The Tinkerer's Accomplice

How Design Emerges from Life Itself

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Preface

This book is about why organisms work well, or to put it another way, why they seem to be "designed."

Before I elaborate, I should mention two things the book is not. First, it is not about Intelligent Design (ID). Although I touch upon ID obliquely from time-to-time, I do so not because I endorse it, but because it is mostly unavoidable. ID theory is essentially warmed-over natural theology, but there is, at its core, a serious point that deserves serious attention. Before your hackles rise too much, let me hasten to say that the serious point is not the one that ID enthusiasts would like it to be. ID theory would like us to believe that some overarching intelligence lurks at the heart of the evolutionary process: to say the least, that is unlikely. Nevertheless, how design arises remains a very real problem in biology. This would be a good point to note the second thing the book is not: it is not a critique of Darwinism, which, as Dr Seuss might have put it, is about as true as any thought that has ever been thunk.[1]

Which brings us back to what this book *is* about …

My thesis is quite simple: organisms are designed not so much because natural selection of particular genes has made them that way, but because agents of homeostasis build them that way. These agents' *modus operandi* is to construct environments upon which homeostasis can be imposed, and design is the result. This is largely the same idea I applied to the problem of animal-built structures in *The Extended Organism*, but here the focus is on more conventional "inside-the-skin" physiology. We do venture outside the skin, though, to explore what the link between homeostasis and design might mean for how we think about evolution.

The problem of design has many dimensions: physiological, genetic, evolutionary, adaptive, psychological, and even philosophical. Any treatment of it, including this one, is bound to lean on a few sacred cows, or even flog a few dead horses.[2] This is not accidental. If you read something provocative in this book, I generally meant it to write it that way. I did so, not merely to be annoying, but because I can think of no better way to open minds than to irritate them a bit. I build the irritation in roughly four stages.

The first stage, which occupies Chapters 1 and 2, lays out the basic problem of design and the solution I propose to explore. Chapter 1 poses two basic questions: what do we mean when we say something is designed; and how good are our standard explanations of it? In Chapter 2, I take a personal digression into how termites led me to start thinking seriously about design, and in the way that I do. I introduce there the important concept of the Bernard machine, an agent of homeostasis that builds a new environment and imposes homeostasis on it. Chapter 2 also tells a story of how life's unpredictable twists

[1] *The Glunk that got Thunk* from Dr Seuss (1969). *I Can Lick 30 Tigers Today!*

[2] As Arthur Koestler famously put it in *The Ghost in the Machine*.

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and turns can open up new worlds. I had fun writing it: I hope you enjoy reading it.

The second phase delves into several examples of how Bernard machines impart design to living systems. Chapter 3 concerns itself with tendons and muscle systems. Chapter 4 looks at design of arterial trees. Chapter 5 deals with bones that build themselves in seemingly knowledgeable ways, even veering perilously close to a kind of intentionality. Chapter 6 is concerned with what I believe to be THE fundamental invention that sets animals apart from all others: the epithelium. Chapter 7 plunges deep into the guts of the matter, exploring how multiple agents of homeostasis can shape and model an epithelium-based structure, the intestine.

The third part of the book takes a more philosophical turn, which is where the irritation will really begin to build. As I was thinking about this book, I concluded early on that one simply could not deal with the phenomenon of design without also tackling the fraught problems of intentionality and purposefulness. I can honestly say that I wish it were otherwise, but that is where the logic of the problem led me. Chapter 8 is a short aside that explores why intentionality and purposefulness are such emotive issues in evolutionary biology, and justifies why I think it is important to go there, even if it might give aid and comfort to Darwin's many enemies. Chapter 9 deals with how systems of sensitive cells come to build mental representations of the world, and why homeostasis make this not just possible but inevitable. Chapter 10 goes deeper into the question of where our own intentionality comes from, and whether we might see parallels elsewhere in nature.

The irritation culminates in the fourth stage, which is also the last chapter, where I bring the discussion back to what place design might have in a comprehensive theory of evolution. If you have not thrown the book against the wall by this point, perhaps this is the chapter that will make you do it. Or perhaps you will find some intriguing things there to think about. I hope it's the latter, obviously, but I will settle for the former if you have made it that far.

