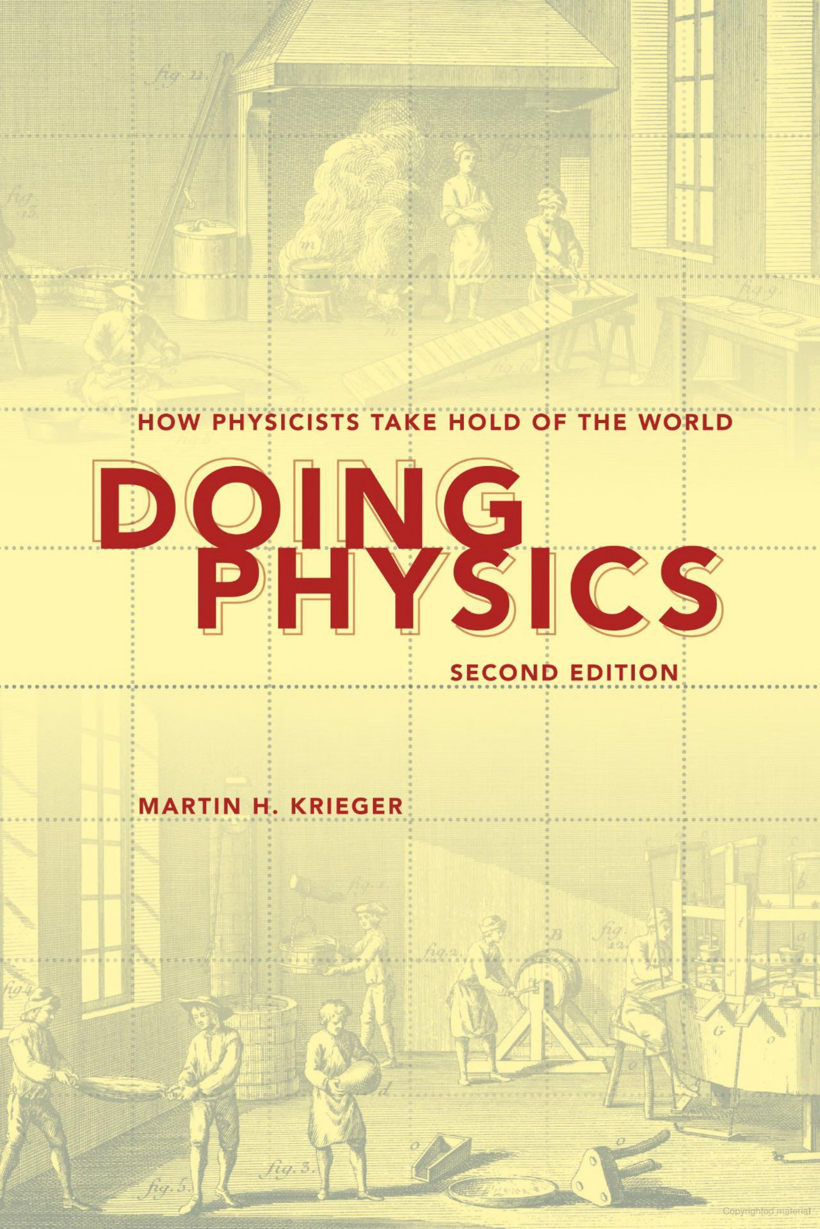

HOW PHYSICISTS TAKE HOLD OF THE WORLD

DOING PHYSICS

SECOND EDITION

MARTIN H. KRIEGER

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Preface

Degrees of Freedom; A Note to the Reader; A Note for the Scholars; This Second Edition; Acknowledgments.

THIS IS A BOOK ABOUT HOW PHYSICISTS TAKE HOLD OF THE WORLD, actually about how some physicists get hold of some of the world. To an outsider watching physicists work, the details of that work and the physicist's obsessive concerns make little sense unless one has some idea what physicists are up to, what their various goals or purposes are. Technical moves *do* something, contributing to certain generic schemes. I want to describe the meanings of some of those moves, not so much to explain the physical world in some semi-technical or popular fashion, but to describe a rather familiar culture we all share.

For it turns out that physicists' goals have much in common with those of other theoretical endeavors which try to make sense of the world – whether by economists or anthropologists, for example – surely in part because those endeavors have been influenced by the work of physical science. And much of modern science developed in accord with economic and political modernization, the growth of both market economies and a strong sense of individual autonomy, and a spread of social alienation. The pervasive problem has been to find the right sort of individuals, and a culture in which such a liberal society might thrive. In vulgar terms, there is an identity of Cartesianism's particles and capitalism's actors and commodities. We might be said to have an economy of Nature.

Again and again, we shall see *analogies between physics and economics, political theory, anthropology, and sociology,* analogies that may be of interest to social scientists.

My claim here is that there is just one culture (rather than the two of C. P. Snow). For the culture of physical science is a subculture, articulating major themes of the larger culture – a larger culture whose ideas and practices have been, reciprocally, deeply influenced over the centuries by the physical sciences.[1]

A Note on Diction: I have deliberately used a number of colloquialisms, such as "getting hold of the world" or "getting a handle onto something," to capture the everyday experience we have in doing physics and to connect that experience with the larger culture. More generally, I have tried to use everyday terms to do technical work, the obligation being to use them consistently. When I describe physicists as being "obsessed" with certain models, I mean an insistent returning to a particular way of doing things and a recurrent compelling concern with certain issues, where such ways and issues might seem unreasonable to an outsider – in short, obsessions. In the same vein, I use "poignant" to describe the strange pervasiveness of physicists' commitments and, again to outsiders, the sometimes even sad doggedness with which these commitments are pursued.

