THE SECRET LIFE OF SCIENCE

THE SECRET LIFE OF SCIENCE

How It Really Works and Why It Matters

JEREMY J. BAUMBERG

PRINCETON UNIVERSITY PRESS
Princeton and Oxford

Published by Princeton University Press,
41 William Street, Princeton, New Jersey 08540

In the United Kingdom: Princeton University Press,
6 Oxford Street, Woodstock, Oxfordshire OX20 1TR

press.princeton.edu

Jacket design by Jason Alejandro

Library of Congress Cataloging-in-Publication Data

Names: Baumberg, Jeremy J., author.
Title: The secret life of science : how it really works and why it matters /
Jeremy J. Baumberg.
Description: Princeton : Princeton University Press, [2018] | Includes index.
Identifiers: LCCN 2017039857 | ISBN 9780691174358 (hardback : alk. paper)
Subjects: LCSH: Science—Social aspects. | Science—Methodology. | Scientists—
Training of. | Communication in science. | Discoveries in science.
Classification: LCC Q175.5 .B395 2018 | DDC 306.4/5—dc23
LC record available at https://lccn.loc.gov/2017039857

British Library Cataloging-in-Publication Data is available

Printed on acid-free paper. ∞

Printed in the United States of America

1 3 5 7 9 10 8 6 4 2

CONTENTS

ACKNOWLEDGMENTS

I am by most measures a very well funded and successful scientist, becoming a professor at thirty and a fellow of the Royal Society before I was forty-five. But I am not a social scientist, so this book is an aberration in my life. It emerged initially from a sabbatical that I took in San Sebastian in the Basque Country of northern Spain in 2012. Every morning I ignored all my science research and administration tasks, as well as my hosts, and sat down asking myself questions about the system I find myself in, and looking for the answers. My career has been relatively unusual in science, mixing experiences in different cultures (the United States, Japan, Spain, the UK) with significant time in industry (IBM, Hitachi, and several spin-off companies). This is perhaps what has prompted me to question the makeup of the system I find myself in. But many of the questions I was asking did not have satisfying answers, and particularly, why the scientists I come into daily contact with do things in certain ways. Part of this book is an attempt to voice this. As you will see it is also partnered by a blog that aims to continue the exploration, at www.sciencemonster.com, to which I hope you will contribute.

The other motivation for writing this book has been my disquiet over many years about the typical view most people have about how science works, and what scientists do. This is only natural because they are fed this view in everything they typically read about science and technology. Even scientists in my experience rarely share the hidden side of their lives, this slight craziness about how it all works. There are many vested interests in the science ecosystem, and it helps to understand how these all work for and against each other.

However this book is in no way antiscience. In many countries some people call into question the very purpose and method of science (such as in the United States), to avoid it gaining an authority that takes away from others claims to power. I am convinced that the scientific process is extremely robust, a fantastic way to invest for the future of our societies, and an ultimate good. Of course, that is why I am a scientist. But this is not for me a sufficient reason to shy away from questioning how it works and how it develops. I am hoping these discussions will interest anyone who has the faintest collision with science, whether as a reader of science, a writer involving science, a funder (all of us), a civil servant, a politician, or even those questioning the role of science in our lives. All the scientists who I have discussed my ideas for this book with over the last few years have unfailingly asked to read the results of my investigation because it makes them realize how little they know of their own system—I hope that they won't be disappointed.

Many people have supported me along the path. The University of Cambridge, my department, the Donastia International Physics Center and the Spanish National Research Council (CSIC) in San Sebastian, and Jesus College Cambridge have all provided resources of one sort or another, including the rare gift of tranquil thinking spaces. My research group, many young researchers and administrators across the university, and colleagues have engaged enthusiastically and made suggestions. In particular a number of readers have given me excellent feedback, including specifically Christophe Febvre, Rob Findlay, Charlie Constable, Simon Schaffer, and Richard Jones, along with many others who devoted their precious time and attention to discussions. I also am indebted to the valuable support from Ingrid Gnerlich and many others at Princeton University Press. I should note that ideas exposed here are not others' responsibility—they result from my personal views alone. Finally my wife and children have been unstinting in encouraging me and allowing me to devote time away from them. This book is dedicated to them for making my science livelihood a full life.

THE SECRET LIFE OF SCIENCE

is much more complicated, and far closer to the way we steer our economy, buffeted by inevitable fashions, gurus, and cycles of booms and busts caused by our social interactions. It is virtually impossible in any country to identify *who* made a decision to do *this* piece of science. On the other hand, most countries are effectively locked into competition to do the "best" science, by trying to identify it and fund it.

As I tried to answer my own questions about the web in which I am involved, I became ever more fascinated with accounting for why I do what I do, and surprised by what this investigation says might be usefully changed. This book tries to capture what influences the science that gets done, and why it matters. To do that we have to look at the motivations of everyone involved, beyond those of just the researchers themselves. The view I will elaborate is that it helps to consider the full *ecosystem of science*. Ecosystems help us see how chunks of the natural world balance themselves, through relationships between many natural organisms all at once. The different parts of the science system act similarly as interrelating organisms. Intense competition—not just between scientists, but between research journals that publish results, universities that house researchers, newspapers, governments, subject areas, and many other contestants—favors survival skills. The resulting ecosystem of science has its own personality and temperament, which leads it toward a future that we might all want to have our own say in.

