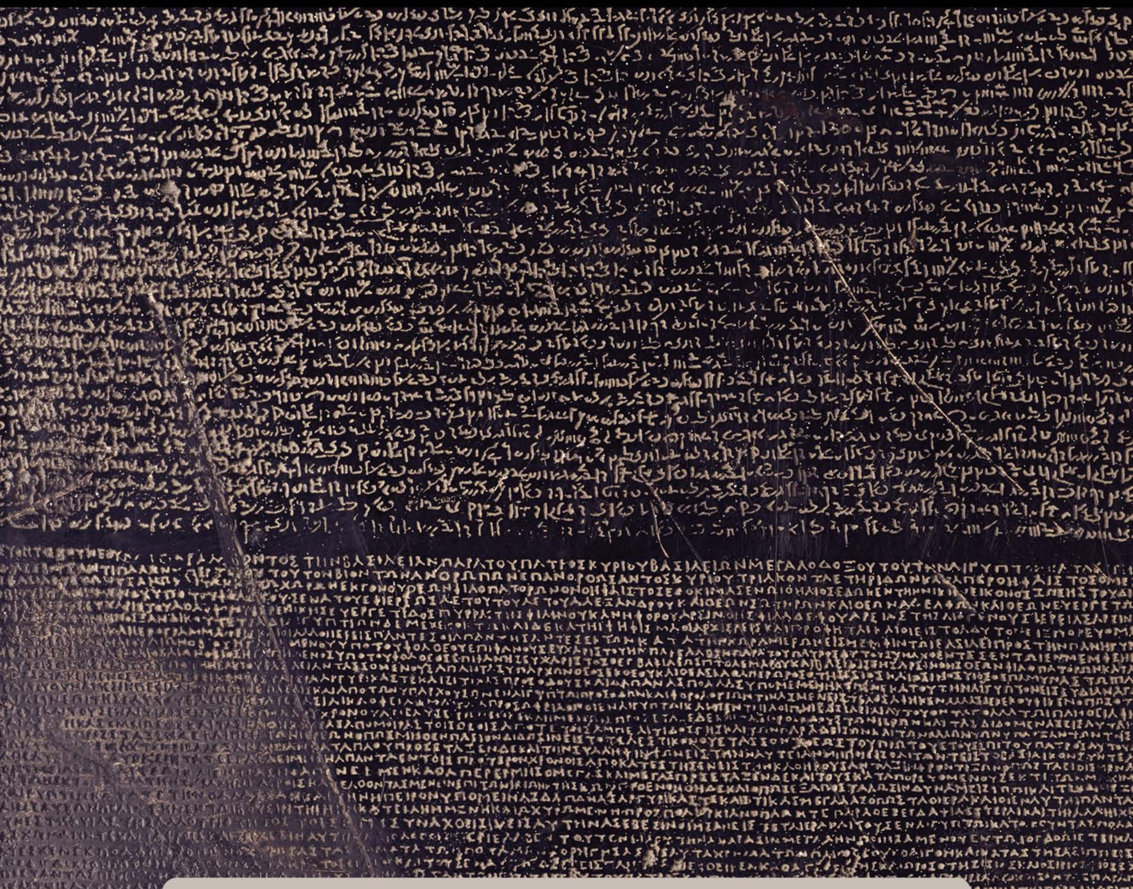
Dennis P. Waters

ROUTLEDGE

Behavior and Culture in One Dimension

Sequences, Affordances, and the Evolution of Complexity



RESOURCES FOR ECOLOGICAL PSYCHOLOGY

"*Behavior and Culture in One Dimension* provides an engaging, highly readable exploration of the foundational role of one-dimensional patterns or 'sequences' in the origin and evolution of complex systems on earth, among them, living systems. These one-dimensional sequences (including, for example, RNA, DNA, linguistic sequences, computer code) serve to organize, harness, and control (three-dimensional) physical systems so that the systems exhibit functional, organized activity at larger spatiotemporal scales including ecologically relevant scales. The book should attract a variety of readerships including popular science readers and students of evolution, ecological science, and language. For language scholars, such as myself, it offers a unique, persuasive, and impactful perspective on the kind of thing that language is, offering valuable insight on how language use in the world (written as well as spoken) can do the work it does. I highly recommend this book."

Carol A. Fowler, *Haskins Laboratories, U.S.A.*

"Over the past 60 years Howard Pattee proposed foundational ideas for understanding the nature of life. With spectacular clarity and force his former student Dennis Waters examines and extends Pattee's work to produce a vibrant framework for thinking how the physical/biological world constructs life itself. Get ready to think and then think again. This book is true scholarship in its finest form."

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"Dennis Waters' *Behavior and Culture in One Dimension* explores the implications of a deceptively simple idea—the concept of a sequence—and shows how much of the complexity of the biological and human world is dependent on it. With DNA at one end of his account and written language at the other, he shows how sequences have played midwife to the emergence of complex life and human civilization."

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"*Behavior and Culture in One Dimension* pursues the bold and intriguing claim that DNA, language, and computer code are not simply metaphorical allies. Waters builds the case that systems of linear sequences have properties in common that allow them to constrain activity in three dimensions. He's after a universal organizing principle that is independent of the embodiment of the sequence—human language, animal communication, behavior by parasites, bacteria, and civilizations are all in his sights. The neglect of language has long been seen by cognitive science as the Achilles heel of ecological psychology. An approach to language that respects the ecological emphasis on natural law is sorely needed and that is very much what Waters provides."