Now, even if the technical moves physicists make are quite conventional and archetypal, the generic character of convention and archetype hides behind some concrete models and specific ways of going about things. Physicists will take the natural world as being much like the division of labor with its alienated individuals, or like a mechanism composed of parts, or like a system of exchange as in kinship, or like a black stage on which the drama can be natural phenomena. They get a handle onto the world by probing it, poking at it and seeing what happens. And, using the machinery of mathematics, they may analyze the meaning of common notions, and highlight and display various aspects of a phenomenon leading to a deeper understanding of the physics. They craft the world by using conceptual tools. Of course, such abstraction leaves lots out of consideration, and this is a good riddance, for it allows the physicist to get on with the work at hand. When physicists try to take hold of the world, to get a handle onto the world and shake that handle to see what will happen, they are quite willing to give up on most of the world so that what happens is simple and nicely related to their original shaking. They take hold of one "degree of freedom," and if they are lucky they have tamed the rest into silence.

James Clerk Maxwell, the great nineteenth-century physicist, put it nicely. He begins with a methodological remark and then presents a poignant clockworks-like mechanical analogy:

> We must remember that the co-ordinates of Thomson and Tait are not the mere scaffolding erected over space by Descartes, but the variables which determine the whole motion. We may picture them as so many independent driving-wheels of a machine which has as many degrees of freedom.
>
> We may regard this investigation [of ignorable coordinates] as a mathematical illustration of the scientific principle that in the study of any complex object, we must fix our attention on those elements of it which we are able to observe and to cause to vary, and ignore those which we can neither observe nor cause to vary.
>
> In an ordinary belfry, each bell has one rope which comes down through a hole in the floor to the bellringer's room. But suppose that each rope, instead of acting on one bell, contributes to the motion of many pieces of machinery, and that the motion of each piece is determined not by the motion of one rope alone, but by that of several, and suppose, further, that all of this machinery is silent and utterly unknown to the men at the ropes, who can only see as far as the holes in the floor above them.
>
> Supposing all this, what is the scientific duty of the men below? They have full command of the ropes, but of nothing else. They can give each rope any position and any velocity, and they can estimate its momentum by stopping all the ropes at once, and feeling what sort of tug each rope gives. If they take the trouble to ascertain how much work they have to do in order to drag the ropes down to a given set of positions, they have found the potential energy of the known co-ordinates. If they then find the tug on any one rope arising from a velocity equal to unity communicated to itself or to any other rope, they can express the kinetic energy in terms of the co-ordinates and velocities. These data are sufficient to determine the motion of every one of the ropes when it and all the others are acted on by any given forces. This is all that the men at the ropes can ever know. If the machinery above has more degrees of freedom than there are ropes, the co-ordinates which express these degrees of freedom must be ignored. There is no help for it.[2]

How physicists take the world is the way that world *is* for them – at least as physicists, at least for most physicists. If it is taken as a matter of the division of labor between particles and fields, that is just what it is. It is not *like* a division of labor, implying there might be a more authentic real existence. Rather, it *is* that model, as long as the model is productive. Surely, there are dis-analogies, leftover pieces, and misfits. Future, presumably better models may be very different from the current one, even while reincorporating its enduring insights. But all of this is always the case. Again, what matters is how productive is a model or a way of taking the world. If it is productive, the world *is* this way. Physicists may justify their taking the world in the ways they take it by means of an argument about its true nature. But in actual practice those justifications and references to its true nature are forgotten: The world *is* this way. In this vein, professional and craft practices generally treat the world as a given, suited to their models, whether it be in medicine or law or plumbing.

Again, I mean this book to give the reader a sense of what's up when physicists do their work: the moves, the rituals, the incantations. It is a cultural phenomenology, not a reductionist exposé. And it is not a textbook. There is no attempt to train the reader to do physics problems or to set up experiments. Nor do I work out the conventional technical formalism, or do derivations, or anything like that. Mathematics and formalism are wonderfully automatic in this field, like all such machinery when appropriately applied, doing all sorts of work by the way, that by-the-way work being physically interesting. (As we'll see the production people have to constantly attend to the machinery so that what appears automatic is in fact adjusted and repaired by hand, so that it can appear "automatic.") To have mastered the technical models, even in a freshman course, is to learn to become automatic in your practice: to think like a physicist, and presumably to be less aware of your conventions and archetypes *as* conventions and archetypes. Still, it would surely help to try out the various practices, even in toy arenas, whether it be by solving problems or by doing an experiment. Nothing is so hard to demonstrate than is the skill of noticing physically interesting phenomena. Laboratory courses usually are too programmed toward getting the right answer to allow the student to get really lost and waste lots of time. But what needs to be appreciated is just the possibility of there not being a right answer, of needing to fudge things by taking the world in one of the ways I describe, so you get someplace at all.

of vibration are its degrees of freedom. If the rigid body could have a crystalline order, then the crystal's symmetries are degrees of freedom. And if the crystal is magnetizable, there are further degrees of freedom, its amount and direction of magnetization. And there are still hidden degrees of freedom, ones we do not see unless we heat the crystal, so that melting or chemical reactions can start taking place.