This book maps my own explorations, asking questions that both scientists and nonscientists have been confused by, and I am startled to find are not well known. Although it has been useful to be a practicing scientist, this is not necessary to appreciate the stories that emerge. In their telling, we might actually understand what it is that our societies want scientists to do (figure 1.1).

In starting to map out the territories of this book I realized that there really is no good place to find a description of the way science actually works. This landscape turns out to be complicated, interesting, and connected. And yet it should also influence how we read explanations of scientific results, visions, funding, and ambition. Many of the issues I raise can be found in fragments, across blogs and letters pages, and discussed by scientists, sometimes widely. However each minidebate is part of a wider frustration that I sense in scientists

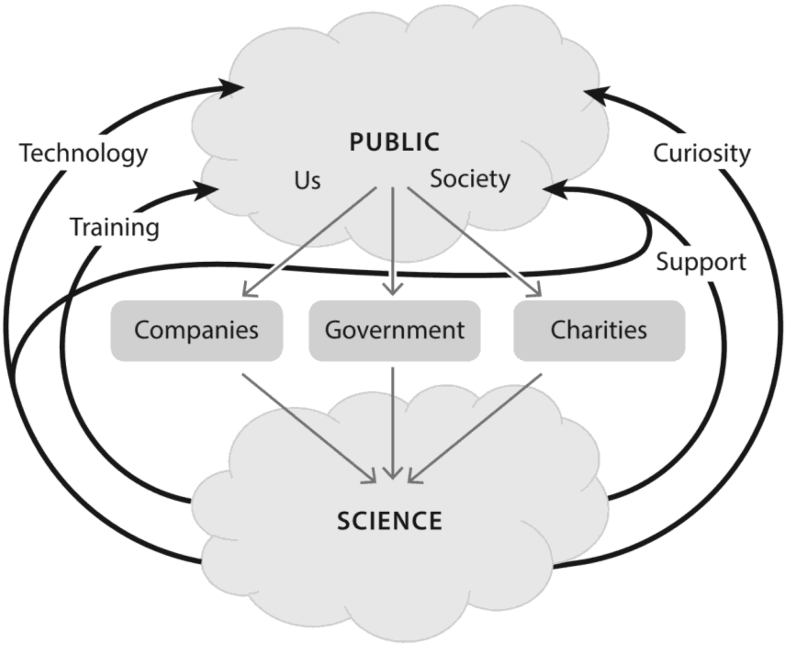

Figure 1.1: The bargain of science.

themselves, of being trapped in a system not of their making. And even worse, they feel that they are powerless to modify this system, because its meshing cogs are so finely aligned that no change is independent of every other part. This book is thus also a stimulus to restore balance: for nonscientists to regain some insight and control into what happens with their funds, and for scientists to regain some insight and control into how it happens.

WHY SHOULD WE CARE?

We pay for science. We accept the tantalizing gifts it provides, though we are sometimes nervous about their effects or about their ethics. And science will frame our future, the future for our children, and the long, deep future for humans on this planet. On average we each pay only a few hundred dollars a year to support science, not very much compared to what we burn up just driving around. But this is one of the best investments we make in our collective future, returning far more than any other opportunity for our savings. How this investment is spent on our behalf is a very peculiar thing, and this is another story of this book. The increasing wealth of our societies has nurtured the growth of a new ecosystem, both insulated from and buffeted by wider forces across society, in which science is mined, amassed, archived, and expanded.

The book is planned as a survey, focusing on different parts of the system in turn to see how the overlapping spheres of influence mesh together to create a science ecosystem. I start with the science itself and show how scientists are fragmented between a pair of interdependent roles. I also ask how realistically we can view science as its own ecosystem, and how this raises questions to consider about science. To ground our discussions I review motivations for doing science in chapter 3, using the lens of what scientists have thought most important over the past half century. In mapping the chains of influence, the next three chapters consider in turn how scientists present their newfound knowledge, how they hear about it from each other, and finally how we all across society get to hear about it through the media. These illuminate the flows that bind the spheres of knowledge, people, and media around scientists themselves. Later in chapter 7 I explore what resources go into science and who controls where this money flows. How the people who make this all happen are shaped along the way is sketched out in chapter 8 to complete the survey of the overlapping spheres and their myriad internal competitions. In chapter 9, I pull all this together to consider how evolution in this landscape is responsible for its current situation, before making some suggestions about ways we might change it in the final chapter, offering tentative prescriptions. Rather than a polemical stance, my main aim is to describe what the state of science really is and how it works.

I am a practicing scientist, and thus deeply implicated in the system, but I had an early career in industry and so already approached research with one eye refracting the perspective of an outsider's prism. My aim is to write as an outsider might look in, as a science sociologist of the mainstream, laying bare the construction of this science system. Popular accounts of science instead tend to focus on larger-than-life personalities, early historical perspectives, and to lay out compilations of mythical and anecdotal stories to provide color and moral fables. I am going in a different direction, both because my theme is about the wider interactions, but also because I want to capture what we have now and where it might be going.

