas to embodied and material worlds of knowledge makers. Historians have begun to concentrate on the actual "work of science" and stress that "all ways of knowing involve crafts" and bodies.[92]

The rhetoric of McClintock's dismissive body talk reflects a theoretically skewed and heavily biased understanding of knowledge production and is strangely at odds with laboratory ethnographies that reveal the conspicuously manual character of epistemic practices in molecular genetics laboratories.[93] McClintock's desire to become a disembodied observer was driven by the idealized model of a knower who attains knowledge by means of detached and unobtrusive observation alone, as if experimental observation and natural inquiries could be done without intervention or manipulation, and without any recourse to technical know-how, material literacy, or skilled handiwork. Such a stance has been strongly criticized since the early 2000s with growing attention to embodied practices in the preceding decades by philosophers, historians of science, and social scientists whose work has contributed significantly to the reconceptualization of "knowing not as a faculty of the human mind, but as an activity of the human body."[94] This shift in attention also fed into the rising field of embodied cognition (e-cog) studies in the cognitive sciences, which has undergone a paradigm shift toward an understanding of the mind as intrinsically embodied, embedded, and extended.[95] In many ways my book is a contribution to this important development, but it can also be read as a critique of universalistic mind theories and a profoundly ahistorical attitude that characterizes much of the e-cog debates.

The Art of Culturing Bacterial Life in the Lab

He travelled around and collected thousands of soil samples from all over Japan which he used for culturing bacteria. In one of Ōmura's bacteria cultures, which was sent to William Campbell's laboratory, a whole new strain of Streptomyces was discovered—one that would change the world.

Hans Forssberg, "Award Ceremony Speech: The Nobel Prize in Physiology or Medicine 2015"

Cultivating a feeling for life science's organisms, living and nonliving, and developing the necessary material literacy and technological dexterity to conduct experiments in a life science lab demands not only bright brains but also meticulous and sensible handiwork, executed with care, precision, and ingenuity. This is reflected in the Nobel Committee's announcement of the Nobel Prize in Physiology or Medicine in 2015, some thirty years after McClintock received the Nobel Prize. Satoshi Ōmura, who shared the prize with William C. Campbell for their collaborative work in developing a new antiparasitic drug, received the highest scientific acknowledgment for his successes in culturing new soil bacteria strains in his microbiological laboratory. During the award ceremony, the committee praised the microbiologist for his "extraordinary skill in developing unique methods for large-scale culturing and characterization," thus acknowledging the expertise and sophisticated practical knowledge that are needed to successfully identify, isolate, and maintain new strains of bacterial cultures under lab conditions.[96]

Ōmura is known for a habit that illustrates the importance of the seemingly mundane, often unnoticed manual work that frequently underpins Nobel Prize–winning discoveries. In an interview Ōmura imparted that he always carries a small plastic bag in his wallet, ready to hand so he can collect soil samples wherever he goes.[97] Let's imagine how Ōmura arrives at a conference, then takes a walk or visits the golf course, where he squats down to inspect the soil under his feet, perhaps assessing the quality of the earth between his fingertips, then taking out his small plastic bag. Maybe he has a spoon with which he can scoop some soil into a sample bag without dirtying his hands. Perhaps he uses bags that he can just slip over his hand—like a glove—to take a handful of soil, turn the bag inside out, seal it, and walk on. From the soil samples he collected over a lifetime, Ōmura and his team were able to identify promising bacterial strains and managed to find the right laboratory conditions to harvest their products. His research laboratory succeeded in isolating and culturing *Streptomyces avermitilis*, the producing organism of avermectin, an organic substance with excellent antiparasitic activity, from which William Campbell's laboratory developed the antiparasitic drug ivermectin.[98]

Already in 1986, Ōmura had received the Hoechst-Roussel Award, a prestigious prize from the American Society for Microbiology. As a recipient of the award, he was invited to publish on his research philosophy, an invitation he accepted "with great pleasure" as it gave him the opportunity to present his own "viewpoint and ideas on research work."[99] In the resulting paper, "Philosophy of New Drug Discovery," Ōmura comments on the art of microbiological research that depends on "believing in the great capabilities of microorganisms" and "the ability to devise various conditions for the successful isolation and cultivation of microorganisms."[100] On the complexities of creating efficient "screening systems" to identify bacteria that produce promising bioactive substances, he explains: "Sometimes we have to spend as much as a year or two to devise a satisfactory one."[101] Although this kind of work depends on diligent execution of various repetitive, manual tasks, Ōmura emphasizes that "screening is not just routine work," and he stresses the importance of participating in daily screening work "to improve one's research capabilities."[102]