The degrees of freedom of a uniform gas or fluid include its temperature and pressure. If the gas or fluid is flowing and turbulent there are lots more degrees of freedom, for the pressure and density of the fluid will vary from point to point. If the gas were composed of different sorts of molecules, their relative concentrations would also be degrees of freedom. More generally, in systems having multiple components (for example, water and alcohol), the number of the various phases of matter (gasses, liquids, solids) that is allowed is a measure of the number of degrees of freedom of the system (such as temperature and pressure), namely, the Gibbs phase rule.[6]

Degrees of freedom are the ways a physical system might change or be different than it is just now.[7] And if we tie the system down in some way, its freedom is restricted and so are its degrees of freedom. Hence, notionally fixing the molecules of a solid in orderly crystalline places tames the degrees of freedom dramatically. Except, those molecules vibrate around those notionally fixed positions and hence there are now many vibratory degrees of freedom (unless the temperature is sufficiently low so that some vibratory degrees of freedom of the lattice must remain quiescent). A good handle onto a system is a degree of freedom that makes it possible to ignore lots of the others since they are otherwise constrained or held in place, and either dragged along with the degree of freedom or left untouched by it. The temperature, for example, is often a very good handle since it determines the extent of excitation of all the vibrational degrees of freedom of a solid in equilibrium. (A bit of detail: The excitation of a degree of freedom requires a quantum of energy, one that is quite rarely available if the temperature is low enough compared to the quantum size (which is proportional to temperature). This fact is used to explain dilemmas in the classical account of specific heats, namely the hiddenness of the degrees of freedom of the core electrons in a solid. For those electronic modes, at about one electron-volt of energy, are not excited at room temperature, equivalent to a few hundredths of an electron-volt average energy, and so they do not contribute to the specific heat.)

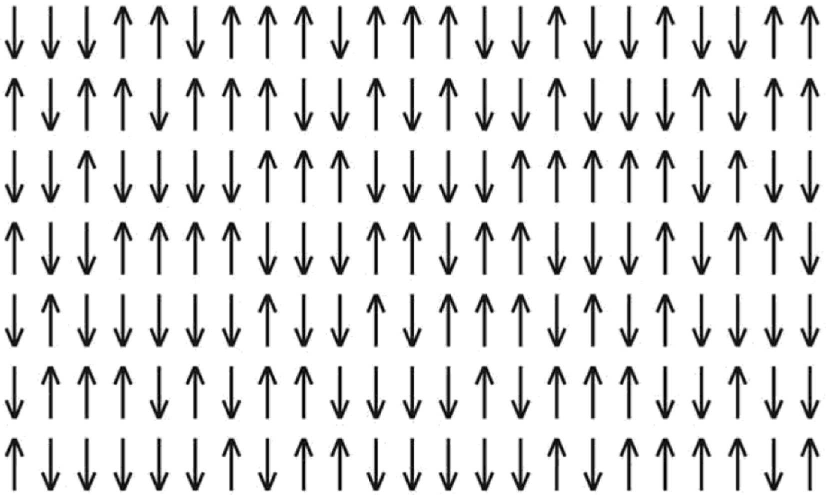
More generally, if there are no degrees of freedom then the world is fully necessary. And so there are accounts of creation that allow for no free variables. And if there is an infinitude of degrees of freedom, where none of them is constrained, nothing fixing things in place, then the world is fully arbitrary. The actual world, as physicists deal with it, is somewhere in between; and I want to sketch how physicists make their peace with that somewhere in between.

In sum, my purpose here is to describe the ways physicists are convinced that the world *must* go, their tradition of models and techniques and phenomena that delimit for the most part what they take as Nature. Here I have in mind an often heard phrase, say, concerning a yet undefined physical situation or problem: "it must go this way" – immediately leading to a suggestion for a simple model or an emendation or a speculation. Here *must* is a combination of reasonable guess, skillful craft-work, and a sense of Nature's character. One would be genuinely surprised if Nature did not go this way.

I want to retell and interpret the stories physicists tell when they take hold of the world. Of course, all of this is an "of course" to a physicist – or at least I hope so. But it is not so obvious to outsiders; nor are the cultural connections, as conceived explicitly, so much part of being a well-trained physicist. Still, again, I would hope that for the practicing physicist my description would possess the ring of truth (to use physicist Philip Morrison's term), leading to a greater integration of what the physicist already knows and to a moment of self-recognition.[8]

ISING MATTER

In chapter 6 I ask, How does mathematics do its work in physics? What is the structure of argument in mathematical physics? My main point is that mathematics is machinery or a tool for doing physics; and, it is a form of philosophical analysis and of phenomenological description. The technical demands of rigor and precision are not merely for show. They reveal more of the physics of the system being described and analyzed. I



P.1. The Ising lattice in two dimensions at a high temperature

use many of the same examples as earlier in the book, namely the mathematical modeling of ordinary bulk matter composed of molecules, and the mathematical modeling of a phase transition such as liquid freezing or an iron bar becoming permanently magnetizable – where by "mathematical modeling" I mean expressing a physical system in mathematical terms, the word "modeling" implying that the expression is schematic and incomplete. As preparation, it may be useful to say a bit more about one of these models, the Ising model of ferromagnetism. The model appears in chapter 4, describing a phase transition as a matter of scaling and choosing the right degrees of freedom, and in chapter 6 as an example of a mathematical *tour de force.*

Schematically, one pictures a piece of iron as a two-dimensional grid or lattice of atomic magnets, each of which can point up or down.[9] The atomic magnets bounce randomly, each on its own, rapidly oscillating from up to down and back, due to "thermal motion" (much as air's molecules move rapidly at room temperature and pressure, bumping into each other many times each second as well as bumping into walls of the enclosure – namely, the pressure). Yet there is also a magnetic force among pairs of adjacent atomic magnets that aligns them with each other. There is a conflict between disorderly effectively-random thermal motion and the ordering force of magnetic alignment. If the temperature is low enough the magnetic alignment force dominates; in fact, that transition to dominance occurs at a well-defined "critical" temperature. Let us call this model of matter "Ising matter," after the author of the earliest papers that described its behavior.