Along the way I find many questions whose answers I felt I ought to know. How many scientists are there in the world? How many physicists, chemists, biologists, or engineers? How many more or less will there be in ten years? Of the thousands of papers published each day, why do a few get into our newspapers and Twitter streams? Who chooses for us, and why? Who chooses what sort of science gets done? What do scientists read? How do they choose what science to do? Are there too many biologists in the world, or too few? What sets the size of a science conference? These are not part of my background knowledge, nor that of most scientists.

Science is in rude health, never having been better funded or producing more results. Any system has its flaws though, and in science many are well known: influences of money and self-interest, sporadic scandals of distorted or false data and conclusions, sensationalisms of wild hype or wild personalities, distorted reporting from the media circus, or individuals stealing credit. All these are persistently aggravating to the cause of science, but they do not fundamentally undermine it because of the self-correcting way that it works.

However another set of deeper worries will emerge from my survey here, ones that are an implicit part of the system of science itself. The contested interactions that are integral to the science ecosystem are inflating competition between its different components. This ever tightening set of global competitions skews how the system works and evolves. Through this book, I hope to show why I am no longer quite so convinced about the globalization of science and why I believe science might be expanding too much. These competitions have other effects that will become apparent, such as reducing the diversity in how science is funded and appreciated. All these pressures focus on the scientist, who, contrary to conceptions of airy independence from societal pressures, is at the nexus of some of the most intense global struggles. But to start at the beginning, we first need to ask what we mean by science.

2

WHAT IS SCIENCE?

Most people have a comfortable familiarity with the idea of science. My first task though is to prise apart this solid-seeming notion of what it is, and to locate two contrasting types of science inquiry and what drives each one. To understand the ecosystem as a whole, I then want to tackle how many researchers there are at the moment, and how this is changing. This tribe of scientists is the core of the science ecosystem, and I will discuss how they divide themselves within it. Finally I will discuss how the science ecosystem might work, mapping out the different parts we will visit on this tour.

THE ROLES OF SCIENTISTS

SCIENCE IN OUR SURROUNDINGS

Look around you now. What do you see that a spirited woman teleported forward through time from prehistory might recognize or understand? Tables, floors, sockets, screens, lights, windows. All are absent from the natural world; all offer intricate wonders. What would intrigue your prehistoric visitor most? Each object has myriad labels are since "purity" emphasizes a greater virtue, in opposition to polluting influences. In society it is associated with ideas such as racial or sexual purity, defining implicitly an undesirable dark side. To understand what motivates scientists, I believe that it is more useful to employ a different (and more neutral) dichotomy, which emphasizes the roles they take when doing science. I will describe these as "simplifiers" and "constructors," and show how they both create fundamental scientific knowledge.

INTRODUCING SIMPLIFIERS

Consider the bands of physicists who survey the nature of different subatomic particles, and what component particles these in turn might be made up of. Some ask "why do the particles have this mass?" or "why do they collide in this manner to produce a shower of new particles?" They strip down complexity to identify more basic component properties, ways that allow us to explain what we see in simple concepts. Such scientists I will call ***simplifiers***, though related epithets might be "explorers," "delvers," or "deconstructors." Their relation to the world is of opening the box of magic and trying to understand how it works, and they are the reductionists of science.

It is not obvious at the outset of any scientific journey that a simplifiers' approach might work at all. Simplifications seem to be possible only because the underlying physical behavior of the world is really governed by laws that conserve various underlying essences. We know that energy is conserved, momentum is conserved, and the number of atoms is conserved. These laws can all be broken in various ways: we can convert energy to mass and back; we can lose atoms from a body by abrasion or chemical conversion into gases; we can convert atoms from one to another in nuclear reactions. What is most useful is that the underlying reasoning behind these laws allows us to convert questions we have now into close correspondence with questions we have asked before, and this allows us to form a scientific intuition. Each situation is not new, but related to those considered before. Without such order, intuition is very difficult to achieve, swamped by a morass of details and information fragments. Simplifiers are at work within every domain of science.

DO SIMPLIFIERS KILL BEAUTY?

Simplifiers are associated with several different emotional reactions to science. They have long been a target for romantics of the world, who see the uncovering of inner workings as inhumanly mechanistic and killing the essence of outward beauty. To some, knowing the simpler reasons that animate complex phenomena (such as why rainbows are colored) is seen as stripping them of power, life, and energy. Similar allegations are made about the destruction wrought by analyzing poetry, literature, or art.

On the other hand, simplifiers are seen as great explorers who find new unknowns in the universe to boldly go beyond. This pioneering aspect particularly unfolds in large-scale megascience projects such as particle accelerators, where the stress is on the romance of breaking boundaries of knowledge and providing new understandings of our human place in the cosmos. They are the knights who vanquish the implacable dragons, overturning past theories. This long-standing fight-back by simplifiers inverts the charge of killing the world when pinning its beauty to a board, like lifeless butterflies. Every person stares at stars and can be awed. Knowing that huge balls of squeezed fusing gases glare out at us blowing off immense canopies of glowing streamers only adds to our awe (figure 2.1). While reduction is indeed part of the task of simplification in science, it is not a reduction in content but a transformation in the task of comprehending, from voluminous fact to stacking and interleaving of scientific principles and implications. This is what is meant by understanding some piece of science.

