Citizen Science Anthology

Bard Microcollege Brooklyn & Harlem - August 2023

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Trees of Life Figure Collection

1. **Tree of Life Diagram 1**: Simplified universal phylogenetic tree made by Wikimedia user Madprime. Accessed from Simple English Wikipedia: https://simple.wikipedia.org/wiki/Tree_of_life_%28biology%29.

2. **Tree of Life Diagram 2**: Figure 3 from Pace, N. R. (2009). Mapping the tree of life: progress and prospects. *Microbiology and molecular biology reviews*, 73(4), 565-576.

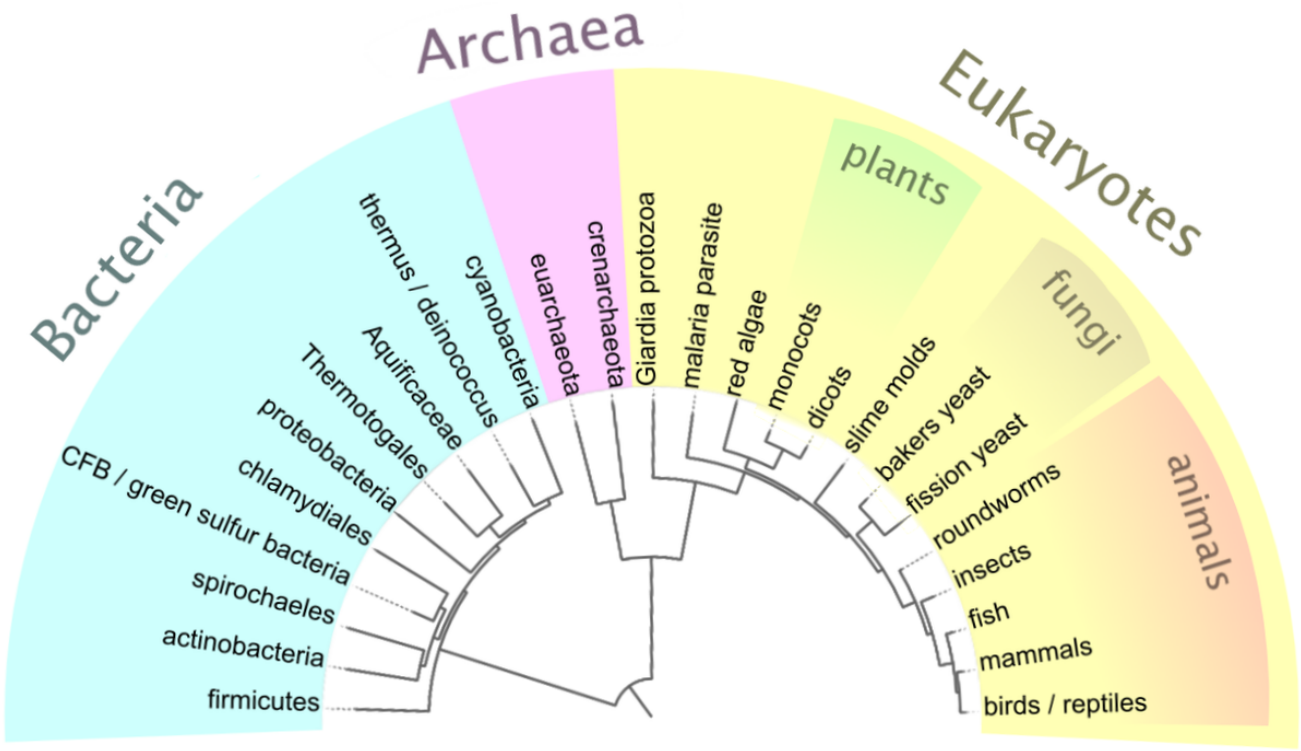
3. **Tree of Life Diagram 3**: Tree made by David M. Hillis, Derrick Zwickl, and Robin Gutell, University of Texas published in Pennisi, E. (2003). Modernizing the tree of life. *Science*. 300(5626), 1692-1697. Accessed from http://www.zo.utexas.edu/faculty/antisense/downloadfilestol.html.