Microbiological benchwork calls for hands-on commitment to the creation and maintenance of a thriving microbiological material culture. It depends on fruitful cohabitation of investigated microorganism and investigating researcher in the research lab—what we could call a living experimental system that depends on years-long working experience, the right tools and technologies, *and* intimate hands-on knowledge of culturing bacterial strains.[103] When Ōmura heard that he had been awarded the Nobel Prize for Physiology or Medicine in 2015, he echoed the main tenets of his philosophy in his first reaction: "I have learned so much from microorganisms and I have depended on them, so I would much rather give the prize to microorganisms"; in another interview he added that he "merely borrowed the power of microorganisms."[104] Ōmura understands his research practice as an intrinsically collaborative endeavor depending on successful cooperation that comes with lifelong training in working with another organism and becoming attuned to the organism's needs. He seems to allude to what we might call “a feeling for the microorganism” as a requisite skill for successful scientific work in a microbiological lab.

* * *

Experiments fail most of the times. Things usually prove to be much more difficult than expected, or just fail. But, sometimes they go surprisingly well, and once you’ve experienced that, you will never get afraid of failure, no matter how often you fail. That’s the fun part of research. Let’s give it another try, another shot, or another night.

Satoshi Ōmura, in Mitsuko Nishikawa, “Japan’s Latest Nobel Laureate”

Successful experimental life science laboratories excel in hands-on knowledge and techniques that have been acquired by research groups over years of failures, as well as innumerable trial-and-error explorations of means, methods, and materials. Ōmura’s comment makes clear that laboratories build up a material culture and accumulate practical know-how over years of experimental work that provide the fertile grounds for the much rarer experimental successes, scientific breakthroughs, and prize-winning discoveries. Why, then, is there a tendency to omit the hands-on making and cultivation of such fertile grounds from knowledge-making theories?

My fieldwork brought me into cellular and molecular genetics laboratories, where I interned with a research group working on the complex processes of dna damage recognition and repair in the genome of yeast, one of the first higher organisms, after the maize plants studied by McClintock, in which so-called jumping genes were observed.[105] After my first months working as an intern in a lab with life scientists, I realized I had quite happily been ignoring my own body during many years of university education in the humanities. Body issues had been of no specific practical concern in art history and philosophy curricula, even though bodies and bodily practices were matters of ongoing concern, for example, in phenomenology and in the theoretical interpretation of installation and performance art. In practical classes in the life sciences, however, it became impossible to ignore my bodily self. To *do* life sciences, it was not sufficient only to memorize all the new facts from the latest edition of Alberts’s *Molecular Biology of the Cell*.[106] I had to pay at least as much attention to training my hands to perform all kinds of unfamiliar benchwork like pipetting, plating cells on agar plates, and pouring agarose gels. Seemingly simple tasks demanded acute bodily awareness, such as donning one glove and remembering to use only my gloved hand when washing carcinogenic chemicals from an agarose gel that I had used for DNA electrophoresis. I quickly became especially intrigued by the strict sterile working procedures that I had to adopt during a gene technology course and a tissue-culturing experiment.

Learning to work in a sterile manner led me to conceive of my body not only in an instrumental sense as something that I avail myself of to conduct scientific experimentation but also as something I had to develop a special awareness of in order to avoid contamination of my samples. On a very practical level, I learned here that paying attention to my body was an important part of learning to conduct scientific research and performing experiments successfully. For example, I could avoid interference with results by polluting bacterial samples with microbes from my hands only by becoming a trained observer of my physical engagement with the media and instruments at the bench. Bodily issues appeared to be of daily concern for life scientists. In my training lab, making phenomena and processes that take place on a cellular and molecular level visible and interpretable was in the first place an embodied activity that involved as much manual know-how as brain work to understand what I was actually doing at the bench. Indeed, I learned quickly that it takes many hours of hands-on lab training to develop the skilled vision of a life scientist.[107] I was surprised to see nothing of this reflected in McClintock's deprecatory body talk. During my fieldwork I experienced a profound lack of literacy when it came to talking or writing about the bodywork of life scientists. This conspicuous discursive and conceptual lack motivated me to write the present book about hands-on knowledge-making practices in the sciences of life on cellular and molecular levels.