COMPRESSING INFORMATION

For simplifiers, a satisfactory outcome in a scientific field is “information compression.” They aim for fewer facts and more connecting description (often in the form of equations defining relationships) to directly account for the world. Sometimes they can show why information compression is not possible, such as in predicting weather, which we are used to knowing only days in advance. In other areas such as predicting the large fluctuations in the stock market, we find it hard to accept such unpredictability. It is interesting that situations

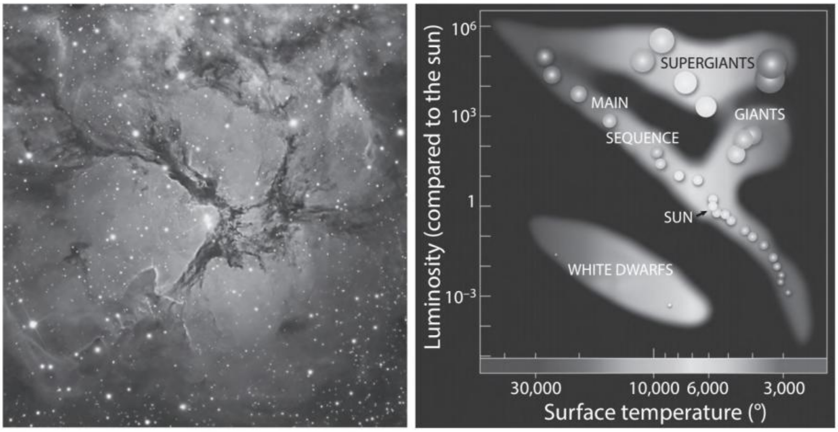

Figure 2.1: Ways of inspiring. *Left*: The ruby-hued Trifid nebula several light years in diameter. The hydrogen gas core is heated by hundreds of brilliant young stars causing it to emit red light (just as hot neon gas glows red-orange in illuminated signs). Image credit: R. Jay GaBany, Cosmotography.com. *Right*: The evolution of stars can be tracked as they cool (from blue-hot on the left, to red-hot on the right) and fade in luminosity. Image credit: © 2017 ESO.

where simplifiers currently hold most authority are now those parts of science *least* amenable to repeated human experimentation, and those that possess a very large number of complex components. These include cosmology (why the distribution of stars, galaxies, quasars, and black holes appears as it does), biology (what is alive, how do cells work, how does the brain work, and how do we experience consciousness?), and particle physics (why is there so little antimatter in the universe, what gives the most basic particles known their mass and charge, and what do we really mean by mass and charge?). Challenges exist for every discipline in situations where full control remains difficult, and observations are problematic. Simplifier science is easiest and has worked best when we can twiddle all the knobs on the box, and if we break it we can try another box. Where this has been possible, simplifiers have already swept through triumphant.

Science can get into difficulties though when testability or repeatability is challenging. If scientists have a theory about how the world works, they need it to make predictions. But if such predictions play out over millennia and involve scales beyond our control (such as collisions between stars) then scientists cannot set up an experiment and wait to check that their expectations are fulfilled. Nor can they try this experiment several times to check it works, even with small variations in the initial setup conditions (to test if the predictions are *robust*). Similarly it is not yet possible to set up a particular set of thoughts or new memories in someone's brain and observe the repeatable electrical firing of billions of neurons. Problems with testability and repeatability are found in disciplines and questions that are precisely the ones which have *not* proceeded so far, because we cannot travel experimentally in lockstep with our theories. Instead scientists have to resort to observations in which they catch specific occurrences in the act (looking everywhere in the cosmos with telescopes to find a few galactic collisions), or they wait until something they want to test comes along (watching a brain seizure develop). Such a strategy depends on the richness and density of components under study (stars, neurons). This makes the strategy rather more difficult for improbable events or those in sparse situations, such as abrupt climate changes, stock market crashes, supernovas, or the development of life on a planet.

As a result we have a distinct class of hard science problems in which simplifiers are currently richly represented, but that are hardly amenable to testability. These must be set against a huge number of scientific areas in which the simplifier approach has already been enormously successful (such as electronics, or molecular bonding). The result of those has been a highly compressed information web that is the seed for much new science. Most of these mapped areas are ones with multiple types of amenable experiments, giving great assurance to the credibility of our scientific understanding. They allow confident predictions about the world, which will be important for the other way of doing science discussed below. It is the success of simplifiers in compressing information that leads to the second role for scientists that I now describe.