4. **Tree of Life Diagram 4**: Figure 2 from Ciccarelli, F. D., Doerks, T., Von Mering, C., Creevey, C. J., Snel, B., & Bork, P. (2006). Toward automatic reconstruction of a highly resolved tree of life. *Science*, 311(5765), 1283-1287.

5. **Tree of Life Diagram 5**: The Evogeneao Tree of Life diagram. Accessed from https://www.evogeneao.com/en/learn/tree-of-life.

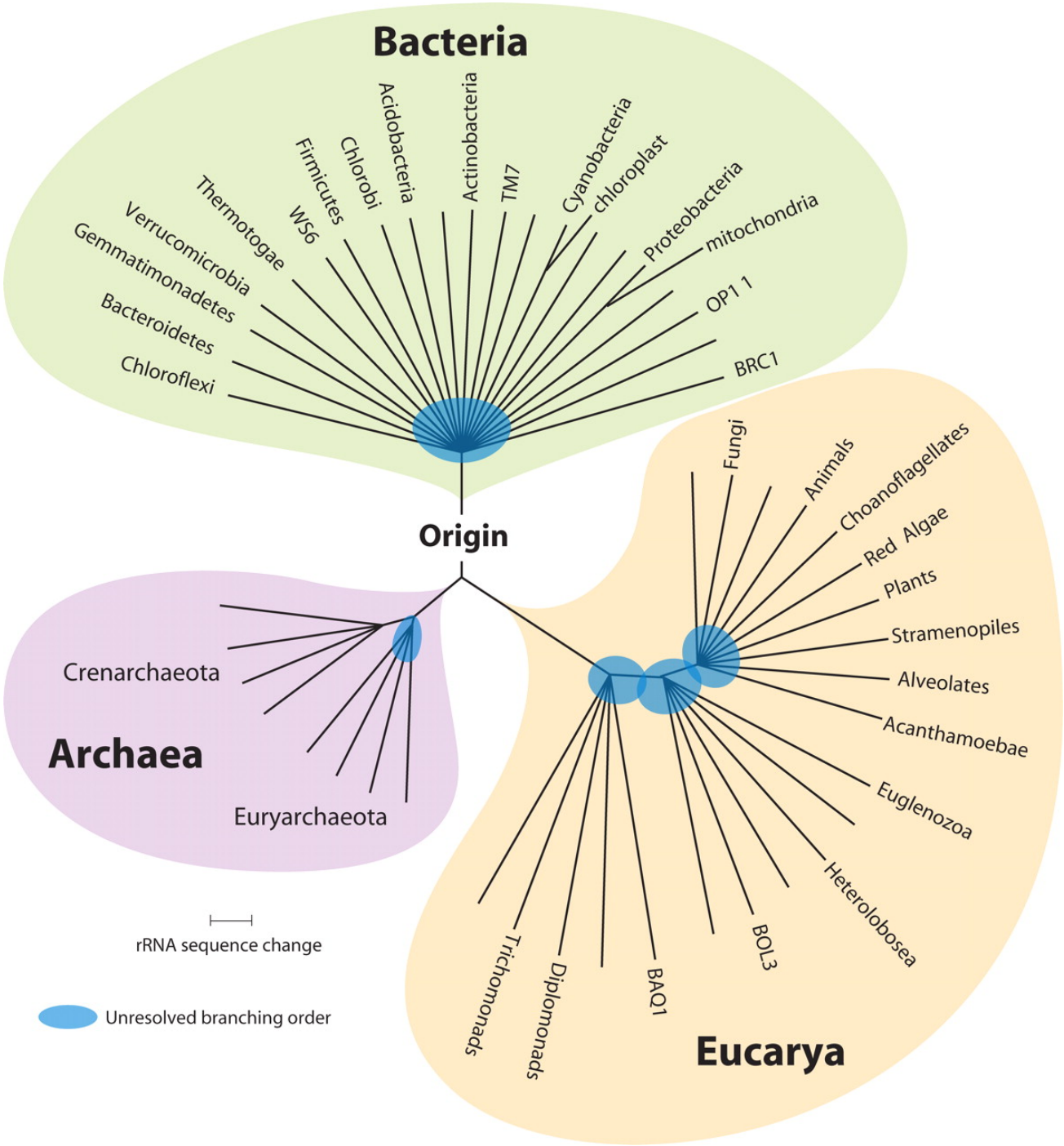
6. Distortions and Limitations in the The Evogeneao Tree of Life Diagram (Tree of Life Diagram 5). Accessed from https://www.evogeneao.com/en/learn/tree-of-life.