Claudia Carello, *University of Connecticut, U.S.A.*

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BEHAVIOR AND CULTURE IN ONE DIMENSION

Behavior and Culture in One Dimension adopts a broad interdisciplinary approach, presenting a unified theory of sequences and their functions and an overview of how they underpin the evolution of complexity.

Sequences of DNA guide the functioning of the living world, sequences of speech and writing choreograph the intricacies of human culture, and sequences of code oversee the operation of our literate technological civilization. These linear patterns function under their own rules, which have never been fully explored. It is time for them to get their due. This book explores the one-dimensional sequences that orchestrate the structure and behavior of our three-dimensional habitat. Using Gibsonian concepts of perception, action, and affordances, as well as the works of Howard Pattee, the book examines the role of sequences in the human behavioral and cultural world of speech, writing, and mathematics.

The book offers a Darwinian framework for understanding human cultural evolution and locates the two major informational transitions in the origins of life and civilization. It will be of interest to students and researchers in ecological psychology, linguistics, cognitive science, and the social and biological sciences.

Dennis P. Waters received his Ph.D. from Binghamton University in 1990. He became a publishing entrepreneur, founding technical news services like GenomeWeb.com. After retiring, Waters continued his Ph.D. research, how one-dimensional patterns of DNA, language, and code guide the three-dimensional world. He is a visiting scientist at Rutgers University.

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BEHAVIOR AND CULTURE IN ONE DIMENSION

Sequences, Affordances, and the Evolution of Complexity

Dennis P. Waters

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PREFACE

It's not uncommon for new Ph.D. graduates to turn their dissertations into books, but very few wait three decades to do it. In my case I think the wait was justified. When I graduated in 1990, many of the fields that inform *Behavior and Culture in One Dimension* were in their infancy. Steven Pinker and Paul Bloom were just planting the flag for the revitalized study of language evolution.[1] Richard Dawkins and Jared Diamond had just organized the first conference comparing evolution in biology and the social sciences.[2] The Human Behavior & Evolution Society was less than two years old. High-throughput genomics technology was about to reveal the complexity of how sequences of DNA orchestrate the living world. Hardly anyone had heard of bioinformatics or affordances or the RNA world. All of this subsequent research has made for a better book.

I never finished high school and dropped out of college to pursue a career in media, which led me to New York, where a chance visit to a newsstand introduced me to the work of Howard Pattee at what is now Binghamton University. I paid him a call, which convinced me at age 30 to drop what I was doing (or not doing) and move to upstate New York to resume my education. While in the Ph.D. program at Binghamton I started a marriage, a family, and a small technical publishing business. These have kept me busy in the intervening decades. Howard has remained a friend and mentor throughout.

This leaves me with 30+ years' worth of thank-yous, which I shall try to compress into a small space. The biggest go to the three individuals who read every word of early drafts, sometimes more than once, and encouraged me to continue. They are Howard Pattee, Carol Fowler, and Laura Waters, my wife. Others have read and commented on various sections. They are Laura Hyatt, Tom Neubert, Bernadette Toner, Joel Pisetzner, and Hannah Waters, my daughter.

For many years of helpful conversation, I thank Claudia Carello, Michael Turvey, Bill Mace, and Bert Hodges of the Center for the Ecological Study of

Perception and Action at the University of Connecticut. Likewise, to the Biosemiotics and Distributed Language communities, especially Joanna Rączaszek-Leonardi, Stephen Cowley, Sune Steffensen, and Marcello Barbieri.

For answering questions and other helpful interactions I thank Thomas Hackl, Robert Boyd, David Hughes, Edward Holmes, Morten Christiansen, Penny Chisholm, Sarah Tishkoff, Christopher Chyba, Bernd-Olaf Küppers, Dick Lipton, Charles Bennett, and David Gifford.

For early career advice, thanks to Ted Cloak, the late David Rindos, the late Donald Campbell, and Steve Straight. And as always, warmest appreciation for my Pattee Ph.D. program colleagues from long ago: Michael Kelly, Peter Cariani, and Eric Minch. For logistical support, I am grateful to Richard Hunter, Lena Struwe, Paul Schindel, and Masha Finn.

And for unwavering belief in my entrepreneurial instincts, which have given me the freedom to pursue this research, I thank Michael Ridder. My friend and agent Susan Cohen has tolerated hours of head-scratching conversation about what to do with a book like this.

Thanks to Carol Fowler, Jeffrey Wagman, and Julia Blau for suggesting the book for the Resources for Ecological Psychology series, and to the team at Routledge: Alex Howard, Cloe Holland, Lucy Kennedy, and Ceri McLardy.

My family has been loving and supportive through it all. My wife Laura (for our entire marriage) and my offspring Hannah, Jacob, Emily, and Jonah (for their entire lives) have heard me muttering on and on about sequences and constraints. Their patience is a marvel of the world.

The spark for this work undoubtedly came from my grandfather, Chester C. Waters, who died when I was seven years old, and of whom I have only the vaguest memory. Nonetheless, when I was a young teenager I received part of his library, which included most of the foundational works of the General Semantics movement, plus many volumes of their *ETC.* journal from the 1940s and 1950s. I never became a card-carrying general semanticist,[3] but reading this material at a young age got me curious about how language works—I mean how it *really* works—and curious I have remained.

As I write this, a modest sequence of 29,903 bases of RNA known as SARS-CoV-2 has spread rapidly around the world, overriding in its wake many of the sequences that govern the everyday functioning of our civilization. A central theme of this book is that certain sequences have the power to reclassify other sequences, sometimes to momentous effect. SARS-CoV-2 is an example I wish I did not have to offer.