A Multisited Ethnography and Historical Epistemology

This book is an ethnographic, philosophical, and historical exploration of bodily ways of knowing in the life sciences. Moreover, it investigates why hands-on practices have rarely been acknowledged as part of scientific knowledge making in modern epistemology since the rise of the experimental sciences in early modern Europe. The study contributes to a growing body of scholarship that has started to laboriously develop—often using ethnographic methods—more sophisticated, mindful, and attentive ways of talking about science as a material and embodied practice. However, for better descriptions and conceptualizations of how life science is *done in practice*, we also need to understand *why* the exclusion of embodied aspects became so pervasive in Western thinking about scientific knowledge making in the first place. What are the philosophical underpinnings of this profound uneasiness or awkwardness in expressing and conceptualizing manual work in life science laboratory research? This is not an analytical problem that can be solved through reasoning; it demands a historical understanding of the conditions under which a particular philosophical attitude or project could arise and flourish. The conspicuous absence of hands-on notions in Western modern epistemologies has traditionally been explained by gesturing toward the intellectual legacy of the French seventeenth-century philosopher René Descartes, who has remained a celebrated figure in curricula of college programs and philosophy departments as the founding father of modern epistemology and rationalist philosophy. In modern philosophy the establishment of a separate realm for the human mind as the primary site of knowledge production that is independent of the body and the material world has traditionally been associated with a philosophical attitude that is grounded in a categorical distinction between mind and body. The Cartesian mind-body dualism posits a dichotomy between the knowing subject and the knowledgeable object that has profoundly shaped Western thinking. This Cartesian legacy has been as pervasive as it has been criticized in Western philosophy. Many scholars before me have, for example, convincingly shown that the conceptual erasure of the embodied experimenter from experimental scenes of knowledge is a theoretical desideratum that is impossible to achieve in practice.[108] However, in history and philosophy of science the recent shift in attention from ideas and theories to embodied and material practices of the sciences most commonly goes hand in hand with a call for anti-Cartesian approaches.

On a closer look, however, I found that anti-Cartesian approaches remain deeply flawed and that anti-Cartesian frameworks are actually not very helpful to describe the constitutive role of the manual in experimental life sciences; instead, they help to obscure the complexities and idiosyncrasies of life sciences hands-on practices. How, then, can we gain a better understanding of the embodied dimensions of experimental life science research? In this book I show that this requires a radically historicized understanding of the Cartesian epistemological project. Drawing on historical sources, I portray Descartes as a fervent anatomical experimenter and hands-on practitioner who cannot be reduced to the figure of a thinking meditator and rational epistemologist. The mind-body dualism is not the product of a philosophizing mind but took shape in the hands of an experimenting anatomist. Hence, the starting point for this epistemological discussion is not the "first philosophy" that Descartes sets forth in his *Meditations* but *the making of a first philosophy* in the context of Descartes's natural philosophical hands-on explorations. In short, I argue that we need to understand Descartes's epistemological project from *within* his own experimental practice in the early modern manual art of anatomy.

At the core of this study is a radical rereading of the famous "wax argument" in Descartes's *Meditations on First Philosophy* (*Meditationes de prima philosophia*; first Latin edition, Paris, 1641; second Latin edition, Amsterdam, 1642).[109] The Latin work was soon translated into the vernacular, and the first French edition, *Les méditations métaphysiques de René Des-Cartes touchant la première philosophie*, authorized by Descartes, was published during his lifetime, in 1647. My rereading of the French text in the context of other historical sources reveals a yet unacknowledged double movement in Descartes's doing and thinking: I trace how the natural philosopher and anatomical experimenter departs from hands-on embodied practices of knowledge making that are only in a subsequent philosophical operation obscured. I argue in this book that the rise of an epistemological attitude that deliberately obliterates modern epistemologies' grounding in hands-on experiences can, in fact, not be properly understood from the perspective of the thinking philosopher alone but needs to be understood in the context of Descartes's *manual* experimental practice. In chapters 1 and 2 of this book, I provide close readings of passages from the Second Meditation and of Descartes's correspondence on his anatomical experimentation in the context of the rise of the experimental sciences and recent scholarship on Descartes's involvement in the "new sciences." My analysis subverts the still pervasive reception of the early modern philosopher as a thinker without hands and instead places hands-on experiences and aesthetic reflection at the heart of Descartes's modern epistemological project. In chapters 3 to 5, I set forth a theory of knowledge making grounded in historical *and* ethnographic observations, for which I combined participatory hands-on observations in contemporary molecular genetics labs and microbiology cleanrooms with a *longue durée* philosophical account starting in the seventeenth century. Building on pioneering work of laboratory ethnographers, beginning at the end of the 1970s, my book demonstrates why we are in need of more embodied approaches to theorize knowledge-making practices in the life sciences. Yet, I disagree with pioneers such as Bruno Latour and Annemarie Mol, who declared that epistemology is a dead discipline. By contrast, the aim of this book is to revive epistemology *from within* Descartes's philosophical undertakings in the role of meditator and experimenter as an inherently historical, aesthetic, and at the same time pluralistic and embodied undertaking.