The mathematical problem of solving this model, going from the atomic situation to ordinary everyday bulk matter, and determining that critical temperature, was solved by Lars Onsager in 1944, and in the subsequent years there have appeared many different mathematical ways of solving the problem. Some just literally count up all the interactions among the atoms: one by one, or in blocks of spins of increasingly larger units. Some discern regularities in the lattice system and the magnetic-thermal forces – such as that a very disorderly high temperature system with a bit of order is like a very orderly low temperature system with a bit of disorder; or, the system looks the same at all scales, so if you get closer you see the same patterns; or, that scaling would seem to define the algebra of devices used to do the counting-up. Some find "particles" (actually orderly rows of spins) in this lattice and work with them. Some model that lattice as a field. All these points of view are it seems true; Ising matter accommodates them all, and we might say that there is an identity in that manifold presentation of its profiles. All the methods come up with the same answers (as we might hope), and a retrospective reading of Onsager's paper suggests how all these methods are built into his solution – although that is apparent only retrospectively. How and why the very different mathematical technologies or methods are applicable is not always easy to discern. It would appear that we have an analogy among these methods, and then an analogy of this analogy with a similar analogy in pure mathematics.

Not only is Analogy Destiny; it would seem to be Analogies all the way Down.

A NOTE TO THE READER

Some of this book is hard going. So I should perhaps say something even more explicit about audience, difficulty, and ethnographic distance, so that the reader will have appropriate expectations for a book that at first might seem to be a popularization of physical science when it is actually an account of aspects of a subculture in our society, a description of the world as physicists take it.

I have tried to write so that readers who are not physicists will readily follow most of the text, employing their everyday intuitions to understand an arcane subculture within their own society. What will help, of course, is that it is a *sub*culture, one sharing in the general culture's central themes and rhetorics. The reader must have some experience of the general culture, say of a factory as a division of labor, so that the models I describe are seen as models. Otherwise, the culture to which I am referring would be as obscure as the physicist's subculture.

The problems with this approach are twofold: First, again, many readers will think of themselves as laypersons; and so they might well expect a popularization, an explanation of the physics. And what they receive is an account of a culture and a rhetoric, about which they are as expert as anyone. On the other hand, for physicists the technical material is more or less obvious. But the cultural and metaphoric account will seem suspicious, since it shifts their everyday work into an alien context. I have tried to put sufficient technical explanatory material in the notes to take care of the arguments I would want to make to these native specialists, especially concerning fine points. I would also hope that physics students might find the stories I tell illuminating, helping them to have richer intuitions about what is "really" going on in their technical courses.

(Technically, I have taken a very particular point of view on physics, much influenced by contemporary ideas in quantum field theory of many-body systems. I imagine that another point of view would produce a different set of models and modes of getting at the world. In any case, I have not at all emphasized the currently popular "mysteries" of modern quantum mechanics, staying within rather more orthodox interpretations. I have made much use of some comments by the very unmysterious physicists Steven Weinberg, P. W. Anderson, and Richard Feynman.[10] The seminal ideas of John Wheeler and Lev Landau are crucial, especially for chapters 1 and 4. What is impressive to me is how the traditional issues and metaphors of mechanical philosophy are replayed in new contexts.)

When I read the philosophic literature, I am most comfortable with the work of Thomas Kuhn and Ian Hacking.[11] Kuhn strikes me as being very close to what the physics is really like, and his notion of paradigmatic exemplar covers much of what I mean by analogy and by concrete archetypal example. Hacking's emphasis on "intervening" is just what I mean by handles, both experimentally and theoretically. I am less sure where I stand on many of the traditional philosophic issues, say as Hacking describes them in the "representing" half of his book. But rather than asking what the world is really like, I would rather say how we take hold of it and so describe its phenomenology.

The analogies which concern me here are cultural analogies, stories or narratives connected to other such stories, with no necessary mathematical or structural link.[12] It is in the terms of art and how they are used and what they refer to, or in the technical tasks and how they are carried out and the other tasks they are linked to, that the analogy is made apparent. I have given a great deal of discussion of model and analogy under the rubric of tools and toolkits in a previous book, *Marginalism and Discontinuity: Tools for the Crafts of Knowledge and Decision* (1989), and will not repeat it here. When we talk about tools, what is crucial is that tools are used to do work. A set of tools provides a provisional way of taking hold of the world and doing something with it. Toolkits have a small number of tools and we adapt those tools to new situations. Hence the small number of major analogies I use here.

Social studies of science have shown that "practice should be seen as a process of modeling, of the creative extension of existing cultural elements."[13] Such extension is contingent and open-ended, the exact extension of a model dependent on how it is taken to fit a new situation. Good models have a high degree of analogy with what they are to model, along the way requiring modification if they are to overcome initial mismatches. Put differently, insofar as physicists are Kantians with no direct access to Nature, they are committed to allegory and imagery – much as the pastoral theologian, such as Augustine, employs allegory for lack of direct knowledge of God (as a consequence of the Fall).[14] The physicist's commitment is expressed not so much by a creedal statement, but by the presumption that the world *is* this way, the world *is* this allegory.

One might ask how I decided which are the major analogies or models. Some, of course, are venerated in myth and scholarship – such as the clockworks. Others play such central roles in our culture, such as economy and kinship and craftwork, that we are not so surprised to see them repeated in a subculture. And others, such as the theatrical stage, are happy realizations that remind one that science is much like the arts in that it is an orderly provision of the world. Other major analogies, such as that of evolution and organism, seem to play a much smaller role in most of physics. In the end, I think one justifies a cultural analysis by its value in epitomizing a wide variety of phenomena, its recognizability to its practitioners, and its being a repetition of analyses for other aspects of the culture.

I do want to emphasize that whatever Nature does, Nature does its work not verbally or textually but through physical interactions. That the everyday phenomenology and the physics go together is perhaps not ultimately surprising; but, to me, how that "going together" takes place is, as craftwork, wondrous and remarkable.