Notes

1. Pinker & Bloom 1990
2. Gibbons 1990
3. OK, to be honest I did have lunch with Neil Postman once and did have correspondence published in *ETC* (Waters 1979).

INTRODUCTION

Sequences, Sequences, and Sequences[1]

0.1 The World in One Dimension

The recent discovery of thousands of planets orbiting stars in our galaxy points to the likelihood of billions and billions of such planets across the universe. The odds are getting better that Earth is not the only planet that is physically and chemically capable of supporting something like life as we know it. But should we find "life" elsewhere in the universe, how *would* we know it? How would we conclude that some bag of chemicals is actually alive?

This book will argue that the answer is to be found in one-dimensional patterns, the linear arrangements that we call sequences. On Earth, sequences of DNA guide the functioning of the living world, sequences of speech and writing choreograph the intricacies of human culture, and sequences of code oversee the operation of our literate technological civilization. The persistence and diversity of life and civilization are made possible by one-dimensional patterns orchestrating three-dimensional activity. Physics and chemistry play crucial roles as well, but sequences are something special. They operate according to their own rules, and those rules have never been fully explored. It is time for them to get their due.

Back in the day, of course, our Earth was like all those other planets, *capable* of supporting life but not yet doing so. It was a stark place. Volcanoes erupted. Continents collided and mountains emerged. Water flowed and winds blew. Sediments deposited and oceans evaporated. As with every planet we know about, the behavior of the prebiotic Earth could be described and explained by the primeval processes of physics and chemistry following their universal and inexorable laws. Nothing to see here, move on.

What changed, then? When the first sequences arrived on Earth, probably in the form of RNA molecules, forces of nature like gravity and electromagnetism continued without interruption, and matter and energy were neither created nor destroyed. So, in one sense nothing changed. But sequences did guide matter and energy to become organized into things like cells and cities and computers, harnessing and channeling the forces of nature to maintain that organization and elaborate upon it. And in that sense, everything changed.

Which brings us to today. As literate humans, you and I occupy a complex habitat overseen by three kinds of sequences. One-dimensional molecular arrangements of RNA, DNA, and protein enable the diversity of the living world, sequences of sounds in speech and characters in text allow human culture to flourish, and patterns of zeros and ones in computer code make our high-tech civilization possible. Geophysical events like eruptions, hurricanes, earthquakes, tsunamis, landslides, and floods are still with us, but they are not what makes our planet interesting. Most of the time we attend to a world colonized and orchestrated by sequences.

What, then, are these sequences that have profoundly changed Earth's environment? How did linear patterns of tiny molecules allow life to emerge from a background of ordinary physics and chemistry? How did sequences of vibrations in the air, marks on paper, and voltages in silicon allow civilization to emerge from a background of Tennyson's "Nature, red in tooth and claw?"

These are the questions that animate this book. Fundamental to advancing our understanding is a simple but profound question asked by biophysicist Howard Pattee: "How does symbolic information actually get control of physical systems?"[2] It is easy to envision a one-dimensional arrangement of molecules or letters or zeros and ones, but it is not so easy to envision how these patterns *actually get control* of the physical world, how they guide matter to behave one way rather than another.[3]

A fertilized egg packs into a one-dimensional pattern of DNA much of the three-dimensional information needed to make a chicken. How is it possible to get three dimensions of chicken out of a single dimension of genome? Further, the sequences of instructions that you need to assemble a bookcase are made of the physical substances of ink and paper, but no detailed study of the ink and paper will help you understand the meaning of the sequences. Something more is needed for the symbolic information (the instructions) to actually get control of a physical system (you).

On Earth or any other planet, we have learned that life does not require new laws of physics or chemistry, just some special, idiosyncratic infrastructure. In essence we start with physics and chemistry and we get biology for free. Further, human culture does not require new biological principles, just more special but different infrastructure. We start with biology and get civilization for free. In each case the special infrastructure that makes everything possible is built around the one-dimensional arrangements we call sequences.

The goal of this book is twofold. First, I would like to persuade you that sequences are indeed different and worthy of study in their own right. To create a unified account, I will show that sequences of DNA, language, and code have at least as much in common with one another as they do with the ordinary world of physics and chemistry. Second, I will offer a preliminary sketch of how they do what they do, their rules of operation. This will require an interdisciplinary march through physics, molecular biology, linguistics, anthropology, computer science, and other related disciplines. I have found this march exhilarating and I hope you will too.

0.2 The Linguistic Model in Biology

That different kinds of sequences share common properties is not an idea new to science, but it is an idea that has never been fully developed by scientists. It has had its greatest impact through a powerful metaphor which has animated the field of molecular genetics from its inception in the middle of the 20th century. Molecular biologist and Nobel laureate François Jacob calls this metaphor the *linguistic model in biology*, the recognition that the linear pattern of the DNA molecule is like a text, with an alphabet, punctuation, a one-dimensional layout, and an internal grammar.[4]

"One measures the value of a model by its operational efficiency," Jacob says, "and in this sense, the linguistic model has played a long role in recent progress in genetics." This is evident, writes cognitive scientist Steven Pinker, "in the reliance of genetics on a vocabulary borrowed from linguistics. DNA sequences are said to contain letters and punctuation, may be palindromic, meaningless, or synonymous, are transcribed and translated, and are even stored in libraries."[5]

There exists a substantial but scattered literature in which biologists, linguists, and social scientists have pointed out and commented upon the linguistic model in biology.[6] However, to date no one has produced a unified account, one that identifies and explains the organizing principles of systems of sequences. Here are a few samples of what researchers have said:

C. H. Waddington (evolutionary biologist, 1960): "The analogy often made between the DNA chain and writing can be used in reverse; and language can function as we are used to thinking that DNA does."