Central to this book is the notion of *hands-on* with which I draw together an argument that threads between seventeenth-century natural philosophy and experimental practices, laboratory practices in the present-day life sciences, and contemporary artistic practices. I interweave observations taken from fieldwork with bio artists whose work was instrumental for my reconceptualization of hands-on notions in life science research. Throughout the book, these three heuristic methods—philosophical and historical analysis, ethnographic accounts of lab work and cleanroom conditions, and bio art experiences and interpretations—are combined into a multisited historioethnographic study.[110] *Multisited*, or *multilocale*, refers here to studies across diverse historical and contemporary sites of inquiry, drawing on historical sources and experiential accounts of life sciences and bio art practices. My approach embraces the famous adage by the microbiologist Ludwik Fleck (1896–1961) "no epistemology without history" and transforms it into the motto of this book: to reflect on knowledge making in the life sciences, we need history *and* ethnography.

The Structure of This Book

In chapters 1 and 2 of this book, I describe shifts toward experimentation in seventeenth-century natural philosophy against the background of my participatory observations in life science laboratories. My multisited ethnographic approach takes me from the bench in an instruction lab, in which students are trained to study life on the molecular level, to the specialized contexts of experience where early modern natural philosophers investigate phenomena that lie beyond the limits of human perception. I discuss the work of exemplary experimenters, such as the innovative networker Marin Mersenne (1588–1648), and then turn to the French philosopher and anatomist René Descartes, who engaged actively in the emerging experimental scene in seventeenth-century Amsterdam. At the heart of these chapters is a radical rereading of a famous epistemological argument, set forth by Descartes in his *Meditations*. I provide a reading of Descartes's meditation on a piece of wax from a hands-on perspective. Though Descartes plays a prominent role in these chapters, my interpretation is not restricted to Cartesian exegesis. Rather, I take Descartes and Mersenne as case studies that make palpable how shifts toward experimentation and manipulation in early modern experimental sciences brought about an epistemological dilemma.

Chapter 3 is dedicated to methodological reflections that reframe my historical inquiry as a philosophical project. Drawing on the work of the German philosopher Edmund Husserl (1859–1938), I first describe how the philosophical method of *epoché* made it possible to reread the famous wax passage in Descartes's Second Meditation in the context of his anatomical experiments. Second, I argue that we can understand the elimination of hands-on notions from the Cartesian epistemological project as the result of a philosophical operation that can be described as a form of substitution with the Husserlian concept of *Unterschiebung*.[111] The idea of a hands-on perspective as a point of departure for epistemological considerations is further elaborated with a phenomenological description of my own bodily experience. Drawing on recent interpretations of Husserl's and Maurice Merleau-Ponty's (1908–1961) phenomenological body, this chapter explicates how I experience my body both as mine and as a foreign or strange thing.[112] The chapter prepares the ground for further reflections on the resistance of experimenters' bodies to become transparent in a form of thinking that wants to ignore the persistent presence of bodies.[113]

In chapter 4, I discuss what the relevance of these findings is for today's discussion of experimental practices in the (life) sciences in the context of the practical and material turn in science studies. I critically explore how the authors of pioneering ethnographies of life science laboratories laid the foundations for thinking about *science as practice* but framed their participative bench approach as an intrinsically anti-Cartesian take on scientific knowledge formation and epistemology. My analysis of Bruno Latour and Steve Woolgar's *Laboratory Life* (first published in 1979) and Karin Knorr-Cetina's *Epistemic Cultures* (1999) demonstrates the shortcomings of anti-Cartesian frameworks in explicating the embodied aspects of life science laboratory work. In chapter 5, I turn to Don Ihde's and Shaun Gallagher's influential studies of body-instrument-relations and incorporation processes and argue that these embodiment philosophies are deficient in accounting for the peculiar hands-on/hands-off dynamic of sterile regimes practiced in today's technoscientific spaces.[114]