Finally, a brief remark concerning history of science. What I have tried to do here draws from the history of ideas and culture and science, in that it insists that contemporary notions have a history, a history of repetition and modification of previous notions. Just how self-conscious scientists are of economies, mechanisms, kinship and plenitude, stages, and toolkits is a matter for historical scholarship. For that consciousness surely changes, some larger cultural notions going into comparative eclipse for a while. Moreover, such a history of science is not reducible to a history of ideas or of economic relations. Scientific events – experiments and phenomena – will resist ideas and economies, a resistance that then leads to real work for the scientist.

THIS SECOND EDITION

Rereading the book so many years after it was first published has been a curious experience. Almost on every page I would think of something I left out or an apparent error, or that some proviso or modification was needed. I would check the notes, and discover often that I had dealt with the issue. Or, I found that perhaps two pages hence in the main text there was the needed discussion.[15] And, there were other errors, conceptual, technical, and verbal, that I have corrected. (Surely, others remain.) I was repeatedly struck by my commitment to the themes of Analogy is Destiny and to The Craft of Doing Physics, and again how my work on an earlier book, *Marginalism and Discontinuity* (1989), is a foundation for *Doing Physics.* In the more than twenty years since I wrote *Doing Physics,* I have written two fairly technical books on how specific mathematics and models realize those analogies and enable that craft: *Constitutions of Matter: Mathematically Modeling the Most Everyday of Ordinary Phenomena* (1996) and *Doing Mathematics: Convention, Subject, Calculation, Analogy* (2003). For this edition, in chapter 6 I have provided a nontechnical epitome of those two books, while making minor changes throughout the original text and notes.

In some of my other work, as a professor of city planning, I have spent a good deal of time in factories and workshops in Los Angeles. I realized that I was following in the footsteps of the encyclopedist Denis Diderot, who with d'Alembert are the authors of the *Encyclopédie* (1750–1772). Diderot tried to describe and illustrate the *arts et métiers,* the crafts and manufacture of his time, the actual practices of the workers. I, too, have been describing some of the crafts and modes of manufacture of physics: the design of a factory, the engineering design that produces an object out of components, and so forth – the actual practices of the workers, the physicists. I have focused on the conceptual and theoretical work, not on the design of experimental setups. And for the most part I have focused on descriptions that are microscopic and molecular physical processes, rather than the macroscopic (as in celestial mechanics or the proverbial block-and-tackle pulley).

One last proviso. This is not a book describing the practical how's of doing physics, even theoretical work. For example, here is a description of the ways of working of one theoretical physicist, John Bardeen:[16]

- Focus first on the experimental results via reading and personal contact.
- Develop a phenomenological description that ties different experimental results together.
- Explore alternative physical pictures and mathematical descriptions without becoming wedded to any particular one.

- Thermodynamic and other macroscopic arguments have precedence over microscopic calculations.
- Focus on physical understanding, not mathematical elegance, and use the simplest possible mathematical description.
- Keep up with new developments in theoretical techniques – for one of these may prove useful.
- Decide on a model Hamiltonian or wave-function as the penultimate, not the first, step toward a solution.
- DON'T GIVE UP: Stay with the problem until it is solved.

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My teachers at Columbia taught me how to think like a physicist. Those teachers thought it important to speak to "the other side of campus," as my advisor Leon Lederman puts it. I still do. Almost twenty (now forty) years ago I was a fellow at the Center for Advanced Study in the Behavioral Sciences the year that Yehuda Elkana, Robert Merton, Árpád Szabó, Arnold Thackray, and Harriet Zuckerman were there – and to boot, Chie Nakane and Terry Turner were also fellows. They made it possible for me to be fruitfully struck by the fact that the revolution in particle physics in the 1970s (the "standard model") was once more a repetition of the structures (namely, Maxwell's equations) we had seen before, much as my teacher of classical mechanics, Herbert Goldstein, insisted on quantum mechanics' being a repetition of classical mechanics, suitably understood. I owe to Hunter Dupree, at the National Humanities Center, the conviction that all of this is about science.

At the University of Southern California, Paul Bohannon, Alan Kreditor, and Karen Segal gave me the chance to teach an honors science course for nonscientists, from which this book arose. David Richardson gave an early draft a close reading. Abraham Polonsky has been the kind of literate fan – recognizing just what you are up to – one wants when writing a book or a screenplay or even in getting through life.

My friends have taught me a very great deal, and besides the many persons mentioned above let me add Jay Caplan, Tom and Jehane Kuhn, Eric Livingston, Andy Pickering, Gian Carlo Rota, Sam Schweber, and Gerry Segal. And Miriam Brien, Susan Krieger, and Elizabeth Kuhn. And John Bennett. And there are more.

No parent writes a book without a child who goes to sleep on time. For that, and a lot lot more, I love you David.

As for this second edition, many of the colleagues and friends mentioned above have passed away. I will not repeat the acknowledgments in my later books *Constitutions of Matter* and *Doing Physics,* for perhaps not surprisingly, they are much like what I have written above. Bob Sloan of Indiana University Press encouraged this second edition. And my work in this area, while not supported directly, benefited from a variety of foundation grants.

My son, David, is now a young adult still asking the best of questions.

ONE

The Division of Labor: The Factory

Nature as a Factory; Handles and Stories. What Everyday Walls Must Do; Walls for a Factory; Walls as Providential. Particles, Objects, and Workers; What Particles Must Be Like; Intuitions of Walls and Particles. What Fields Must Be Like.