John Platt (biophysicist, 1962): "The analogy between genetic information-transfer and a complex instruction-manual would seem to give us a coherent and fairly accurate schema for relating various kinds of phenomena."

Clifford Geertz (anthropologist, 1966): "Though the sort of information and the mode of its transmission are vastly different in the two cases, this comparison of gene and symbol is more than a strained analogy of the familiar 'social heredity' sort. It is actually a substantial relationship."

Roger Masters (social scientist, 1970): "One means of isolating the underlying similarities between the genetic code and speech, without erroneously overstating their identity, is to specify the broad class of systems to which both human and DNA languages belong."

Roman Jakobson and Linda Waugh (linguists, 1979): "Obviously we are not yet in a position to explain this salient correspondence, as long as for linguists the origin of language and, similarly, for geneticists the genesis of life remain unsolvable problems."

John Maynard Smith (evolutionary biologist, 2000): "Linguists would argue that only a symbolic language can convey an indefinitely large number of meanings. I think that it is the symbolic nature of molecular biology that makes possible an indefinitely large number of biological forms."

Wolfgang Raible (linguist, 2001): "Both systems have to cope with the same fundamental problem: how can a one-dimensional medium transmit the information required for the construction of three- (or even more-) dimensional entities?"

None of these scholars has taken what to me is the obvious next step, as Masters puts it, to "specify the *broad class of systems* to which both human and DNA languages belong" (emphasis mine).[7] Before we can tackle this, however, we must first acknowledge that such a broad class of systems exists, that sequences of DNA in the cell and sequences of text in human culture are not *two different things*. Rather, they are two different examples of *one sort of thing*: a system of sequences. As Jacob writes, "two hitherto separate observations can be viewed from a new angle and seen to represent nothing but different facets of one phenomenon."[8] For sequences, this book is that new angle.

The linguistic model in biology is not the only metaphor out there, however. DNA sequences have been usefully compared not only to language but also to code, to the sequences of zeros and ones in Turing Machines, computer software, and information storage.[9]

David Baltimore (biologist, Nobel laureate, 1984): "DNA could easily be seen as the embodiment of principles first realized in the late 1930s by Alan Turing and enshrined in the Turing machine, which responds to signals encoded on a tape."

Charles Bennett and Rolf Landauer (physicists, 1985): "A single strand of DNA is much like the tape of a Turing machine."

David Gifford (computer scientist, 1994): "As we begin to understand how biological systems compute, we will identify a naturally occurring universal computational system."

David Searls (computational biologist, 1997): "Biological transformations can be seen as analogous at a number of levels to mechanisms of processing other kinds of languages, such as natural languages and computer languages."

Nick Goldman (computational biologist, 2013) and colleagues: "DNA [is] an attractive target for information storage because of its capacity for high-density information encoding, longevity under easily achieved conditions and proven track record as an information bearer."

I don't wish to waste time arguing whether DNA is or is not *really* a language or a cell is or is not *really* a computer. Rather, I think it will be more productive to look at genes, human language, and computer code for what they unquestionably are: sequences of interchangeable physical elements whose linear arrangements somehow manage to orchestrate the three-dimensional behavior of objects in the world. We can readily see their differences, but what properties and behaviors do they have in common? How can we produce a unified account of their function and evolution? What is the new angle?

0.3 Shoulders to Stand On

This book relies upon the work of researchers in many fields, but a small group are key influences worthy of specific introduction. One companion throughout will be Howard Pattee, not least because he was my Ph.D. advisor.[10] Pattee trained as a physicist at Stanford University and his early career was focused on x-ray microscopy.[11] In the late 1950s, his research interests expanded into biophysics and theoretical biology, and he helped to found the biophysics program at Stanford.

Since then Pattee has been working to clarify the question of how living systems differ from the physical world from which they arose, how, as he says, *molecules become messages*.[12] He has assembled a kit of conceptual tools for answering this question by focusing on the simplest case: the role of sequences in guiding the operation of the cell.[13] This book exists because I found his toolkit to be equally useful in explaining how sequences have come to orchestrate human behavior and choreograph our literate technological civilization.

In Chapter 1 I open Pattee's toolkit to demonstrate how the behavior of sequences differs from the behavior of the physical world: time, space, matter, and energy. In Chapter 2 you will see how an idea he borrowed from classical physics—the concept of *constraint*—helps to explain the operation of sequences, and how constraints are organized into *control hierarchies*. In Chapter 3 I focus on Pattee's view that the *enzyme molecule* is the simplest case of interaction, of pattern recognition and behavioral response in the living world.

Among other biologists, Richard Dawkins, Francis Crick, Sydney Brenner, Jacques Monod, and Carl Woese are important influences. In his classic book *The Selfish Gene*, Dawkins provides the first gene's-eye view of natural selection,[14] which I hope to generalize into a sequence's-eye view of life and civilization. His book *The Extended Phenotype* provides a framework for thinking about the grammar of language and human behavior in Chapter 4.[15] Dawkins also brings us the *meme*, which will be taken up in Chapter 8.

Besides winning the Nobel Prize for figuring out the structure of DNA, Crick thought deeply about the role of sequential patterns in living systems.