INTRODUCING CONSTRUCTORS

Once simplifiers can confidently predict how a chunk of the world works, a new phalanx of questions emerge that head in completely different directions. "How can we use this breakthrough, not just to simplify, but to build something?" Descriptions based not on assemblies of facts, but on toolboxes harnessing interactions and conservation laws, inherently give birth to a different sort of creativity that generalizes these to new arenas. "What happens if I do this to that?" or "how might this operate if I heat it?" Notice that this sort of science is not directly asking how an aspect of nature works. It is already making constructs, mostly never found before in nature, in which questions of "how it works" are always twinned with "how can we make it work differently?" For this reason, I will refer to such scientists as ***constructors***, though related descriptions might be "builders," "composers," "creators," "makers," or "assemblers." They may not be applying this knowledge to any concrete goal (so "applied" science is not a good description), and they may be theorists or experimentalists.

Constructor science is based on initial simplifier discoveries and would simply not be possible unless those discoveries were robust in almost every way. Imagine the scientific landscape as a city of buildings. The architectural toolbox produced by the simplifiers includes cables, concretes, columns, struts, and beams. Constructors put these together in imaginative ways testing the principles of rigidity, stress, and design rules in arches, domes, and buttresses to their limits, as well as sculpting elegant forms. Any flaw in understanding the components and how they might go together is rapidly uncovered by the resounding sound of buildings collapsing. The reason we don't hear a cacophony of scientific rubble crashing to the ground is the sheer robustness of most of our knowledge. One might interpret this peaceful city as evidence of resistance to new forms, conservatism, or sloth. But actually the serene silence pays tribute to the success of science. Computers rely on our understanding of complex physics being correct and remaining correct, trillions of times every second, everywhere.

This web of knowledge that is the historical accumulation of all the science-building work of the past is our legacy to future societies. It is composed of all the written-up reports of scientists published in journals, their collected technologies and equipment, the know-how of all scientists alive, and the network of relationships between all these. The web is built both by the simplifiers and the constructors, who interact with each other to stimulate new science, and who and then considers their implications. These completely idealized experiments nevertheless suggested such bizarre and wondrous conclusions that they stimulated a raft of new theories. Eventually improved technologies enabled real experiments, which then agreed with the predictions almost entirely. Now ever more beautiful realizations of these Gedanken experiments help young scientists (and us all) to be convinced of the essential truths of the quantum mechanical theories. We are forced to see splattered onto a detector the waves from chunky protein molecules that each somehow squeeze through two close-spaced pinholes at the same time. Even such big objects defiantly have a wave-like aspect.

While simplifiers verify the truth of ever more sophisticated tests of quantum mechanics on individually observed particles, building such ideal constructs has stimulated constructors to envisage ways to exploit quantum systems. An entire subfield has emerged around the use of quantum mechanics to encode information that bucks the pervasive digital paradigm of binary zeros and ones (figure 2.3). Quantum information is recorded as *simultaneous* combinations of one and zero, as if future electronic circuits could exist switched into both "on" and "off" states at the same time, calculating both situations at once (and thus faster). Related research measures single

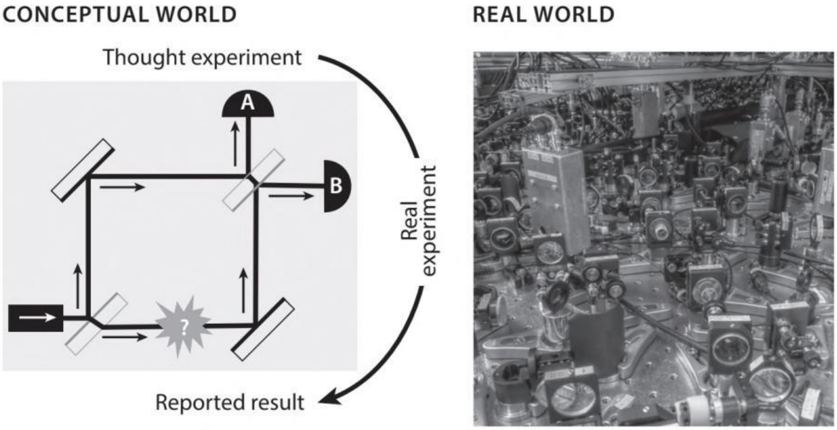

Figure 2.3: Relation between *thought experiments*, the reality of their realization in a modern lab, and the reporting of their results in scientific publications translated back into a conceptual framework.

electrons, or discusses ultrasecure quantum cryptography, ensuring no one can read and duplicate critical information you are sending (such as your bank password), or explores the teleportation of images and even possibly objects. Quantum instruments are now built that measure the gravitational pull of underground oil reserves with exquisite sensitivity, and can also detect the local electrical currents directly in your sparking brain. Thus are the models of simplifiers now reborn as tools for constructors.

WHAT DO CONSTRUCTORS DO?

This gives a feeling for how constructors work. They are more interested in building a new model system and seeing new behaviors emerge than in answering questions about a system provided by nature. Sometimes they have an idea, but in working through their hunch they stumble across something completely unexpected. This is why they find it harder than simplifiers to explain why they do what they do, since they are not "curing cancer" or addressing similar-scale grand challenges. In fact they often produce the critical breakthroughs that are most helpful in tackling such grand-challenge problems. They cannot say beforehand that this is likely to happen, but only what they hold in their sights and its possibilities. A good example is the material science community, who are spread widely across companies and universities, with most practitioners trying to achieve diverse ambitious fragmented goals but not to solve any single grand deep mystery. On the other hand, their advances enable solutions to the other deep mysteries, such as building cameras capable of seeing the furthest galaxies or the smallest cell scaffolding.