Tree of Life Diagram 1



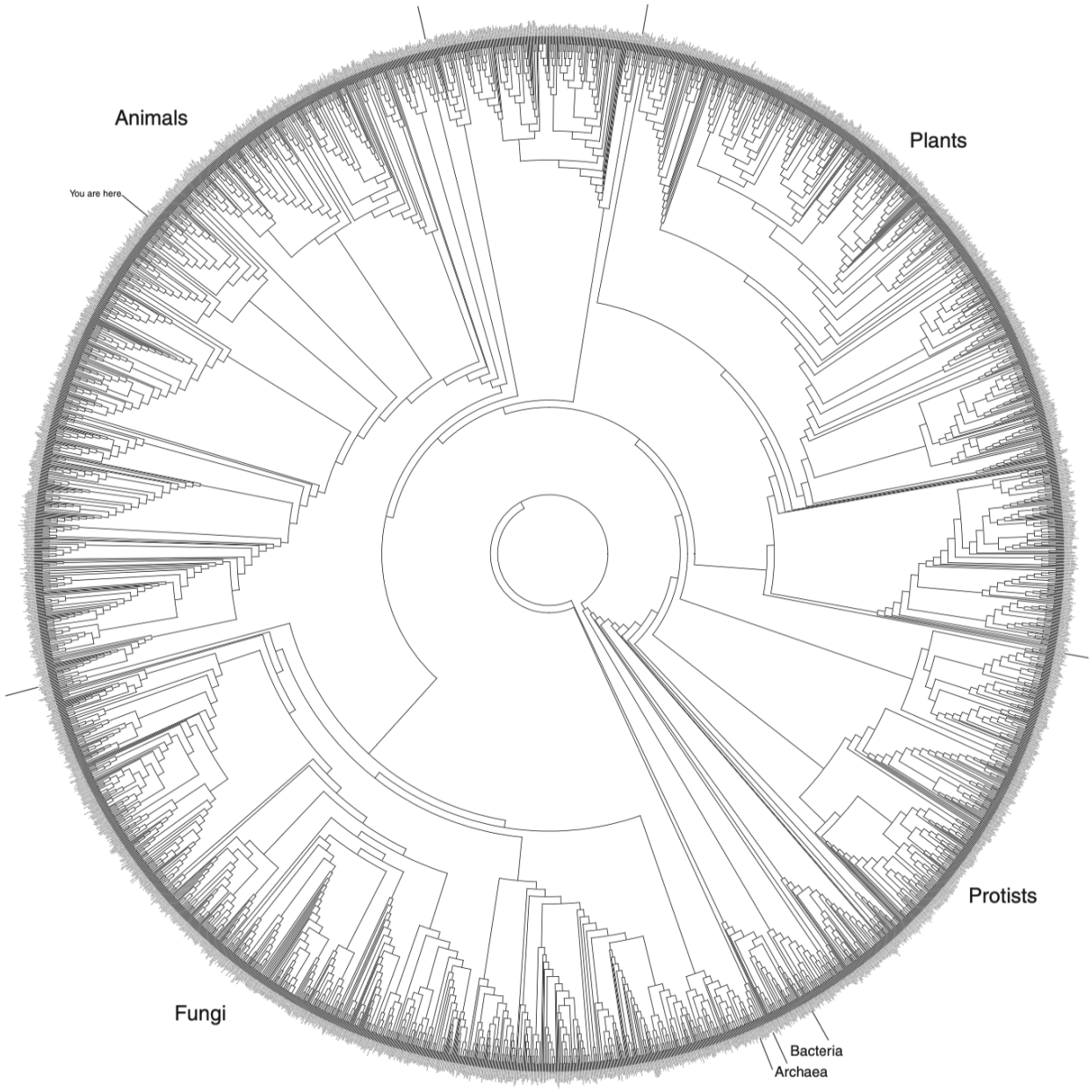
Simplified universal phylogenetic tree, made using information from the Interactive Tree of Life (https://itol.embl.de/) by Wikimedia user Madprime. Ciccarelli, et al., Mar 3 2006, Science Vol. 311. Additional information and colors added with GIMP. Accessed via Simple English Wikipedia: https://simple.wikipedia.org/wiki/Tree_of_life_%28biology%29.