He will appear at many points, and his *Central Dogma* of molecular biology will play an important role in Chapter 6.[16] Brenner, another Nobel laureate, also contributes several important concepts, especially underdetermination in biological systems, what he calls *don't-care conditions*. Woese's and Nobel laureate Monod's observations on the organization of the living world can be found throughout.

Two psychologists, James Gibson and David Olson, are worth special mention. Gibson's book *The Ecological Approach to Visual Perception* and its concept of *affordance* are introduced in Chapter 3, and the affordance turns out to be the key to explaining how grammar works; language is a constraint on perception and behavior.[17] Olson's book *The World on Paper* and his other studies of literacy are central to Chapter 7's discussion of the evolution of complexity,[18] as are anthropologist Jack Goody and his books like *The Logic of Writing and the Organization of Society*.[19]

The works of two computer science polymaths, John von Neumann and Nobel laureate Herbert Simon, also play a valuable supporting role. Von Neumann's *Theory of Self-Reproducing Automata* is at the heart of Chapter 6[20] and Simon's work on *hierarchies* and complex systems permeates the book, and stands out in Chapter 2.[21]

Among philosophers, David Hull stands out with the essential concept of the *interactor* in Chapter 3 and Kim Sterelny, another philosopher of biology, provides us with a salient definition of *interaction*. John Searle's book *The Construction of Social Reality* helps to explain *abstraction* and *regulation* in Chapters 5 and 8.[22]

Linguists Morten Christiansen and Nick Chater make important contributions to the discussion of *language evolution* in Chapter 4, as does neuroanthropologist Terrence Deacon. Linguist Charles Hockett's *design features* of language come up throughout the book as we try to make sense of the differences between the rules that govern sequences and the laws that govern the physical world.

Other fields have too many researchers to call out by name, but the book would not have been possible without the many contributors to the fields of cultural evolution, genomics, astrobiology, bioinformatics, parasitology, the RNA world, economics, and animal communication.

Looking ahead, Chapter 1 shows how sequences differ from the physical world and why they need to be studied in their own right. Chapter 2 introduces constraints, which are how sequences actually get control of physical systems, and hierarchies, both physical and functional. Chapters 3, 4, and 5 show how complex behaviors can be governed by sequences through the internal organization of the sequences themselves, what we call grammars. Chapter 3 introduces the grammar of interaction, Chapter 4 the grammar of extension, and Chapter 5 the grammar of abstraction.

Chapter 6 takes on the question of replication, showing that copying sequences and expressing sequences logically must be distinct processes. Chapter 7 tackles the evolution of complexity, showing how sequences guided both the emergence of life and the emergence of civilization. Chapter 8 demonstrates how sequences constrain populations and institutions, and Chapter 9 offers a simple model for visualizing the emergence of abstraction.

0.4 What to Expect From This Book

Behavior and Culture in One Dimension is interdisciplinary, and it makes claims, especially about human language, that many readers will find provocative. It also omits topics that some readers might reasonably envision. Thus, I would like to give you a sense of what to expect before you get started. You may not agree with my decisions, but at least they will be explicit. Let's address in turn interdisciplinary research, provocative claims, and overt omissions.

Interdisciplinary research is risky business. It entails importing technical concepts from many specialized fields and then tying them together, often metaphorically. Settling on the right level of detail is tricky. How much molecular biology is necessary to make a point? How much is sufficient to satisfy relevant experts that I have done my homework? A psychologist might be put off by more molecular biology than is needed, while a molecular biologist might be put off by omission of the nuances of the field. In this, the book can be at once too scholarly for some and not scholarly enough for others. This challenge is baked into all interdisciplinary research, and the more interdisciplinary the research, the more prominent the challenge. You can judge for yourself whether I have struck the right balance. If you need a quick review of the basics of molecular biology, visit the Appendix.

The book is animated by one big, provocative claim, one grand unified theory, that sequences of DNA in the cell and sequences of text in human culture are not two different things. Rather, they are two different examples of one sort of thing. But what sort of thing is that? How can we characterize this thing independently of its two exemplars? Answering these questions, unpacking the details of this one big claim, requires further subsidiary claims, which in turn can branch into even more claims. In navigating this tree of argument, some readers may accept the big claim while reserving judgment on the rest. Others may be intrigued by a specific claim that relates to their field, while still thinking that the overall project is flawed. I hope you will find this book sufficiently laden with new angles and novel arguments in many fields that you will encounter a few things to latch onto.

As noted earlier, the obvious parallels between genetics and linguistics date to the earliest years of molecular biology in the 1950s. Still, some scientists may consider this all to be *just a metaphor*. To these I would reply that the role of metaphor in discovery has been extensively studied by philosophers of science and found to be of great value.[23] Other scientists may consider Jacob's linguistic model in biology to be valid, but still a *tired metaphor*, trivially true but conceptually empty. Indeed, it could reasonably be asked why, if several generations of researchers have noted this metaphor, no one has taken it much beyond the "isn't this interesting?" stage. Why the question has remained underdeveloped for so long I do not know, but I can speculate.