Any author will tell you that the most difficult thing about writing a book is deciding what to leave out, and this book is no exception. Many of the topics are represented by a vast literature, some are areas of exciting new research, still others are descriptions of well-plowed ground. I apologize in advance for the many holes and superficialities that experts in these fields will see as gaping chasms. I can only plead that the first duty of any author is to write readable prose, and this sometimes means glossing over many fascinating details and subtleties. I've strived always to get the broad picture right, and I can only hope I've succeeded more than I've failed. Good narrative is also why the citations and strained parenthetical asides[3] that litter most scientific writings are absent from this one. I am not trying to deny credit to others or to try and claim credit for myself that I do not deserve: I doubt there is a single idea in this book that

[3] *E.g.* "Dr XXX, a YYYologist from the University of ZZZopolis, shows in some fascinating experiments that …"

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originates with me. A fuller picture of both the ideas and who should get the credit for them is provided in extensive reading lists at the end of each chapter.

At two stages in the preparation of this book, I gave the manuscript a test run before two groups of students in a seminar on the problem of biological design. As is typical with bright students, they were equal parts boundless excitement and merciless criticism. They were a genuine pleasure to work with, a continual reminder of what is best about the academic life. I think they have helped make this a better book. There are too many to thank individually, but a collective "thank you" goes to: Kim Adams, Ryan Allen, Aaron Aureli, Nadia Bennett, Caroline Brady,"TJ" Conley, Katie Cubera, Jaime Cummings, Heidi DeFries, Paul Doherty, Cynthia Downs, Maya Durand, Angie Eddy, Heather Flaxman, Dan Gefell, Alex Gerson, Val Grose, Nancy Harris, Laura Heath, Jan Herr, Amalia Kenyon, Dan Kleinman, Amber Knowlden, Alexis Krukovsky, Lillie Langlois, Steve Letkowsky, Nadine Lont, Christina Maglaras, Courtney McCormack, Jamie Nelson, Wendy Park, Mary Penney-Sabia, Ayesha Prasad, Jill Rasmus, Lawrence Reeves, Liz Reif, Phillip Robbins, Collin Shephard, Marissa Sobolewski, Brooke Talgo, Natasha Urban, Christy White, Cheryl Whritenour, and Nicole Williams. Thank you!!!

Authors in the early 21st century are blessed with an abundance of new technologies – web logs, open-source publishing, and publish-on-demand - to make their words available to readers. This greater freedom to publish has raised an interesting question: is it authors or editors that ensure there are books in the world worth reading? The answer is clear to me: it's editors. If you find this book enjoyable and readable, it will be because Ann Downer-Hazell, my editor at Harvard University Press, lets me get away with nothing: the book is immeasurably better because of her. That you find it in published form at all owes to her steadfast support through a long, and sometimes rocky, road of peer review. Several anonymous reviewers also took great pains to read the manuscript and to give me the benefit of many thoughtful and penetrating insights: Needless to say, there were many areas of disagreement, and many criticisms, some I could resolve, and others I could not. Even if it was the latter, I am astounded by the generosity of these individuals and am grateful for their help. I hope they like the result, even if they remain unpersuaded by it.

As always, my family, Debbie, Jackie and Emma, has been immensely supportive, and where that was not possible, immensely tolerant of a husband and father who was often absent, mentally or physically, as he wrote. If I haven't told them enough that I treasure them, I say it now.

Finally, I want to say a word or two about the two gentlemen to whom I've dedicated this book: Hermann Rahn and Charles Paganelli. When I was a post-doctoral fellow, I became interested in the problem of how birds' eggs were warmed. At that time, it was obligatory for anyone with an interest in eggs to spend some time in Rahn's and Paganelli's "Egg Lab" at the University of Buffalo. My own pilgrimage there began in 1985, and lasted for about eighteen months, which I count as some of the best of my career. I can't fully do justice to why in the little space I have here, but I can offer a small taste.