Tree of Life Diagram 2



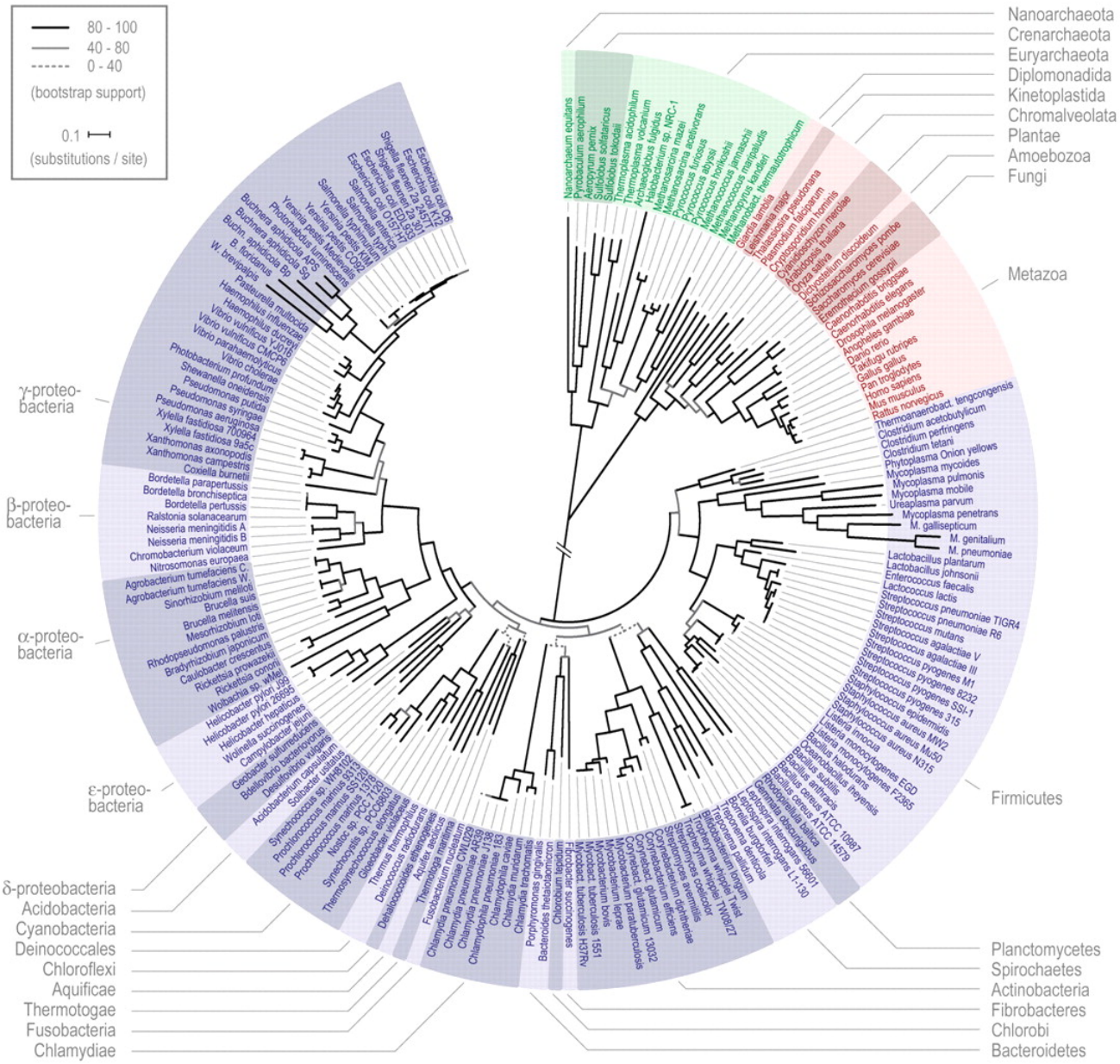
A molecular ToL based on rRNA sequence comparisons. The diagram compiles the results of many rRNA sequence comparisons. Only a few of the known lines of descent are shown. Figure 3 from Pace, N. R. (2009). Mapping the tree of life: progress and prospects. *Microbiology and molecular biology reviews*, 73(4), 565-576.