How sequences do what they do, how one-dimensional patterns of symbols actually get control of physical systems, is understood better at some levels than at others. At the highest level, that of human engineering, we can explain in physical terms how sequences of zeros and ones govern the behavior of computers and robots. At the lowest level, in the cell, we can explain in biochemical terms how sequences of DNA are transcribed and translated into three-dimensional proteins that guide metabolism and build cellular structure. But extrapolating from this concrete knowledge into the vast sequential world in between, the human cultural world of speech, writing, and mathematics, is challenging. I can readily see how fixating on this question could be career-limiting for almost any researcher in almost any discipline. As David Hull writes, "officially we are all supposed to value interdisciplinary research, but in reality just about every feature of academia frustrates genuinely interdisciplinary work. Those of us who are engaged in it are the last hired and the first fired."[24]

As to the question of deliberate omissions, to avoid making *Behavior and Culture in One Dimension* much longer and more technical than it already is, I have chosen to sidestep nuance, ambiguity, and controversy unless it is germane to the point being made. This is not the place to relitigate the intramural disputes of perceptual psychology, linguistics, evolutionary theory, cognitive science, anthropology, astrobiology, and the rest. In building my argument, I do not want to befuddle non-specialists by hashing through these abundant controversies. I am happy just to import the relevant concepts and let the reader follow the endnotes and references to whatever depth is desired.

I should also point out that while this book has plenty to say about complexity, function, organization, and evolution, it has very little to say about brains, minds, intentions, or human consciousness. This omission may give you pause, but I have concluded that explaining the details of brains and consciousness is not a necessary part of the study of sequences. Without question, humans require brains (and bodies!) in order to interpret and replicate sequences, but there is no need to assume that we require exactly the brains and bodies that we have. As we shall see, sequences do have certain hardware requirements in order to function and evolve, but any mechanism that fulfills these requirements will get the job done. Other brain-like equipment might do just as well as the kind we have.[25]

The same is true of consciousness. We assume we have it, but we don't know how the sequences of language fit into the puzzle. Is consciousness a prerequisite for speech? Is speech a prerequisite for consciousness? Or is consciousness just a side effect of other more fundamental processes, what philosophers like Daniel Dennett call *epiphenomenal*?[26] Consciousness, like the brain itself, may be personally important to us, but to build a theory about the sequences of language we can consign it to the big blue bucket I have labeled *true but not important*.[27] As linguist Nikolaus Ritt says, "there is a sense in which languages are insensitive to the existence of their users as conscious beings."[28]

Another reason not to spend too much time worrying about brains is that we cannot observe sequences in the brain. We hardly know what it means for sequences to exist in the brain—or even if they exist there *as sequences*. But we do know that sequences exist in the world; they are observable material patterns, pulses of air or marks on paper or voltages in a chip.[29] "Language studies are uniquely positioned to contribute to our knowledge of human behavior," writes linguist William Croft, "because language is an 'externalized' entity that can be studied more concretely than other aspects of mind, culture, and society."[30]

This book is about the means by which one-dimensional patterns organize three-dimensional behaviors. Genetic and linguistic sequences can be potent constraints, but we can specifically disavow genetic determinism or, more generally, "sequence determinism." Chapters 2 and 3 explore this and related questions in detail but suffice it to say at this introductory stage that what sequences do is change probabilities, making specific behaviors more or less likely. Sometimes they can increase a probability to the verge of certainty or decrease a probability to the very edge of impossibility. However, they lack the inexorable causality of the laws of physics. Thus, I have tried to avoid claiming that sequences *cause* behaviors; rather, I try to say that they *constrain* or *guide* or *orchestrate* or *choreograph* them. As Nobel laureate physicist Max Planck writes: "There must be an unfathomable gulf between a probability, however small, and an absolute impossibility."[31] The same gulf exists between high probability and deterministic causality.

Finally, this is a book published in a scholarly series about ecological psychology, the field founded by James Gibson. Though its interdisciplinary scope carries it well beyond ecological psychology as such, it remains relevant to the field in two ways. First, it demonstrates the universality of Gibson's affordance concept, extending it to the molecular level, to evolution, to animal communication, and to human institutions. Second, it provides a new angle for understanding human language in Gibsonian terms by showing that perception and behavior are the *sine qua non* of grammar.

This circles us back to Pattee's question: How does symbolic information actually get control of physical systems? Sequences are largely inert; physical systems are anything but. It is not enough to claim that sequences orchestrate the behavior of physical systems. The trick is to explain the mechanisms which allow this to happen, that bridge the gap between the static world of sequences and the dynamic world of matter and energy. Our point of departure in Chapter 1 will be to compare the world of sequences with the ordinary physical world of time, space, matter, and energy.