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Hermann Rahn was a legendary pioneer of human respiratory physiology, but his interests went far beyond lungs. At Buffalo, he built one of the world's premiere departments of environmental physiology, united by Rahn's eclectic approach to physiology. He initially came to study eggs as a perfect model for exploring respiration in the hard-to-reach innermost recesses of lungs. Eggs were not simply a handy tool to Hermann, though; they became his scientific passion, which drew anyone interested in eggs irresistibly into his orbit. During my time at Buffalo, it was a rare day that I could pass by his office door without him calling me in to go over some new brainstorm. Some were brilliantly original, but even when they turned over well-plowed ground, he often brought a brilliant twist to it. Hermann died in 1990: I miss him greatly still.

Charles Paganelli was one of the world-class physiologists that Hermann Rahn attracted to Buffalo, bringing with him an equally passionate attachment to birds' eggs and their possibilities. Together, they made a sparkling scientific team: where Hermann was effusive, eclectic, willing to go wherever a problem led, Charles was reserved, down to earth, disciplined by the physical realities of the world. He is also one of the nicest men I have ever worked with, a walking refutation of the false notion that high achievement requires self-serving ambition. Nor did his mental discipline make him a stuffy drudge: our daily "physiology lunches" in the physiology department library were an ongoing symposium on topics that ranged widely, from science to medicine to philosophy to politics. No other place I've worked, before or since, has been able to match the spark that animated that place.

It was during my time at Buffalo that I learned from Hermann and Charles how to "think like a physiologist." Since leaving there, I have tried, with varying levels of success, to emulate them. It is to these two men that I dedicate this latest effort to think like a physiologist.

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Chapter 1: Cleanthes' dilemma

Are living things designed? Simple though the question might be, the answer is anything but, because, to paraphrase a famous prevaricator, it depends on what the meaning of "designed" is. Design can mean, among other things, an action (I will design the widget), an attribute (the widget is well-designed), or a noun (what is the widget's design?). I am using the word, though, in the sense most biologists use it, namely to describe a peculiar harmony of structure and function in the devices organisms contrive to accomplish things. Put this way, design is no more easily *defined*, but it is easier to identify. Whether some object be an ancient artifact or a perishable plastic toy, whether it be simple, like a crowbar, or sophisticated, like an interplanetary probe, whether it works well, like a garlic press, or badly, like most can openers, we possess a seemingly innate recognition of certain objects as being designed, somewhere, somehow. Our powerful intuition of design almost renders definition unnecessary.

It is no wonder, then, that when most people contemplate the natural world, they conclude that they inhabit a designed place. Consider this small example. Sunbirds are nectar feeders, pretty little birds which inhabit the mediterranean and subtropical regions of southern Africa. In many ways, they are similar to hummingbirds, even sporting brightly colored and iridescent plumage. Sunbirds' beaks are proportionally longer and substantially more curved than those of hummingbirds, however, and if one is fortunate to see both hummingbirds and sunbirds in their native habitats, one quickly sees why. The flowers on which hummingbirds feed commonly have relatively straight tubes to the nectaries, while the nectaries from which sunbirds draw their food are commonly at the bottom of deeper and more curved tubes. In contemplating the ways that the beaks of sunbirds and hummingbirds each fit them so admirably to the flowers they visit, it is hard to avoid feeling there is a sort of harmony at work. Extend this observation to the beaks of other birds, from the pincer-like beaks of warblers, to the feather-fringed nets of poorwills, to the sorting sieves of flamingoes and ducks, to the nutcrackers of finches, toucans and hornbills, and the impression of harmony – of *design* – gets only stronger.

So it is particularly jarring when biologists come along and say this picture is all wrong. What most people perceive as design and harmony, biologists say, is only a figment of the beholder's imagination, arising from a fundamental confusion between what design is and how it comes about – that definition thing, in other words. When *we* design a device to accomplish a task, there is appreciation of purpose, foresight, intelligence and creativity. The *apparent* design we perceive in the natural world, so the story goes, arises through an entirely different process, adaptation by natural selection. A sunbird's beak is curved because for many generations only those birds with beaks curved just so get the goodies they need to reproduce, or at least to reproduce better than most[4]. Virtually none of the attributes of the human process of design apply

[4] One could as easily argue this case from the point of view of the plants, to wit, the only flowers that will spread their pollen will be those with nectaries curved so that that sunbirds can get their beaks down them.