This fragmentation of the raison d'être of constructors is what makes them both more invisible but more pervasive than simplifiers. In physics we might take the paradigm of the hunt for the Higgs particle as archetypal simplifier science (figure 2.4). A similar scale of effort for constructors would be the vast group of people trying to understand the implications of Maxwell's electromagnetic equations for the last century. Recent fashions (known in science as *bandwagons*) have shown how little understanding we have for the inherent potentialities hidden in such equations of light waves, despite our knowing exactly how to write them. We simply cannot

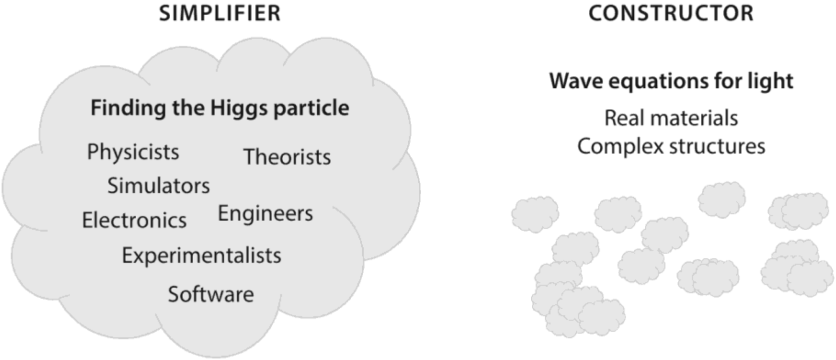

Figure 2.4: *Simplifiers* tend to congregate around grand challenges. *Constructors* explore research areas in many competing research teams, congregating fleetingly around hot topics.

predict what situations might be interesting to construct with intricate networks of submicroscopic metallic wires to make "metamaterials," illuminating what Abraham Flexner in 1939 referred to as "the usefulness of useless knowledge." Perhaps tens of thousands of scientists worldwide are chipping away at different parts of this challenge to understand the waves of light. But the scientific participants never think in terms of it being a universally motivated grand challenge, because they work in small groups competing with each other on tiny detailed parts of this whole. Intellectual fragmentation is the order of the day in constructor science.

Public perceptions of constructors have developed more recently and do not evoke the same distinct emotional response as simplifiers. Later we will discuss their relation to engineering and technology, but they often appear to be involved in an abstruse and complicated problem that is distanced from us by unfamiliarity. It is not always easy to identify a clear visionary goal for a constructor: just as buildings can always support a new extension and cities a new suburb, small features accrete. But, out of the whole process of constructor science emerge new ideas and technologies that pervade society. Their creative process emerges not just from one individual or a specific research group, but often from a large network of cooperating and competing research teams. Depicting such a story can be very complex and is rarely attempted in its breadth. We are mostly thankful for the technological advances as they come into our hands, but unclear and disconnected from what science made them and when. We also have an ambivalence about the uses to which this science is put, from weaponry to resource extraction, which is different from merely knowing the simplifying answer to a scientific question. When we give scientists the responsibility for their offspring, is it the initial simplifiers or the following constructors who we mean to implicate?

These roles of simplifier and constructor scientists will be useful throughout this book, such as in considering why so much media and political attention is focused on simplifiers. We will see however that many more researchers identify with being constructors. This disconnect can be understood better through the ecosystem of science. Before I discuss this though, we need some better idea of how many scientists in the world there really are.

HOW MANY SCIENTISTS ARE THERE?

WHAT COUNTS?

The throwaway answer to the question of how many scientists there are, is "over six billion," given the in-built propensity for *every* human, from their earliest childhood, to express curiosity about their surroundings through experiment and musings. Toddlers have been clearly shown to make hypotheses about their physical observations, test them, and come up with theories and beliefs. Despite the complaint that our school education systems seems to squeeze out this innate curiosity, I really don't believe it. Challenging my friends, young or old, with puzzles from my hoard of brainteasers such as three-dimensional interlocking "burrs" or undulating arrays of poised magnets, and they *all* tend to interact with them in ways that precisely mirror scientific research. It is just that only a fraction of our societies are formally employed to use these talents on science itself.

The global scale of professional scientific research can be recognized by estimating how many scientists there are, and how this number might be changing. Most scientists themselves, while they have a sense of the researchers in their own subfield and a strong sense that the number they have to deal with is surging, have only a hazy idea of the total number of scientists burgeoning around the globe. The scale of the community as a whole is not in their grasp.

The most recent estimates produced by UNESCO (from national governments' data) suggest that the number of professional scientists in the world is over eight million. This was up from five million in 2002, to the most recent data from 2013 giving nearly eight million. That is a lot of research projects, each of the eight million involved in threading a gap in the web of knowledge. On first encounter this number seems frighteningly large to me, especially since they are highly concentrated within small parts of the planet. Imagine a city on the scale of London, Cairo, Moscow, or Beijing, with each occupant a scientist and all vying for recognition, intensely involved in their profession. This is a very large number of people doing research, and also a staggering rate of increase. Already in 1961 Derek de Solla Price studied several measures of science activity and showed them all growing at an exponential rate. One of his conclusions was that more than 90 percent of all scientists who have ever lived are alive today, and this appears to have been true at every point for nearly three hundred years. But things are changing.