The epilogue is devoted to an exploration of contamination-controlled spaces that play a key role in life science research, such as isolator technologies and microbiological cleanrooms. These technoscientific phenomena give us insight into the conceptual complexities of embodied benchwork. In these final reflections, I introduce the concept of cleanroom aesthetics for which I draw on historical sources, in situ observations, and interviews with laboratory personnel. My "snapshot story" of a cleanroom visit provides a description, or perhaps better, a "practiography," of hands-on experiences and bodily practices in microbiological cleanroom facilities.[115] From this experiential grounding, I reassess the Cartesian legacy and argue that epistemology is not dead but needs to be revived and rethought as a historical, contextual, and pluralistic endeavor from the embodied standpoint of a hands-on practitioner—*with* and not *against* Descartes. This book is an interdisciplinary contribution to scholarship in historical epistemology, science studies, philosophy of embodied practices, and anthropological investigations into life sciences, biotechnologies, and artistic explorations of technoscientific life-forms.[116] It provides the philosophical and historical groundwork to study life science laboratories as idiosyncratic sites of embodied knowledge production processes.

NOTES

Introduction

Epigraph sources: On p. 8, E. F. Keller, *Feeling for the Organism*, 125. On p. 13, E. F. Keller, *Feeling for the Organism*, 117. On p. 16, Mulligan, "Uplands Farm"; E. F. Keller, *Feeling for the Organism*, 57. On p. 24, Forssberg, "Award Ceremony Speech." On p. 26, Nishikawa, "Japan's Latest Nobel Laureate."

1 The fieldwork for this book was mainly conducted at the Gorlaeus Laboratories, Leiden University, over a period of about a year and a half. It included coursework (552 hours) with practicums selected from the Life Science and Technology curriculum and practical benchwork during an internship at a molecular genetics research laboratory. At Utrecht University, I also participated in a two-week laboratory animal science course (80 hours). The fieldwork included visits and interviews at the isolator facilities for specific pathogen-free animals at the Netherlands Vaccine Institute; at the cleanroom facilities at Kavli Institute for Nanoscience, TU Delft, and at the Leiden University Medical Center; interviews and prolonged conversations with a cleanroom consultant and trainer; and participation in a Cleanroom Behavior Course for microbiological cleanroom users.

My field explorations also included participation in bio art workshops in London, Amsterdam, and Leiden, and a research stay at SymbioticA—An Artistic Laboratory Dedicated to Research and Hands-On Engagement with the Life Sciences, at the University of Western Australia in Perth, in November and December 2006, where artists introduced me to tissue engineering techniques in the research laboratories of the School of Anatomy and Human Biology, and where I worked for the first time with living cells in a flow cabinet.

My field studies benefited greatly from the lively discussions with researchers and bio artists I engaged in as a member of the interdisciplinary research project New Representational Spaces: Investigations of Interactions between and Intersections of Art and Genomics, led by Robert Zwijnenberg and Miriam van Rijsingen.

2 I thank René Peschar for his help with translating the chemical terms of this Dutch protocol. All translations are my own unless otherwise indicated. For information on the translations of works by René Descartes that appear in this book, see the "Note on Descartes's Texts and Their Translation."

3 See, e.g., Walls, "Kayak Games and Hunting Enskilment"; Grasseni, *Skilled Visions*; Grasseni, "Skilled Visions"; Mauss, "Techniques of the Body."

4 On adaptation processes of instruments and experimenters in history of science, see, e.g., Hötteke, "Zur experimentellen Tätigkeit Michael Faradays," 363–64.

5 Oxford English Dictionary, s.v. "pipettor (n.)," July 2023, https://doi.org/10.1093/OED/1788160077.

6 E. F. Keller, *Feeling for the Organism*.

7 See, e.g., the following books by E. F. Keller: *Reflections on Gender and Science*; *Refiguring Life*; *Century of the Gene*; and *Making Sense of Life*.

8 See, e.g., E. F. Keller, *Feeling for the Organism*, 148–49, 197, and on "new biology" esp. 153–70; Landecker, *Culturing Life*; Chadarevian and Kamminga, *Molecularizing Biology and Medicine*; Kay, *Molecular Vision of Life*.

9 E. F. Keller, *Feeling for the Organism*, 36.

10 E. F. Keller, *Feeling for the Organism*, 36.

11 E. F. Keller, *Feeling for the Organism*, 35.

12 Nanney, "Role of the Cytoplasm in Heredity," quoted in E. F. Keller, *Making Sense of Life*, 151.

13 On the fuzzy concept of the gene, see, e.g., Lenoir, "Epistemology Historicized," xviii; on Watson's notion of the "molecular object," see Watson, *Molecular Biology of the Gene*, cited in E. F. Keller, *Feeling for the Organism*, 159; Watson and Crick, "Molecular Structure of Nucleic Acids."