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here. Natural selection is immediate, contingent upon the past but with no view to the future, and with certainly no purposefulness or intelligence guiding the process. When we behold an object designed by a fellow human being, our *perception* of design arises because we see the mental processes of the designer reflected in it. But a perception of design in adapted beings in no way implies a similar mental process has been at work shaping them.

François Jacob, the Nobel laureate[5], coined an apt metaphor for this distinction. Does adaptation, he asked, and hence the *appearance* of design, result from the workings of a "designer", a natural "engineer" which brings it into being through a process similar to the way people design things? Or is it the product of a "tinkerer", cobbling together slapdash solutions to adaptive problems as they arise, using whatever materials happen to be at hand, and with no foresight, planning, or attention to goals? Everything we know of natural selection and how it works points clearly to the latter view: design is the product of tinkering, not engineering.

Case closed? Well, not really …

I have always been uncomfortable with this solution to the problem of biological design. I want to make clear at the outset that my discomfort does not arise from a belief that evolution, natural selection or Darwinism is in any way wrong. Evolution by natural selection has to rank as one of the truest things ever thought, and nearly all, save for a few on the fringe, are in agreement on this. Amidst all the comity, though, we should remember that even the best-established scientific principle contains, at its heart, something of a political consensus: we all will agree that [principle X] must be true, so that we can get on with the fascinating business of exploring the questions that follow from it. We enforce the consensus in many ways: by indoctrination of students, by systems of rewards and punishments to seekers of professional advancement, research funds and so forth. For the most part, this is a good thing. It encourages cooperation, rigor and focus on solvable problems, all the benefits that follow anytime people enter into a social contract. Embedded within any political consensus, though, is a pernicious tendency for the convenient assumption to become unquestioned dogma. This is why science is not democratic: it is not good scientific practice to suppose that something must be right because, to paraphrase the old song, "fifty million Darwins can't be wrong."[6]

So what, precisely, is the difficulty with our conventional understanding of biological design? This, to a large extent, is the subject of this book, and I hope you will read on. But in the hope I can draw you in a bit further, let me offer a whimsical illustration of the problem.

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[5] Awarded jointly in 1965 with André Lwoff and Jacques Monod, "for their discoveries concerning genetic control of enzyme and virus synthesis"

[6] Billy Rose and Willie Raskin 1927

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When I was a child, orange juice came not from oranges but from frozen slush in a small metal can. Since that distant day, the juice package, like life, has evolved in many spectacular and interesting ways. The prevailing design when I was young was eventually succeeded by larger cans with the tubes made from cardboard rather than metal. This was an adaptation of sorts: these containers were cheaper, could hold more juice and could better survive the rigors of shipping. Eventually, the simple cardboard can was superseded by a still better adapted design which did not require a tool to open. Sandwiched between the rim of the lid and the cardboard tube is a thin plastic strip with a little tab on the end, which one gripped and pulled away to cleanly and safely separate the lid from the tube. Recently, I discovered in the supermarket the latest improvement in this design. The tab, which was always hard to grip, has been replaced by a grommet to give your finger additional purchase to pull and remove the plastic strip.

Just as this archetypal can plan has evolved, so too has there been an adaptive radiation of the fruit juice package, with many different families of packaging coming onto the market, "hopeful monsters" of the juice-packaging world, if you please. For example, waxed cardboard boxes have become popular, and these come in different "species" themselves. Some you have to open with a pair of shears, some have a handy plastic spout incorporated into the box, some are small with a drinking straw attached, some are tetrahedral, some have plastic bladders enclosed in larger supporting containers.

Let us now pose a question: what has driven this evolution of the juice package? In the terms of Jacob's metaphor, is it tinkering, or is it engineering? Leave aside the obvious expedient of simply calling up the companies that supply the packaging and asking them whether they designed their packaging or not. In evaluating putative biological "design", that option is simply not available. Rather, we must be good scientists about it, coming to a judgment based upon the evidence presented to us.

Being good scientists, we begin by formulating hypotheses for judging that evidence. Three come immediately to mind. The first we will designate as "engineering." Here, orange juice packaging has evolved as intelligent and forward-looking engineers and managers have decided it should. These individuals have aims in mind, they evaluate different ways of realizing them, and agree among themselves the best way to achieve their goals. At every step of the way, there is intelligence, creativity, foresight, planning: all the attributes of design as we imagine intelligent people practice it.