Notes

1. This chapter title is inspired by the autobiographical paper of the same name by biochemist Frederick Sanger, two-time Nobel laureate and inventor of techniques and instruments to determine the sequences of proteins and nucleic acids (1988). Sanger's sequences, sequences, and sequences were protein, RNA, and DNA, whereas mine are DNA, human texts, and binary code.
2. Pattee 2007
3. At a slightly higher level, science writer Roger Lewin puts the question this way: "What we have to do is find out how the genes get hold of the cell" (1984).
4. Jacob 1977b
5. Pinker 2006. Even critics of the linguistic model concede that it is "so pervasive that it almost seems impossible that, short of pathological convolution, the experimental results of genetics can even be communicated without these resources" (Sarkar 1996).
6. Molecular biologist Gunther Stent drew the distinction between *structurists* and *informationists* in the early decades of the field: "There have existed, and there still exist, two schools of molecular biologists—structurists and informationists, three-dimensionists and one-dimensionists" (1968). For a broad history and critique of the role of informational concepts in biology, see Lily Kay's *Who Wrote the Book of Life*? (2000). Küppers 1990, Maynard Smith 2000, Oyama 2000, Roederer 2005, Sarkar 2005, Keller 2009, and Barbieri 2015 are also valuable.
7. Additional references on the linguistic model in biology include Kalmus 1962, Sankoff 1973, Ratner 1974, Lees 1979, Abler 1989, Sebeok 1991, Sereno 1991, Ji 1997, and García 2005.
8. Jacob 1977a
9. The analogy between cells and computers led computer scientist Leonard Adleman to show that a molecular computer built around DNA can solve certain problems beyond the practical reach of conventional computers (1994). (Those interested in computer security may note that Adleman is the "A" in the RSA encryption algorithm.) In practice using the parts list of a cell to build physical computers has proven difficult to scale; it remains not much more than a curiosity in computer science (Rambidi 2014). Recently, however, there has been interest in using DNA for large-scale data storage, like a molecular flash drive (Bancroft et al. 2001; Church et al. 2012). The idea is that the sequences of zeros and ones found in a digital computer are mapped to sequences of DNA, where they are stored and subsequently read out.
10. Some of the ideas in this book were originally roughed out in the dissertation Pattee supervised (Waters 1990).
11. See, for example, Pattee 1953.
12. Pattee was a participant in all four of the influential Serbelloni meetings on theoretical biology organized by Waddington in the late 1960s and early 1970s (Waddington 1968, 1969b, 1970, 1972b).
13. Most of the Pattee papers referenced in *Behavior and Culture in One Dimension* can be found in the collection *Laws, Language and Life* (Pattee & Rączaszek-Leonardi 2012). For a discussion of how Pattee's work can be applied in cognitive neuroscience, see Gazzaniga 2018. For his relation to ecological psychology, see Turvey 2019.
14. Dawkins 2006
15. Dawkins 1982
16. Crick 1958, 1970
17. Gibson 1979
18. Olson 1994
19. Goody 1986
20. Von Neumann 1966
21. Simon 1969, 1973, 2005

22. Searle 1995
23. Boyd 1979; Brown 2003; Hallyn 2000
24. Hull 2002b
25. Anyone who assumes *a priori* that the human brain is the most sophisticated object on Earth has most likely never met a ribosome or spliceosome. These are the huge, complicated, ubiquitous molecular aggregates central to the functional expression of gene sequences. But as with brains, we can imagine other possible ribosomes and spliceosomes which could perform comparably to the ones we have, so long as they fulfill the functional requirements of sequence processing.
26. Dennett 1991. "Part of the problem of explaining consciousness is that there are powerful forces acting to make us think it is more marvelous than it actually is," he says (Dennett 2003).
27. A good theory is "a model that tells you what is important, as distinguished from what may be true but unimportant," as Pattee puts it (1980).
28. Ritt 2004
29. Linguists will recognize this as focus on linguistic *performance*, rather than linguistic *competence* as put forward by Chomsky 1965.
30. Croft 1991. As psychologist Monica Tamariz writes, "Only public, observable information can be replicated by humans" (2019b).
31. Planck 1925

1

THE PROBLEM OF SEQUENTIALIZATION

1.1 Our World as Sequences See It

In the beginning there were no sequences. The Earth of four billion years ago was devoid of one-dimensional patterns. Everything was predictable, humming along in accordance with the laws of nature. But then sequences appeared, and nothing was the same again.

The Earth we inhabit today is overrun with sequences and their products. First to emerge on our lifeless planet were the sequences of RNA, DNA, and protein that govern the function of living things. Later a certain kind of living thing, a social primate, developed sequences of speech and eventually of writing. Today all of these molecular and linguistic sequences are routinely transformed into one-dimensional patterns of zeros and ones that flow through wires and over the air. All day, every day, we swim in an ocean of sequences. And like the proverbial fish who does not know what water is, we are largely oblivious to their profound influences.

But on the sequence-free Earth of four billion years ago there was just the ordinary stuff of matter and energy, all obeying the predictable and inexorable laws of nature. Matter and energy are still with us and still obey the same laws but, thanks to sequences, they are much better organized across time and space, into liver cells and violins and universities. That's a big change. How did it happen?

To appreciate how sequences achieved their hegemony, we must first understand how they differ from the ancient sequence-free physical world from which they arose. What are the properties of sequences—systems of sequences, really, because sequences never travel alone—that distinguish their behavior from that of ordinary matter governed by the laws of nature? Despite the long tenure of sequences on our planet, this is a relatively recent question, unasked before the modern age of molecular biology. This chapter will set out exactly why sequences are different and why they are worthy of study in their own right.

In the decade after Nobel laureates James Watson and Francis Crick figured out that the DNA molecule was in fact a sequence of smaller molecules,[1] the field of molecular genetics struggled with the problem of what Crick calls *sequentialization*. "It is this problem, the problem of 'sequentialization', which is the crux of the matter," he writes.[2] DNA was known to be a sequence of nucleotides, as was its cousin RNA, and proteins were known to be sequences of amino acids. What was not known was how these sequences related to one another.

By the late 1960s, researchers had worked out a fundamental explanation of the genetic code, which shows how the one-dimensional patterns of nucleotides in DNA are mapped to the one-dimensional patterns of amino acids in proteins.[3] That is what a code is, a mapping from one kind of sequence to another. In Morse Code, for example, unique sequences of dots and dashes map to the letters, numbers, and symbols of the alphabet. In the genetic code, three-letter sequences of DNA (codons) map uniquely to each of the 20 individual amino acids found in protein sequences.

But Crick's *problem of sequentialization* can be viewed more broadly. How did Earth's surface become sequentialized? How did systems of sequences emerge? How did they create and propagate their own complex world of coordinated matter and energy, a world that exhibits functional coherence and temporal endurance in ways that could never be predicted from the laws of nature, but which in no way contradict those laws? How did inanimate matter give rise to life and life in turn give rise to civilization?