Tree of Life Diagram 3



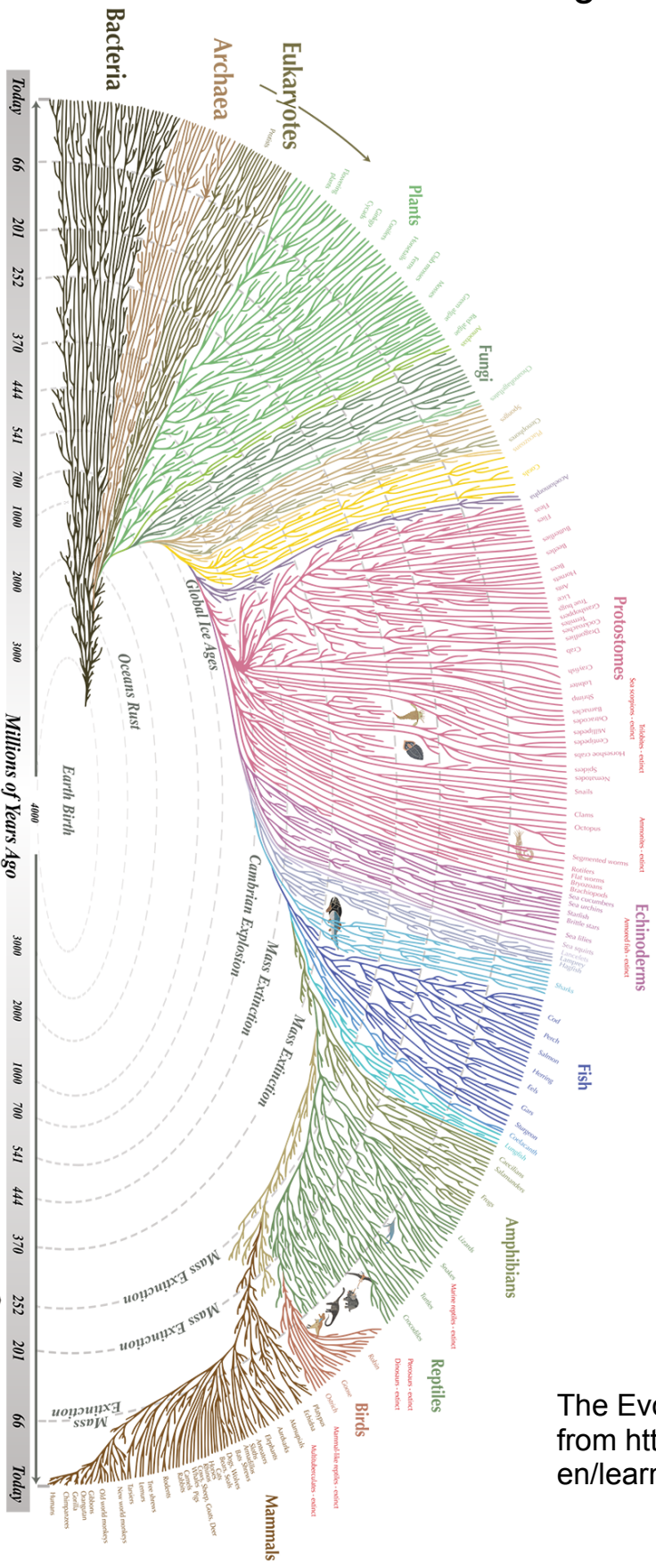
David Hillis has incorporated 3000 species into this circular tree of life, best viewed when enlarged to a 1.5-meter diameter. Tree made by David M. Hillis, Derrick Zwickl, and Robin Gutell, University of Texas published in Pennisi, E. (2003). Modernizing the tree of life. *Science*. 300(5626), 1692-1697. Accessed via http://www.zo.utexas.edu/faculty/antisense/downloadfilestol.html.