A second hypothesis we will call "tinkering." Let us imagine a juice packing plant with its operations guided by items submitted to suggestion boxes placed in local supermarkets. Once a week or so, the plant engineers retrieve the suggestions and separate them into those that are feasible to implement, and those that are not. The infeasible suggestions get tossed into the trash. The feasible ones, on the other hand, are implemented, but with no forward-looking consideration of whether they will produce successful packages. Consequently, all manner of juice packages go out of the plant to the supermarket. Those that displease consumers will prompt them to submit more suggestions to undo the modification that produced the disliked packages, and these will go extinct,

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gradually disappearing from the market. Packages that do please consumers will either be left uncommented on, or suggestions for improvements will be made. Over time, the quality of juice packaging will sometimes regress, there will often come onto the market some poor or risible designs, but gradually, inexorably, juice packaging will converge onto well-designed solutions that meet the needs and wishes of consumers. Remarkably, despite the complicated machinery in the packaging plant, and the sophisticated systems of distribution, marketing and sales, there is no real intelligence at work here – the engineers and managers, in whom the intelligence would be expected to reside, simply implement whatever suggestions are feasible. Consumers, for their part, simply register their likes and dislikes, which likewise requires no intelligence. If such a plant existed, the evolution of the orange juice package would qualify as tinkering.

A third scenario we might call "intelligent tinkering." In this scenario, we have an "adaptive" juice plant that functions like the one just described. But now there is something else: a secret commission of juice manufacturers that has in its possession a design for the ideal juice package. For some reason, this juice cabal has decided that its design, and even the existence of the cabal itself, must be kept secret. This the cabal accomplishes through a devilish plan: they will guide the evolution of the juice package using the existing system of suggestion boxes and adaptive packaging plants. Instead of relying only on suggestions from the public, however, the cabal will occasionally plant their own that will guide the evolution of packaging toward their ideal design. To avoid suspicion, the cabal occasionally plants suggestions that result in an apparent regression in package design, just as it would if fickle consumers were the only ones guiding the process. Even so, the juice cabal would guide the evolution of the juice package slowly, inexorably and stealthily to their intended design.

Now, how does one decide which of these alternative scenarios is the correct one? One place to start would be to ask what features all scenarios have in common: such features could not, by definition, distinguish one scenario from another. So, for example, we cannot use the existence of a juice plant, or the presence or operations of any of the complex machinery and logistics involved in operating the plant and shipping its product. Likewise, the presence of workers to operate the plant, or consumers that, intelligently or not, register their preferences, cannot distinguish one scenario from another. We cannot even use the existence of the engineers that determine how the plant will operate, or what designs will eventually be implemented: all scenarios have engineers. We could, however, use the *intelligence* of the engineers as a distinguishing feature. In the first scenario, the engineers are intelligent, foresightful, and capable: in the other two, they are mere puppets, automata that carry out whatever instructions are provided them. But keep in mind that we cannot query the engineers themselves about what is going on in their minds. All we can do is infer their nature from the record of their products. If they are intelligent fellows, capable of setting a goal and intent on reaching it, we might expect to see a fairly direct pathway toward the best container design. Indeed, we wouldn't expect to see evolution of the juice container at all: the best design is, after all, the best design, and if someone is capable of apprehending

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it, there would be no reason to bother with marketing inferior intermediate designs. The fact that the juice container has evolved is *prima facie* evidence that the first scenario cannot be correct: engineering has not guided the evolution of the juice package.