THE MULTIPLICATION OF LAB COATS

Clearly eight million scientists cannot be aware of each other's daily work, so science is necessarily fragmented. Where are they all? In most of the Western nations, the fraction of the population counted as being in research and development (R&D) consistently settles around 0.4 percent. We will discuss definitions later, but essentially all these people are involved in finding out new things. So far there are many fewer scientists than this in China (0.1 percent), India, and all Africa (0.01 percent). One implication is that as these nations industrialize and develop, they will focus similar fractions of their human resource on science, and the total number of scientists worldwide will exceed twenty-five million, a further tripling in the next fifty or more years. It is unclear whether they will enter existing subfields, or the branches of science will multiply. Perhaps the existing concentration of scientists will just spread out more evenly with decreasing numbers in Western countries. Perhaps the pace of science research will increase, and we can look forward to reading

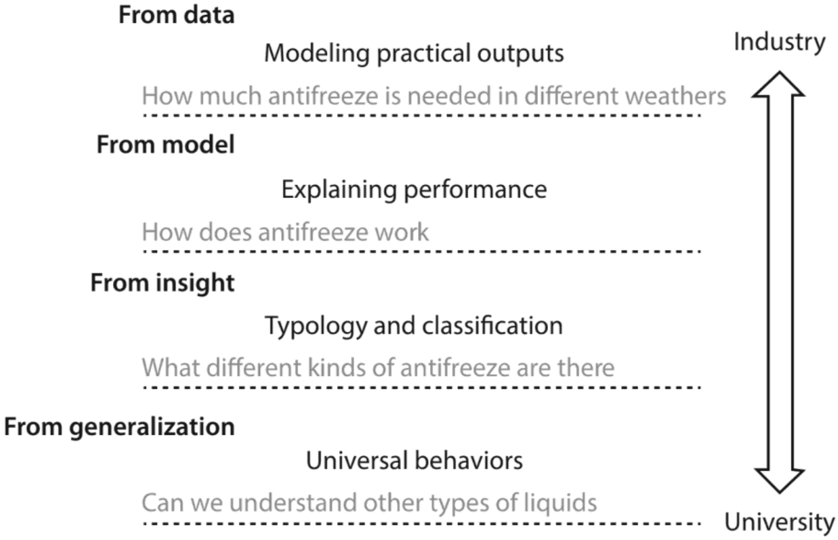

Figure 2.6: How different focus on the same problem can support technology and basic curiosity.

To see the richness of approaches to science more clearly, I will imagine a situation that uses real data to identify optimal performance properties, for instance the formulation of antifreeze to add to a car engine coolant system in different seasons (figure 2.6). One type of approach to "exploring" this might be to find the exact mixtures that seem to be useful (modeling practical outputs). A slightly more general approach instead is to find out why it works this way, producing a model dependent on the particular antifreeze properties (explaining performance). Another type of approach asks how different behaviors might arise and under what conditions, predicting performance of different types of cooling fluids (typology and classification). A further level might be to develop the thermodynamics of liquids when heated and cooled in pressurized flows, encompassing many types of liquid effects, and considering whether these can be seen in nature, or can be created in a lab (universal behaviors). All these studies have both clear questions and answers and divide between pure science, applied science, engineering, or technology. They also span theory and experiment. Some answers have only a limited region of applicability, perhaps of interest for a particular company honing its production parameters. Other answers might provide an entirely new way for a scientific field to organize its observations. And these different types of science emerge from the same problem, so that a researcher might pass rapidly through all these disciplines by slightly changing the details of their inquiry. As long as new knowledge is built by creative systematic novel inquiry, it seems right to me to call all of it science.

The boundary between engineering science done in a university environment and that done in a company is the degree of particularity—how focused the scientist is on a specific aspect. Most researchers I have known in companies bemoan the fact that they never are allowed the time to understand things properly—they are just required to fix a problem as quickly as possible, provide the pertinent data, and move on to the next issue. In some cases, they aren't creating new knowledge so I wouldn't consider what they are doing to be science. University researchers by contrast are asked to understand a problem more abstractly, providing knowledge that is reusable in other contexts. Flows of money back and forth between the different funders mix up these compartments. Since technology is able to head onward even when being based only on trial-and-error advances, its underpinning science understanding can often be far behind, and this catch-up has been one of the drivers of science for over five hundred years.

The Frascati definition also insists that postgraduate students learning to do research (the apprentices in the guilds of science) should be considered to be researchers, expanding the higher education totals far more than the number of permanent academic scientists. In the UK for instance, there are only thirty-one thousand or 0.05 percent of the UK population who have *permanent* university jobs in the sciences, medicine, or engineering, which is 20 percent of the total researchers in higher education, and 12 percent of the total number of UK researchers reported to UNESCO. For comparison in the United States in 2010 there were 270,000 academics or 0.09 percent of the population with science and engineering faculty jobs, about 23 percent of the total number of researchers. Which types of researchers are growing the most varies between states: permanent academics (China, India), researchers in industry (Korea, Spain), or more short-term contract researchers (UK, the United States). The fraction of scientists who are in universities or institutes in each country (as we will see in chapter 3) varies from over 60 percent in Spain or the UK, to below 25 percent in the USA and Korea, reflecting how much businesses are able or willing to invest in research compared to their governments.