THE ARGUMENT IS: THE WORKINGS OF NATURE ARE ANALOGIZED to a factory with its division of labor. But here the laborers are of three sorts: walls, particles, and fields. Walls are in effect the possibility of shielding and separation; particles are the possibility of sources and localization; and fields allow for conservation laws and path dependence. Different kinds of degrees of freedom are associated with each type of laborer, and the laborers naturally restrict each other's degrees of freedom – if the Factory of Nature is to be as productive as it is. Corresponding to the efficiency of the division of labor in a factory or an economy is the comparative richness, elegance, economy, and wide applicability of a physical mechanism or theory or model. Technically, Maxwell's equations for electromagnetism are one realization of this political economy of a transcendental aesthetic, to honor both Adam Smith and Immanuel Kant in one phrase.[1] (We discuss other mechanisms of production in subsequent chapters, for example ones in which exchange and the extent of the market are crucial features.) My claim is that physicists take Nature in this sense of manufacture; of course that sense being interpreted in terms of empirical "peculiarities," as Smith employs the term.

I

NATURE AS A FACTORY

Here is Adam Smith in the beginning of *The Wealth of Nations* (1776), describing the division of labor:

> The greatest improvement in the productive powers of labor, and the greater part of the skill, dexterity, and judgment with which it is any where directed, or applied, seem to have been the effects of the division of labor. . . .
>
> But in the way in which this business [of pin making] is now carried on, not only the whole work is a peculiar trade, but it is divided into a number of branches, of which the greater part are likewise peculiar trades. One man draws out the wire, another straights it, a third cuts it, a fourth points it, a fifth grinds it at the top for receiving the head; to make the head requires two or three distinct operations; to put it on, is a peculiar business, to whiten the pins is another; it is even a trade by itself to put them into paper; and the important business of making a pin is, in this manner, divided into about eighteen distinct operations, which, in some manufactories, are all performed by distinct hands, though in others the same man will sometimes perform two or three of them. . . .
>
> This division of labour, from which so many advantages are derived, is not originally the effect of any human wisdom, which foresees and intends that general opulence to which it gives occasion. It is the necessary, though very slow and gradual, consequence of a certain propensity in human nature which has in view such extensive utility; the propensity to truck, barter, and exchange one thing for another. . . .
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> As it is the power of exchanging that gives occasion to the division of labour, so the extent of this division must always be limited by the extent of that power, or, in other words, by the extent of the market. (Book 1, chapters 1–3)[2]

The great invention here was to appreciate that in order to make pins or anything else, and to understand how they are made, one divides the work into specialized functions (those "peculiar trades"), attributes those abstracted functions to individual workers, and then provides for a system in which their labor is coordinated. Such an economy or a factory turns out to be both efficient and comprehensible. No individuals need do everything for their own livelihood, as they might on a farm. Nor would they need do everything to make a piece of equipment. What is needed is a mechanism to make sure that each individual knows what to do, and a means of organization and communication – whether it be a factory with its distinct tasks and processing lines, or a market economy with its specialized jobs, processes of exchange, and the prices attributed to labor and to goods. Such a division is not only efficient, it readily allows us to pinpoint what is going wrong if the factory does not function as we expect it to: some specialized task is not being done properly, or some particular means of coordination has become sticky. Rarely, if ever, is the whole factory to be reorganized. One almost always need merely to get hold of some specialized part and fix it.[3]

Of course, it is a very great achievement to create such a factory or economy, to figure out a workable division of labor and a mechanism of production. Careful prior analysis may help, but often it is a matter of trial and error, and perhaps even of settling into a configuration that is not the best one, but at least it works – as David Hume (1779) would have suggested, a consequence of its having been until then "botched and bungled."[4]

Now imagine that we, as economic anthropologists, were to come upon a seemingly productive system, and then tried to figure out how it worked. We may have some general ideas about how factories are organized and have some particular models or examples in mind. If the system just fits our ideas and templates, we are, so to speak, in business. But this particular system may be of a different shape and size, its boundaries uncertain or idiosyncratic. It is not quite so manifestly analogous to our models, not quite so readily gotten hold of with our regular toolkit – or so it seems. So we try out a tentative organization-and-flow chart drawn from our ideas, models, and tools, and see if it makes any sense of the workings of the factory. Along the way, we have to label the workers and work stations correctly, the product has to be distinguished from the garbage, the sections of the factory have to be delineated. Eventually, we might begin to understand how the factory works, why it is productive, and how it might break down and so exhibit new phenomena, and what to do to repair it if it does break down. (Recently, I have had this experience in an actual workshop, a small foundry.)

Such is the task, I would argue, that many physicists see themselves as taking on (as do many a theorist more generally) when encountering the world. Nature is in effect taken to be a factory or an economy.[5] Can the physicist discern a division of labor within Nature, and a mode of organization, that makes sense of what Nature is doing – in that sense of a factory?

Soon after Smith, Immanuel Kant too provided a way of thinking of the division of labor required to make up Nature as physicists came to view it. The Transcendental Aesthetic that begins *The Critique of Pure Reason* (1781) might be taken as suggesting that space is just what is needed, grammatically and physically (what Kant called the "transcendental condition"), for objects to be separated and distinct from each other, and that time is the condition for there to be sequences of events and a causal relationship among them. Here, the natural division of labor in making up the world is between objects and space, between events and time. So we might ask: Which properties do we give to discrete objects, which to field-like space, and what mechanism do we prescribe for their interaction, so that we have an account of how the world works?[6]

I take it that the physicist's initial problem is to discern "the political economy of the transcendental aesthetic": (1) to describe the precise modes or mechanisms by which objects are delineated and so separated from each other – the *walls,* shields, and surfaces; (2) the names or labels or properties through which objects have their own identity and are influential in the world – *particles;* and, (3) the provision and delineation of space with its own properties, so that in space's interaction with particles we have an account of Nature's workings – *fields.* As in a factory, the various laborers work together to produce Nature, according to rules which are often traditional and conventional – such as the rules that interaction between particles is "local" rather than "at a distance" and that neither particles nor fields have a memory of their past. Other divisions and rules are possible, but if the factory is to be productive the divisions and rules have to work together.