This leaves the second and third scenarios: tinkering, or "intelligent" tinkering. On the face of it, identifying the correct one seems easy – it's tinkering, obviously – but it's not as simple as that. Suppose someone came to you with a story of secret cabals guiding the evolution of juice packaging. Once you had suppressed the urge to laugh in the person's face, you would explain to him patiently that his theory is probably misguided. After all, you would say, look at what we know of the evolution of the thing. Why posit unknowable "ideal" designs for juice containers, or mysterious powers that guide their evolution in obscure ways? Isn't it far more rational to assume that there is a simple process of tinkering at work? Though your arguments might seem reasonable to you, they would be unconvincing to your interlocutor. As anyone knows who has delved into the many "conspiracies" that supposedly permeate our lives – what are UFOs really; who killed Kennedy; is Elvis really dead – if someone absolutely believes that occult forces rule his life, there is simply no evidence that will persuade him otherwise. You can't use the argument that monstrous conspiracies are impossible, because, after all, these *have* occurred in the past, and it is unreasonable to flatly rule out that others are not ongoing. Indeed, one can even use the *absence* of evidence of a monstrous conspiracy as evidence of the conspiracy's monstrosity. However unreasonable the juice conspiracy might seem to you, it simply cannot be refuted, neither by reason nor by experiment. Indeed, the juice conspiracy buff might turn the tables and ask you to justify *your* outlandish claim that a collection of mindless automata, no matter how complex and wonderfully contrived, could produce something as seemingly well-designed as a juice box with a straw conveniently attached. You would have a hard time. You could try to point to the historical record, but the expected record would be similar for both tinkering and intelligent tinkering. You could perform experiments, putting suggestions of your own into the suggestion box and observing the response. If you were very clever, you could even gain access to the maintenance and operations logs of the juice plants and trace out precisely how the juice container has actually evolved. None of it would sway your conspiracy-minded antagonist. Your only recourse would be to fall back on appeals to reasonableness, such as Occam's Razor, or that failing, rudeness, dismissing your opponent as an ignorant bumpkin. In fact, the only potential common ground between the two of you would be to posit human engineers that are themselves imperfect. One would expect their package designs to improve through a process of trial and error, sometimes making mistakes, sometimes making improvements, sometimes coming up with radically new designs to accomplish their task. Such a compromise would obviate the need to posit unknowable forces guiding the evolution of the juice package. Unfortunately, it doesn't rule them out either, and it forces one to posit intelligence of *some* sort driving the evolution of the cans. Even imperfect engineers are intelligent.

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So let us ask again: is the evolution of juice packaging the result of engineering or of tinkering? The metaphor actually doesn't get us very far, does it? If we approach the question as good scientists should, namely on the basis of evidence and tests of hypotheses, the three (or at least two) scenarios are fundamentally indistinguishable. Ultimately, we are forced to decide the issue on the basis of our prejudices – it seems reasonable to believe that tinkering is the correct scenario, so we will believe it to be so. On the other hand, to distinguish between the three scenarios requires such fundamentally different views of the world that, in any case in which we could try to apply it – evolution of juice packages, evolution of bills of nectivorous birds, etc. – agreement is impossible. This is the real difficulty with the question of biological design. It is not that everyone agrees there is an answer out there that we can all come to understand one day. Rather, everyone knows the answer with absolute certainty: the only trouble is that nobody can agree on what that answer is.

This is not a new dilemma. One of the most influential books of the 18th century was David Hume's *Dialogues Concerning Natural Religion*, which, interestingly, was concerned with this very problem: what is the meaning of the self-evident design of the living world? Hume was concerned with the best explanation of his day, the argument from design, which held that one could discern the existence and nature of God from the nature of his works. If we inhabited a world that was self-evidently designed, that had to mean then that there was a self-evident intelligent designer at the heart of it. Or so the story went.

To explore this question, Hume used a dialogue in which three friends gathered one evening to discuss the matter. Philo was the true enlightenment man, widely-read, educated, skeptical to his very bones, with little patience for sentimental gushing over nature's supposed "wonders." Opposite Philo was Demea, the theist, in awe of nature, well-versed in natural history and acutely appreciative of nature's wonderful complexities. Between these two squabbling dogmatics was Cleanthes, rational, stolid, moderate, thoughtful, devout, who strove to find some common ground on which all could agree. Cleanthes seems to have failed at his task, since Hume had Demea storm out of the gathering two-thirds of the way through the evening. Nor did Hume himself fare much better. By the end of his dialogue, Hume left the matter unresolved, hinting even that Demea had made the stronger case. There was also proof of the pudding: one of the greatest expositions of the argument from design, William Paley's *Natural Theology,* was published twenty-three years *after* Hume's *Dialogues,* and Paley arguably exerted more influence on natural history in the 19th century than did Hume: Darwin himself cited Paley as an inspiration.