Tree of Life Diagram 4



Global phylogeny of fully sequenced organisms. The phylogenetic tree has its basis in a cleaned and concatenated alignment of 31 universal protein families and covers 191 species whose genomes have been fully sequenced. Green section, Archaea; red, Eukaryota; blue, Bacteria. Labels and color shadings indicate various frequently used subdivisions. The branch separating Eukaryota and Archaea from Bacteria in this unrooted tree has been shortened for display purposes. Figure 2 from Ciccarelli, F. D., Doerks, T., Von Mering, C., Creevey, C. J., Snel, B., & Bork, P. (2006). Toward automatic reconstruction of a highly resolved tree of life. science, 311(5765), 1283-1287.

Tree of Life Diagram 5



The Evogeneao Tree of Life diagram from https://www.evogeneao.com/en/learn/tree-of-life

Distortions & Limitations in the Evogeneao Tree of Life Diagram

In order to make the Evogeneao Tree of Life easy to understand, a number of distortions have been purposefully built in.

First, this Tree of Life is drawn from the human point of view. That is why humankind, instead of some other organism, occupies the end of the tree, and why our vertebrate cousins (animals with a backbone) occupy a large part of the tree. This falsely suggests that humans are the ultimate goal of evolution. In fact, if that asteroid or comet that hit the earth 66 million years ago had instead missed the earth, there might not be a dominant, tool-using, space-faring species on earth. Or if one evolved, it might be a dinosaur, not a mammal.

Second, the world of **bacteria holds far more genetic diversity**, and accounts for far more biomass than animals and plants do, yet bacteria occupy only a relatively small portion of the Evogeneao Tree of Life. Trees of Life drawn from the bacterial point of view look very different; the whole world of animals and plants occupy only a tiny part of the tree.

Third, the Evogeneao Tree of Life suggests life steadily increased in diversity through time, such that the greatest diversity appears to exist at the present time. This is not at all the case and only appears that way because, for space reasons, only a few of the branches of life are shown. The evidence suggests that 99% of species that have ever existed on earth are now extinct.

Fourth, for space reasons many minor branches of life have not been included or labeled on the Evogeneao Tree of Life diagram. Also, the diagram suggests a specific

time of common ancestry where branches join, but DNA and fossil data only suggest a broad time window in which the common ancestor lived.

Fifth, the Evogeneao Tree of Life breaks out Birds as a separate major branch, although the scientific consensus now is that **birds are a branch of theropod dinosaurs** that survived the mass extinction 66 million years ago. The branch could be labeled "Avian Dinosaurs," but to make the diagram easier to follow, the more familiar designation "Birds" has been retained.

Sixth, current thinking proposes that 1) Bacteria and Archaea probably evolved from a common ancestor, either a non-living proto-cell, or something alive but more primitive than either, but now extinct, and 2) that Eukaryotes evolved from Archaea. Everything alive on earth today can trace ancestry back to that common ancestor between Bacteria and Archaea, which is known as LUCA (Last Universal Common Ancestor). Hug, et al., 2016 (Nature Microbiology 1:16048)

In order to keep the diagram simple for beginning students, the Evogeneao Tree of Life shows a simple, traditional progression from Bacteria to Archaea to Eukaryotes.

Seventh, for a recent common ancestor, we can reasonably be sure it didn't look too different from a modern descendant, and fossil data is often available to guide the illustrations that we've created.

But science has only an approximate idea of what ancient common ancestors may have looked like. For these ancient ones, we've made highly speculative illustrations and assumed in most cases that they looked like a modern example of the next oldest branch. This assumes that little evolutionary change has taken place in the form of that organism, which is a big assumption. But this admittedly flawed protocol has been followed, rather than just replace those common ancestor illustrations with a big question mark.

How to Use the Tree of Life

The geologic time scale begins at the center bottom, at Earth's birth, more than four billion years ago. As you move away in any direction from this point toward the outer margin of the tree, geologic time gets younger and younger, until at the outer edge of the tree you arrive at the present day. Times on the geologic time scale are shown at the base of the diagram in millions of years before the present. These are traced through the tree of life along curved, dashed lines of equal time value. Any point on the Evogeneao Tree of Life can be placed in geologic time by using these curved timelines.