14 Lawler, "Rosalind Franklin Still Doesn't Get the Recognition She Deserves."

15 Gann and Witkowski, "DNA."

16 Pietzsch, "What Is Life?"

17 Max Delbrück, "A Physicist Looks at Biology" [1949], in *Phage and the Origins of Molecular Biology*, ed. John Cairns, Gunther Stent, and James Watson (Cold Spring Harbor, NY: Cold Spring Harbor Laboratory of Quantitative Biology, 1966), 22; cited in E. F. Keller, *Feeling for the Organism*, 165, and in Strauss, "Physicist's Quest in Biology," 647.

18 E. F. Keller, *Feeling for the Organism*, 160.

19 E. F. Keller, *Feeling for the Organism*, 6 and 160.

20 Delbrück, "Experiments with Bacterial Viruses (Bacteriophages)," cited in E. F. Keller, *Feeling for the Organism*, 161.

21 Delbrück, "Experiments with Bacterial Viruses (Bacteriophages)," cited in E. F. Keller, *Feeling for the Organism*, 161.

22 Delbrück, "Experiments with Bacterial Viruses (Bacteriophages)," cited in E. F. Keller, *Feeling for the Organism*, 161.

23 On Delbrück's attitude toward biochemical wet lab work, see, e.g., Strauss, "Physicist's Quest in Biology," 648.

24 Chadarevian and Kamminga, *Molecularizing Biology and Medicine*; Kay, *Molecular Vision of Life*; Rose, *Politics of Life Itself*, 5.

25 E. F. Keller, *Feeling for the Organism*, 94.

26 Watson and Crick, "Molecular Structure of Nucleic Acids."

27 Darlington, *Recent Advances in Cytology*; Kofoid, review of *Recent Advances in Cytology*.

28 E. F. Keller, *Feeling for the Organism*, 90–91.

29 The opening address is reprinted in Darlington and Lewis, *Chromosomes Today*, vol. 1; quoted in E. F. Keller, *Feeling for the Organism*, 91.

30 E. F. Keller, *Feeling for the Organism*, 92.

31 E. F. Keller, *Feeling for the Organism*, 94.

32 E. F. Keller, *Feeling for the Organism*, 147.

33 E. F. Keller, *Feeling for the Organism*, 92.

34 E. F. Keller, *Feeling for the Organism*, esp. 115–17, 198–200.

35 E. F. Keller, *Feeling for the Organism*, 117.

36 E. F. Keller, *Feeling for the Organism*, 200.

37 E. F. Keller, *Feeling for the Organism*, 198.

38 E. F. Keller, *Feeling for the Organism*, 200.

39 E. F. Keller, *Feeling for the Organism*, 101.

40 Witkin, "Remembering Rollin Hotchkiss," 143; on Hotchkiss's work with the bacteriologist René Dubos (1901–1982), see Van Epps, "René Dubos."

41 On the notion of "skilled vision," see Grasseni, *Skilled Visions*; Grasseni, "Skilled Visions." On Hotchkiss's recollections, see his foreword in E. F. Keller, *Feeling for the Organism*, xiv.

42 E. F. Keller, *Feeling for the Organism*, 116–17.

43 E. F. Keller, *Feeling for the Organism*, 113.

44 E. F. Keller, *Feeling for the Organism*, esp. 101 and also 67, 80, 103.

45 On McClintock's staining techniques, see E. F. Keller, *Feeling for the Organism*, 130.

46 E. F. Keller, *Feeling for the Organism*, 40.

47 E. F. Keller, *Feeling for the Organism*, 103.

48 E. F. Keller, *Feeling for the Organism*, 137.

49 E. F. Keller, *Feeling for the Organism*, 69.

50 E. F. Keller, *Feeling for the Organism*, 104.

51 E. F. Keller, *Feeling for the Organism*, 200.

52 E. F. Keller, *Feeling for the Organism*, 80.

53 E. F. Keller, *Feeling for the Organism*, 80.

54 E. F. Keller, *Feeling for the Organism*, 46, 148.

55 Nobel Foundation, "Press Release."

56 Ringertz, "Award Ceremony Speech."

57 Nobel Foundation, "Press Release."

58 Ringertz, "Award Ceremony Speech."

59 Ringertz, "Award Ceremony Speech."

60 "The inheritance of a series of characteristics can *easily be studied simply by examining* the structure, starch content or pigmentation of the individual kernels. Mutations affecting pigmentation are particularly useful, not only because they can be *easily observed*. . . . Another advantage of maize as an experimental system was that individual chromosomes are *easily studied*"; Nobel Foundation, "Press Release" (my emphasis).