Remarkably, after all the revolutionary developments in biology during the twentieth century, we are today no closer to a resolution of the disagreement than was Hume more than two centuries ago. On the one hand is Philo – the evolutionary biologist, the molecular biologist, who sees the world as being shaped by the "tinkerer" of natural selection, and who excludes on principle any possibility that a designing force or purposefulness can shape the natural world. And on the other hand is Demea – the naturalist, the creationist, the deep ecologist, for whom the natural world virtually shouts that it is designed, some way, somehow. For the most part, dialogue between the two is non-

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existent, and often hostile. At its most civilized, dialogue consists of Philo patiently explaining to Demea why he's got it all wrong, and Demea appealing to Philo to just open your eyes, please. Usually, the discourse is less civil, with Philo going to the courts to seek restraining orders against Demea, who shouts back loud accusations of persecution against Philo. It seems that, a quarter of a millennium after Hume, one hundred and forty years after Darwin, eight decades after Haldane, Fisher and Wright, there is still little agreement, only ample certitude. We are still impaled on the horns of Cleanthes' dilemma.

This book is written in the spirit that perhaps Cleanthes was right after all: that there *is* a common ground between Philo and Demea and that a satisfactory explanation for the phenomenon of biological design rests there. We are at this persistent impasse, though, because that common ground has not been the arena for the argument. The modern Demea, on the one hand, uses the phenomenon of apparent design to advance a philosophical agenda, usually explicitly religious, as in scientific creationism, or sometimes deist, as in the recently fashionable theory of "intelligent design." The modern Philo, for his part, has eschewed design as a problem worthy of legitimate attention, and decrying those who disagree. On the whole, the argument so far has gone decisively to Philo: it is hard to see the hand of an intelligent Master Craftsman in the burgeoning fossil record, in our greater understanding of the marvelous complexities of heredity and cell function, and in the often puzzling ways that organisms live their lives. But it's worth remembering that the battle has been fought, for the most part, independently of the very thing – the phenomenon of design – that so captivated Demea.

At the heart of the problem is yet another definition issue, this one over the nature of adaptation. Biologists commonly use the word in two very different ways, each corresponding to the two fundamental things that organisms do. On the one hand, organisms store information about themselves, replicate it and pass it on to future generations. Adaptation in this sense is a phenomenon of genetic evolution, a progressively "good fit" over many generations between assemblages of genes and the environment in which they live. This is the tinkerer at work. On the other hand, adaptation is a physiological process, in which the "good fit" between organism and environment is a more immediate and active affair, involving the work of thermodynamic machines that maintain the ephemeral and orderly assemblage of matter we call an organism. Neither definition of adaptation is entirely satisfactory on its own. On the one hand, without the thermodynamic machines that underpin function, the gene is nothing more than an interesting polymer, utterly incapable of anything, let alone the tinkerer's kind of adaptation. On the other, good function can never arise reliably without some memory of what worked well in the past and what didn't – without this, physiology is mere chemistry. Thus, adaptation is neither one thing nor the other: it is the product of a conspiracy. The tinkerer has an accomplice.

Theodosius Dobzhansky once famously remarked that nothing in biology makes sense except in light of evolution. I have no quarrel with that, but there is an alternative view, which I sometimes express to students and colleagues as an aphorism: "It's all physiology." By this, I mean that life is, at root, a physiological phenomenon, and *no* attribute of life, including its evolution,

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really makes sense unless we view it through a physiological lens: to turn Dobzhansky's aphorism on its head, nothing about evolution makes sense except in light of the physiology that underpins it. Without that lens, we wear blinders, and modern biology's most glaring blind spot is this phenomenon of design. It will continue to be as long as the physiological lens is set aside, leaving the tinkerer's accomplice to lurk in the shadows.

This book is my modest attempt to pick up the physiological lens anew and take what I hope will be a fresh look at design and evolution. My thesis is simple: organisms exhibit their marvelous harmony of structure and function – an attribute I call designedness – not because natural selection of genes has made them that way, but because agents of homeostasis build them that way. Key to this is what I believe to be a universal phenomenon of life: the inexorable partitioning and creating of environments upon which homeostasis can be imposed. Out of this relentless busyness comes the exuberant diversity of well-functioning – well-designed – life.

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