But first things first. What is a sequence, anyway? In everyday usage, it is one thing following another: a sequence of steps to bake a pie or a sequence of stages in the development of an embryo or a sequence of floats and marching bands in a parade. *Sequence* is rooted in the Latin *sequor* ("to follow"), best known today for describing a lapse in logic: a *non sequitur* ("it does not follow").

The steps required to bake a pie form an *instructive* sequence; the sequences of text in a recipe tell us what actions to perform and in what order. Navigational directions to a destination, the user manual for a kitchen appliance, instructions for erecting a tent, and lessons in how to tango are all examples of instructive sequences. They tell us how to behave, how to move in time and space; their one-dimensional arrangement specifies the order of steps to be performed in an activity.

The sequence of stages in embryonic development, however, is a *descriptive* sequence. We observe an event as it unfolds and, based on our perceptions, generate a one-dimensional pattern to record how it changes over time. Almost all observations of the natural world—most of science, from how stars form to how horses canter—take the form of descriptive sequences. The point is that descriptive sequences do not tell us how to behave; they result from our perception of how the world behaves.[4]

The sequences of human language can both describe and instruct. This may seem obvious, but it is also crucial. A single set of letters and words, and a single set of grammatical rules for combining them, can not only create a record of something that has happened in the world but also can guide worldly activities like baking a pie. We may not think twice about this, but try to envision a world that requires one language for instruction and a completely separate language for description. How cumbersome would that be? Imagine the instructions for assembling a bookcase where the text describing the parts is in Estonian and the text telling us how to put them together is in Hindi.

Instead, we have unitary languages in which instructive and descriptive sequences complement one another. We can receive instructions that guide our behavior: what to do, when to do it, how to do it, etc. We can also perceive the world and create a record of what we observe, what scientists call measurement. Since a single language can do both, the interplay between description and instruction gives systems of sequences extraordinary power to organize the world. See something, do something.

1.2 Persistence of One-Dimensional Patterns

When we think of sequences, we envision events in a fixed order in time: first this happens, then that happens, etc. This is true regardless of whether the sequence is descriptive ("I saw this, then I saw that") or instructive ("Do this, then do that"). The later steps are usually dependent in some way upon completion of the earlier steps. Embryologists observe that the retina develops only after formation of the neural tube. The developmental sequence is fixed: it makes no sense to speak of the retina emerging before the neural tube. Likewise, in baking a pie the crust is made before the pie is placed in the oven; trying to make the crust after baking does not produce good results.[5]

However, the sequence of floats and marching bands in a parade does not quite fit the model.[6] The pattern of the parade sequence persists even when the parade is not moving; it exists independently of time. Unlike the performative steps of a mechanical procedure or the observed stages of a natural process, the sequential ordering of a parade is a one-dimensional pattern of *interchangeable* elements (bands, floats, drill teams, etc.). Further, if the Navy Band follows the Chamber of Commerce float, in no way does this imply that other arrangements are impossible. It could just as easily be the other way around, with the Navy Band in the lead.

This is how I will use *sequence* in this book: sequences are persistent, one-dimensional patterns composed of interchangeable elements. Many sequential arrangements describe and coordinate activities like baking a pie or building an organism, but it is their persistence, their stability in time, that accounts for their power. A pie recipe is made up of sequences of letters and numbers forming a pattern we call a text. It comprises individual elements drawn from an alphabet, elements that have no inherent meaning in and of themselves but which gain meaning when combined and recombined into one-dimensional patterns.

Before life emerged on Earth there were no sequences, no one-dimensional patterns either to describe what was going on or to guide the behavior of matter. The forces of nature that governed earth, air, fire, and water operated of their own accord. Once sequences appeared, however, strange behaviors emerged that are difficult to explain satisfactorily with the universal laws of nature. If you drop a $20 bill, the laws of physics can tell you that it will fall to the ground, but they cannot tell you that someone else will quickly pick it up.[7]

To be sure, sequences—whether DNA molecules, ink on a page, or voltages in a chip—are nothing other than ordinary physical objects that obey the laws of nature like everything else. There are no special laws or supernatural activity that somehow exempt sequences from the physical and chemical processes that control the universe. In this sense, sequences are quite ordinary, just more stuff. But in another sense, in their ability to orchestrate the behavior of matter, they are extraordinary.

We must stand ready to look at sequences both ways, as ordinary matter and as something much more. "Central to the notion of a 'message' is the difference between the structure of a physical object which follows necessarily from its physical makeup and that which does not," explains David Hull.[8] You and I may readily acknowledge that this book is made of paper, ink, and glue, but unless we are bookbinders by trade, the details of its fabrication are of little interest. The pattern of sequences in the book is what interests us. Sequences lead us to ignore their own physical details and attend instead to their persistent one-dimensional arrangement.

1.3 Sequences, In and Out of Time

Time, space, matter, and energy are the great quartet of physics. So unusual are sequences that their behavior can be contrasted across all four domains. We shall take them in turn, starting with time. When a gym class runs a 100-meter dash, the student who finished ahead of all the rest always wins. Likewise, when a linguistics class takes its final examination, the student who completed the test ahead of the others always gets the best grade. Uh no, wait, that's not right. The student who finished the test first might easily get the worst grade, and the student who finished last might get the best. Why is this? Why should time be decisive in foot races but not in finals?

The answer is central to how sequences function. It is to be found in the difference between behaviors that call for processing sequences, like taking a test, and behaviors that entail only dynamic motion, like running a race. Taking a