61 E. F. Keller, *Feeling for the Organism*, 198.

62 E. F. Keller, *Feeling for the Organism*, 198 (my emphasis).

63 E. F. Keller, *Feeling for the Organism*, 198.

64 E. F. Keller, *Feeling for the Organism*, 198.

65 E. F. Keller, *Feeling for the Organism*, 198.

66 E. F. Keller, *Feeling for the Organism*, 198.

67 E. F. Keller, *Feeling for the Organism*, 80.

68 E. F. Keller, *Feeling for the Organism*, 74.

69 Awiakta, "How the Corn-Mother Became a Teacher of Wisdom," 200; Ducey, "Technologies of Caring Labor."

70 Nobel Foundation, "Press Release."

71 Mulligan, "Uplands Farm."

72 Mulligan, "Uplands Farm."

73 Blackburn, "Elizabeth Blackburn on Barbara McClintock," 0:29–0:38. On Blackburn, see Nobel Foundation, "Elizabeth H. Blackburn."

74 Blackburn, "Elizabeth Blackburn on Barbara McClintock," 1:00–1:05.

75 Nobel Foundation, "Elizabeth H. Blackburn"; Blackburn, "Elizabeth Blackburn on Barbara McClintock," 0:00–1:15.

76 E. F. Keller, *Feeling for the Organism*, 200–201.

77 Such an idealized disembodied and immaterial conception of science has incited many critical responses; see, e.g., Hacking, *Representing and Intervening*; Lawrence and Shapin, *Science Incarnate*; Haraway, *Modest_Witness@Second_Millennium*; Haraway, *Companion Species Manifesto*; Haraway, *When Species Meet*; Rheinberger, *Epistemology of the Concrete*; Rheinberger, *Toward a History of Epistemic Things*; Barad, *Meeting the Universe Halfway*; Roberts, Schaffer, and Dear, *Mindful Hand*; Daston, *Biographies of Scientific Objects*; Daston and Galison, *Objectivity*. A critical stance toward universalist and reductionist conceptions of science is also reflected in an emerging field focusing on history and formation of knowledge rather than history of science; see, e.g., Daston, "History of Science"; Burke, *What Is the History of Knowledge?* and "Response"; and the peer-reviewed journals *KNOW—A Journal on the Formation of Knowledge* and *Journal for the History of Knowledge*, launched in 2017 and 2019, respectively.

78 E. F. Keller, *Feeling for the Organism*, 147.

79 E. F. Keller, *Feeling for the Organism*, xxii.

80 E. F. Keller, *Feeling for the Organism*, 148, 150.

81 E. F. Keller, *Feeling for the Organism*, 148.

82 Emerson, *Essays and Lectures*, 10, cited in E. F. Keller, *Feeling for the Organism*, 118.

83 E. F. Keller, *Feeling for the Organism*, 118.

84 E. F. Keller, *Feeling for the Organism*, 118.

85 Cerasuolo, *Literature and Artistic Practice*, 69.

86 Not much textual evidence has survived on the training of early Renaissance painters, but we can find in a manuscript copy of Cennino

Cennini's famous *Libro dell'Arte*, dated to the end of the fourteenth century, a description of a painter's extensive apprenticeship; Broecke, *Cennino Cennini's Il Libro dell'Arte*, 138.

87 Zwijnenberg, *Writings and Drawings of Leonardo da Vinci*, 29.

88 "Oder meynen Sie, Prinz, daß Raphael nicht das größte malerische Genie gewesen wäre, wenn er unglücklicher Weise ohne Hände wäre geboren worden?" Lessing, *Emilia Galotti*, 13.

89 Zwijnenberg, *Writings and Drawings of Leonardo da Vinci*, 24, 37. The first decades of the 2000s witnessed a renewed interest in artistic technique and material aspects of artworks and the rise of a new materialism in the humanities; see, for example, two major European research initiatives: Sven Dupré (principal investigator), "ERC ARTECHNE Project," https://artechne.wp.hum.uu.nl; Iris Van der Tuin (chair), "COST Action IS1307 New Materialism: Networking European Scholarship on 'How Matter Comes to Matter,'" https://newmaterialism.eu/.