What controls the number of scientists supported in each society? Given that scientists encourage the interests, training, and funding of ever multiplying generations of younger followers, then fecundity is built into the science ecosystem just as in its biological progenitor. The constraints as in the natural world are the resources that underpin this growth: its funding and the size of its habitat. Health care in each country is funded about ten times more than all publicly funded science research, and the inexorable rise in this cost of preserving health is causing worries everywhere. By comparison science research is a small but noticeable fraction of a society's budget, stabilized at the level about which taxpayers and civil servants are probably comfortable. Science spending seems to rise until it becomes noticed and then stops. But there is nothing well defined about this level, no formula that says funding should not be halved or doubled. How much science is the right amount of science?

Industries employ various numbers of (mostly constructor) scientists to help innovate their products or services. In this constant struggle to generate continued and growing revenues to stay alive, scientific research is one of their drivers. But too much research sucks resources out of other parts of the business and might not pay off, so the balance is delicate. The number of scientists supported by business has been increasing in the last decades. In most cases this rate matches the increase in government-supported researchers (excepting only the UK, where their number has not increased for twenty years). So it seems the increasing wealth of societies becomes mirrored in support both for publically funded science, and for the opportunities companies have for investing to drive forward their technology base.

The number of scientists cheerfully supported by a society in its institutes and universities depends on another aspect of their jobs as well, the training of young undergraduate students. Universities are historically organized into disciple-“owned” departments to do this teaching. The expansion in the number of young people going on to higher education in many countries has justified the rise in the number of their professors. But when science is perceived as a difficult subject to excel at, and there is high promise of well-paid jobs in other sectors requiring numeracy (such as finance), the numbers of students studying science drops. If these perceptions reverse, science student numbers rise. When many fewer study within a department the financial pressures build up on administrators, passed on from government departments. Several times in recent decades there has been concern with students in a specific country fleeing science, and sometimes academics have lost their jobs. A slow rebalancing then comes through the delayed connection to the economic situation of a country, which eventually influences the demand for the number of science educators. These dawdling tugs from the economy also mean that the current status quo rarely satisfies anybody—there are always perceived pressures to change. But the inexorable increase in science students worldwide supports the increase in number of scientists.

Where do new academics go? What fields of science do these permanently employed researchers ally themselves with? Because fields of science are fractured and split across different departments in different countries, such comparisons are incomplete. In the UK a series of government-mandated research assessments provide some useful data, splitting the thirty-one thousand academics into 25 percent physical scientists, 16 percent biological scientists, 34 percent medical scientists, and 25 percent engineers. The United States has a similar balance among tenured academics with 30 percent physical scientists, 52 percent biological or medical, and 16 percent in engineering. In the last decade, the dominant increase has been in the number of bioscientists, so they now outnumber their physical colleagues nearly twofold. While this balance is different in different countries that prioritize different fields, there is no agreement, or even discussion, about what would be the right balance. The juggernaut of opportunity rolls on, and different disciplinary groups manage to fleetingly sway the ear of politicians.

The world growth rate in researchers of 4.4 percent corresponds to over three hundred thousand new researchers each year. In the

United States there are nearly twenty thousand extra new researchers in industry and five thousand extra university researchers each year. In China 190,000 new researchers are employed each year, over 150,000 in industry, and more than 20,000 in academia or institutes. Worldwide, more than ninety thousand university or government researchers are added each year, the vast majority in science, health and technology. That is on top of two million such researchers already and doesn't count all the technicians and support employees that make their research possible. What do all these researchers do? Does the world need this many new scientists? How do they find new research fields? As we survey the science ecosystem, we will later see that instead of sparking entirely new fields, most of these people follow existing paths because these give them greater credit to benefit their careers.

HOW SCIENTISTS SITUATE THEMSELVES

The link between asking questions of the natural world, and unearthing answers that allow technologies to be built, has produced a twin cycle of evolving science and evolving technology. By now these are so entangled that every scientist has a stake in both posing new questions, and working forward the implications from previous answers. However, science is so large that there is no possibility of remaining equally involved in everything. All human society abhors homogeneity. The emerging segregation of the sciences has given us divisions into disciplines, domains, and paymasters, as well as between countries.

Disciplinary boundaries have become immovable. Since natural science expanded in the Renaissance and then exploded with industrial Victorian society, it has been fragmented into disciplines in which different natural laws take center stage. Despite their underlying connectivity, the disciplinary compartments divide science into defined perspectives and levels of scale. Chemists use restricted packages of the truths abstracted from quantum physics to explain the bonding of different atoms into molecules, and their subsequent reactivities. Geologists encapsulate the chemistry of mineral and biological cycles to help them understand the persistence of deep slow time on shaping our bedrock and boundaries. Discipline barriers partly help in