In my discussion, walls, particles, and fields are all taken to be laborers.[7] Now, we might think it more natural to treat particles as most directly analogous to workers, and walls (and perhaps fields) as material and capital infrastructures much like the factory building and its machinery. But here I treat labor and capital as qualitatively similar inputs, so to speak, much as do economists in their formal production functions. I want to describe how they work together, deliberately avoiding any argument about particles vs. fields. As for the factory building (the mechanisms of interaction), we shall discuss its organization later in this chapter and in subsequent chapters.

In chapter 2 we describe the various kinds of individuals suitable for a factory or for an economy of Nature; in chapter 3 we delineate how exchange and the extent of the market define the factory; in chapter 4 we show how we set up both a factory and its outside suppliers so that the factory's production process is fairly straightforward; in chapter 5 we describe how an industrial engineer would investigate the factory's workings and the toolkit needed for making sense of such a factory; and in chapter 6, we describe some of the mathematical machinery in that factory and how scientists creatively use that machinery to do some of the work of physics.

Our first problem will be to describe the dynamics of the walls or shields, how things are kept apart or separated from each other so there could be space between them. Once we appreciate how walls are designed, then the design of particles and of fields follows in a natural way. But before trying to describe walls in some detail, I want to say a bit more about the task we are up to.

HANDLES AND STORIES

The attempt to make sense of Nature in terms of a division of labor may be thought of as participating in one of the abiding human endeavors: an attempt to articulate and analyze our experiences and the phenomena we encounter, in order to provide ourselves with a handle onto the world. Put differently, if we can manipulate the world we can understand it. Now the handles that will concern us here are the degrees of freedom – for example, position, temperature, charge, pressure, energy – of systems physicists concern themselves with. (The Preface provides an introductory discussion of the notion of degrees of freedom.) And those cision.) For purposes of exposition I place ourselves ("we") in the role of a physicist.*

Everyday walls may be defined as boundaries, interfaces, functions, skins, and dynamical processes. Boundaries delineate separation, interfaces describe permeability and interdigitation, functions allow for specific conditions to be maintained at the wall, skins hold together and bind, and dynamical processes respond to the outside world.

The wall may be a *boundary* line, like that between nations. Such a boundary might also allow for interchanges of specific goods in specific directions, and it might maintain certain conditions on itself (of purity or of temperature, for example). The boundary line and its conditions would seem to have to be maintained actively, by border guards, so to speak, if the boundary is not to fall apart. Yet, still, for many analytic purposes we need merely specify the spatial separation that the boundary defines (or its topology) and its exact shape.

Now, that boundary may be between two fluids which do not ordinarily mix, an *interface,* say between oil and water. Interfaces are breached by processes of mixing and intermingling and interdigitation. We might add soap to the water, or in the case of a water-ice interface we begin to melt the ice. The area of the interface can become very large, with fingers of one material jutting out into the other, just what we might mean by intermingling and interdigitation.[10] In effect, the interface has become a permeable wall, allowing material from each side to enter the other.

As I have indicated, some walls are conceived of in *functional* terms. They *do* something. They hold temperature or electric charge constant, or prevent heat from escaping, or ensure that interactions with the rest of the world are weak – by some means. When these interactions are weak,

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*Guidance to the Reader: In order to capture the texture of these endeavors, the material in this part is comprehensive and detailed, and in that sense it is technical. My presentation is quite closely motivated by the structure of contemporary physical theory as well as the phenomenology of physics. Again, the purpose here is to appreciate the moves physicists make, and thereby appreciate what they mean by Nature. And what I have tried to do is to systematically catalog those moves. Some readers may just want to scan the pages in which the detailed phenomenology of what walls do is presented.

the enclosed objects can be more independent of each other.[11] Ordinarily, we do not inquire, at least in theoretical and conceptual discussion, about the size or nature of such a wall, or just how it works. We are concerned with its functionality.

In contrast, consider a binding *skin,* such as a balloon, or as on an apple, or the surface of a solid ball or a nucleus. Surely these walls are functional, but we are acutely aware of their thickness and composition and resilience, and more generally that they have to protect, face the outside, and perhaps hold in something. And, dynamically, stuff could vaporize off such a wall, or accrete onto it. Thinking of a balloon, we expect that the skin balances the inside and outside forces; thinking of a liquid's surface or of a nucleus, the skin balances what might be vaporized off of it with what might be condensed onto it.[12]

Walls are not only between sides, and allow for mixture, are functional, and have thickness – they are also *dynamical.* Like those border guards, walls actively respond to whatever happens on either side so that they shield one side from the other, for the most part holding in what is on each side. A grounded copper cage serves as an electromagnetic shield by rearranging its electrical charges (namely, currents of electrons) over its area and within its thickness. If things change outside or inside, the cage's charges move around so as to cancel or modulate the effect of those changes on the other side. Changes in the internal or external temperature will require a thermodynamic wall to respond appropriately to maintain whatever conditions it is fulfilling. The wall may do its dynamical work on its own, as in the grounded electrical shield, or perhaps require our assistance, as in maintaining a constant temperature wall.

WALLS FOR A FACTORY: A PHENOMENOLOGY

Whatever everyday walls do, physicists have to make their walls do the technical work of manufacturing Nature. Physical walls do this technical work through quite detailed mechanisms or physical interactions.[13] But in abstracting and adapting everyday notions of walls, physicists are up to rather more phenomenological tasks. For example, their walls have to separate and shield.