90 Shapin, *Scientific Revolution*, 4.

91 Lawrence and Shapin, "Introduction: The Body of Knowledge"; Shapin, *Scientific Revolution*, 4; Pickstone, *Ways of Knowing*, 17.

92 Pickstone, *Ways of Knowing*, 17; see also, e.g., Cook, "History of Medicine"; Lawrence and Shapin, *Science Incarnate*; Roberts, Schaffer, and Dear, *Mindful Hand*; P. H. Smith, *Body of the Artisan*; Wolfe and Gal, *Body as Object*.

93 Knorr-Cetina, *Epistemic Cultures*; Myers and Dumit, "Haptics"; Myers, *Rendering Life Molecular*.

94 Mol, *Body Multiple*, 82.

95 For an introductory bibliography, see, e.g., the website of the Embodied Cognition Reading Group, cofounded in 2015 by the author under the auspices of Columbia University's Center for Science and Society, http://blogs.cuit.columbia.edu/embodiedcognition/.

96 Forssberg, "Award Ceremony Speech."

97 Nishikawa, "Japan's Latest Nobel Laureate"; AP News, "The Latest: Discovery on Golf Course Inspired Nobel Winner."

98 See, e.g., Ōmura, "Ivermectin Story."

99 Ōmura, "Philosophy of New Drug Discovery," 259.

100 Ōmura, "Philosophy of New Drug Discovery," 260.

101 Ōmura, "Philosophy of New Drug Discovery," 260.

102 Ōmura, "Philosophy of New Drug Discovery," 259, 268.

103 On the notion of "experimental systems," see Rheinberger, *Toward a History of Epistemic Things*.

104 See AP News, “The Latest: Discovery on Golf Course Inspired Nobel Winner”; Altman, “Nobel Prize in Medicine.”

105 E. F. Keller, *Feeling for the Organism*, 189–90; Fink et al., “Transposable Elements (Ty) in Yeast.”

106 Alberts, *Molecular Biology of the Cell*. The first edition was published in 1983.

107 On the notion of skilled vision, see Grasseni, *Skilled Visions*. For ethnographies of skilled practices in medical and molecular biology contexts, see, e.g., Prentice, *Bodies in Formation*; Myers, *Rendering Life Molecular*.

108 See, e.g., Fleck, *Genesis and Development of a Scientific Fact*; Hacking, *Representing and Intervening*; Lawrence and Shapin, *Science Incarnate*; Latour, *Science in Action*; Pickering, *Constructing Quarks*; Pickering, *Science as Practice and Culture*; Pickering, *Mangle of Practice*.

109 For these Latin editions, see the entries in the bibliography with “*Renati Descartes*” (of René Descartes) at the start of the title.

110 On the notion of multisited or multilocale ethnographies, see, e.g., Fischer, *Anthropology in the Meantime*, 9. On historical ethnography, see, e.g., Harkness, *Jewel House*, 254–60.

111 Husserl, *Krisis*, 50.

112 See especially Slatman, *Our Strange Body*.

113 On transparency versus opacity in life science research, see also Myers, *Rendering Life Molecular*, 231.

114 Ihde, *Technics and Praxis*; Ihde, *Experimental Phenomenology*; Ihde, *Technology and the Lifeworld*; Ihde, *Instrumental Realism*; Ihde, *Bodies in Technology*; Gallagher, *How the Body Shapes the Mind*.

115 Mol, *Body Multiple*, viii; Mol, “Pathology and the Clinic,” 84.

116 For further readings on embodied practices and experimental sciences, see, e.g., Doing, “‘Lab Hands’ and the ‘Scarlet O’”; Hentschel, *Unsichtbare Hände*; Mascia-Lees, *Companion to the Anthropology of the Body*; Mol, *Body Multiple*; Myers and Dumit, “Haptics”; Myers, “Molecular Embodiments”; Myers, *Rendering Life Molecular*; Prentice, *Bodies in Formation*; Polanyi, *Personal Knowledge*; P. H. Smith, *Body of the Artisan*; Wolfe and Gal, *Body as Object*. On anthropological methods for the study of life sciences, biotechnologies, biomedicine, and artistic investigation of emergent life-forms, see esp. Fischer, *Emergent Forms of Life*; Fischer, *Anthropological Futures*; Fischer, “Biopolis”; Fischer, “Science and Technology”; Fischer, *Anthropology in the Meantime*.