So, whatever the kind of the wall (boundary, interface, functional, skin, dynamical) and whatever it does (delimit, be permeable, maintain conditions, bind, or respond to the world) – what it must do is *separate* one side from another. Now so far I have been describing walls as if we could see both sides. But, in fact, we or our apparatus are often on one side of a wall, and at best we can burrow into it. And usually we are on the outside. If a wall is designed to separate, practically that means it controls what we can see of the other side, the inside. Now, in actual fact, if somehow we do have a chance to get to the other side, taking a much more intimate look at it, we are often overwhelmed with the complexity of that other side. What we usually do not see, and about which we would otherwise have little if any inkling, is often more than we want to handle. Walls do the work of manufacturing Nature, and they simplify Nature so that physicists can make sense of it. Put differently, in a division of labor the factory owner need know (and may be pleased to know) only very limited features of each laborer.

Moreover, walls account for the persisting identities of objects. From the outside, an object will appear to possess enduring qualities. No matter how we look, it appears the same. Yet under much closer examination, it may well turn out to be changing inside, none of which changes are ordinarily seen by us. We can say either that the walls hold the changes in or that the walls prevent us from seeing those changes; phenomenologically, they are the same. Walls are said to *shield* many degrees of freedom, so that those degrees of freedom cannot express themselves and so they are not felt by outsiders (or othersiders). In effect, most of what goes on inside cannot show itself to us. And walls also shield against our own actions. They do not allow us to get a peek at or to get hold of most of what is inside. We cannot penetrate the wall, at least in these ways. Any time we try to influence the other side in these ways, so as to find out about it, the walls shield that other side by dynamically working against our action – think of a bulletproof vest. Of course, walls may be breached by energetic impacts or will be briefly penetrated by fluctuations (classical or quantum).

Now, in imputing a factory-design to Nature, a division of labor that produces Nature, the walls that separate and shield turn out to do so by being able to (1) filter degrees of freedom, (2) define nearbyness and own-or-other (or friend-or-foe), and (3) deal with fluctuations. And then, as we shall see, Nature will turn out to be simple, symmetric, and stable – a form of Nature a physicist could take hold of.

(Some readers may want to skip ahead and return later to the details of this section. Again, what is perhaps most interesting here is the nature of the physicists' concerns, not the exact details of how they are fulfilled.)

(1) To separate and to shield is to *filter* the degrees of freedom and so provide good handles. A wall hides or filters out many degrees of freedom. But, most crucially, it lets through or displays a few degrees of freedom which epitomize what we might call internal features of what is otherwise hidden.[14]

For example, the usual properties of a gas of atoms depend on walls that filter out or, say, average out particulate properties, nonuniformities, and fluctuations. And so they transmit what are called bulk thermodynamic variables, such as temperature or pressure. If we are running a steam engine or studying the atmosphere we do not want to know about every atom in the steam or gas. But the temperature and pressure are crucial features. (Technically, here the wall is both the experimental or mechanical setup we employ and our looking for those bulk properties.)

A balloon considered as a wall filters out transient nonuniformities in the density of the gas it encloses. When the balloon is inflated, the balloon material is fairly rigid and so is appropriately unresponsive to small transients. It does not change much. And, just as surely, the balloon shows the average pressure of the enclosed gas.[15] Now, there might well be peculiar transient arrangements of the atoms of a gas in a box (say all the atoms are in half the box, the other half being empty). Taken as a wall, what a box does is to ensure that the effects of such peculiar arrangements are drowned out by others that are both much more likely and more uniform. And so we get the conventional degrees of freedom or handles for a gas in equilibrium: pressure and volume and temperature, so that pressure times volume is proportional to temperature, the ideal gas law. A filter not only lets through a few degrees of freedom but, by the filter's actual construction (a rigid box, for example), some of the degrees of freedom that are let through are so to speak created – for we would not have gotten hold of them without that filter.

Of course, a wall as a filter is only as good as the kinds of assault we are allowed to make upon it and the sensitivity of our probes. The wall must be resilient and responsive to ordinary assaults, giving but not breaking within the usual range of insult. But if we probe a surface with a blunt yet forceful tool, or a very pointed one, we shall not only get through, but rupture the surface as well; and if we are allowed to heat up an object sufficiently its protective shield will vaporize away. Physicists design walls, or can find walls in Nature, that are in just the right balance of filtration, resilience, responsiveness, and permeability.

(2) In this factory called Nature, not only must the walls separate, shield, filter, and be resilient, they must divide the world into places that are "nearby" each other and those that are far from each other – namely, on the other side of the wall. As we shall see, the grammar of nearbyness is technically a matter of connectivity, shared properties, and correlation and symmetry, while phenomenologically it is a matter of own-and-other. These technical and phenomenological demands shape theoretical constructs in not-so-subtle ways.

We might imagine a wall that separates a uniform medium into two sides, but there is otherwise no difference between those sides. Then two points are on the same side, if we can go (by some allowed path) from one point to the other without hitting the wall. Now, if there are properties that differ sufficiently so as to distinguish the two sides – whether they be the density of a liquid vs. that of solid, or the presence of charge inside a particle's wall vs. the absence of charge outside – then rather than pathfinding, we might measure those properties to find out whether we are on the same side as another point, and perhaps which side we are on.

Whatever the properties, what happens on one side of a wall is likely to have a more profound influence on that side than whatever influence it may exert through the wall to the other side. There is greater correlation among aspects of the same side than there is between sides. So, again without being able to see the wall, we might believe we can tell whether we are on the same side as another point.

Often, delineating nearbyness requires not only separation, but the creation of an inside and an outside, effectively a closed shield; namely, no matter how we approach something we encounter the wall, and so that thing looks essentially the same no matter how we approach it.