Biological evolution proposes that all living things, including humans, have a common ancestor with any other living thing. On the Evogeneao Tree of Life, students can discover when in the distant past these common ancestors lived. For example, trace the human branch back through time along the yellow guidelines using the partial Evogeneao Tree of Life below. Follow it back in time to the point where you meet the bright blue fish branch. This point on the Tree of Life represents the common ancestor between humans and fish (in this case, salmon). By using the time scale, you can see that this creature lived roughly 430 million years ago. The time of a common ancestor between any two of life's branches, large or small, can be found in the same way.

Our Understanding Will Evolve

As our understanding of life's history improves (by fossil discoveries and genetics), some of the branching relationships and times of common ancestors depicted on this tree of life will inevitably become outdated.

Protein Synthesis and HIV Figure Collection

1. **Protein Synthesis Diagram:** copied from a previous Bard Prison Initiative Citizen Science Anthology. Caption written by Marta Shocket.

2. **HIV Replication Diagram 1**: from NIH's Office of AIDS Research. Accessed from https://clinicalinfo.hiv.gov/en/glossary/life-cycle.

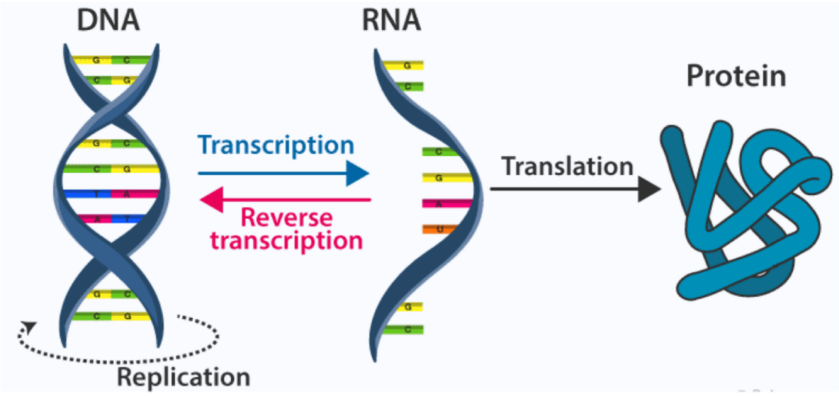
3. **HIV Replication Diagram 2**: from Healthline's 7 Stages of the HIV Life Cycle. Accessed from https://www.healthline.com/health/hiv-life-cycle.

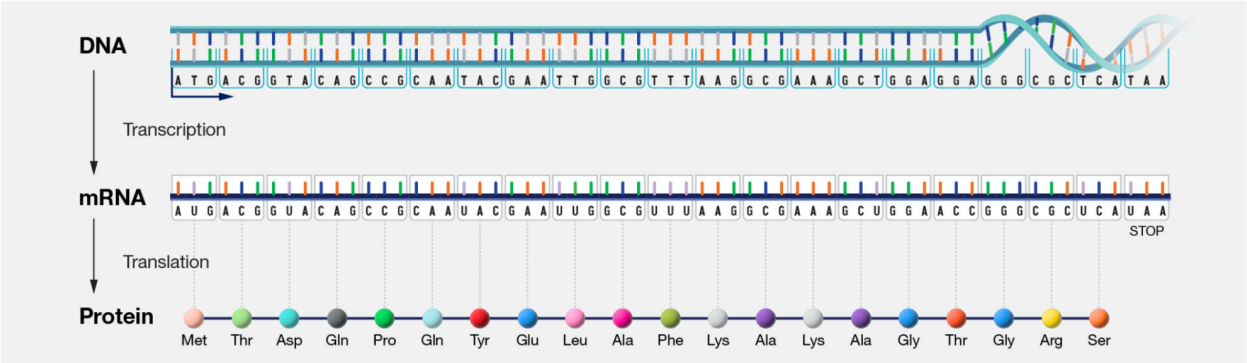
4. **HIV Replication Diagram 3**: from Biorender. Accessed from https://app.biorender.com/biorender-templates/t-5f32d8b236677100ac51c32e-hiv-replication-cycle.

5. **HIV Replication Diagram 4**: from Biorender. Accessed from https://app.biorender.com/biorender-templates/t-624f053131d1ee47731847bd-hiv-mechanism-of-infection.

6. **HIV Replication Diagram 5**: Figure 1 from Engelman, A., & Cherepanov, P. (2012). The structural biology of HIV-1: mechanistic and therapeutic insights. Nature Reviews Microbiology, 10(4), 279-290.

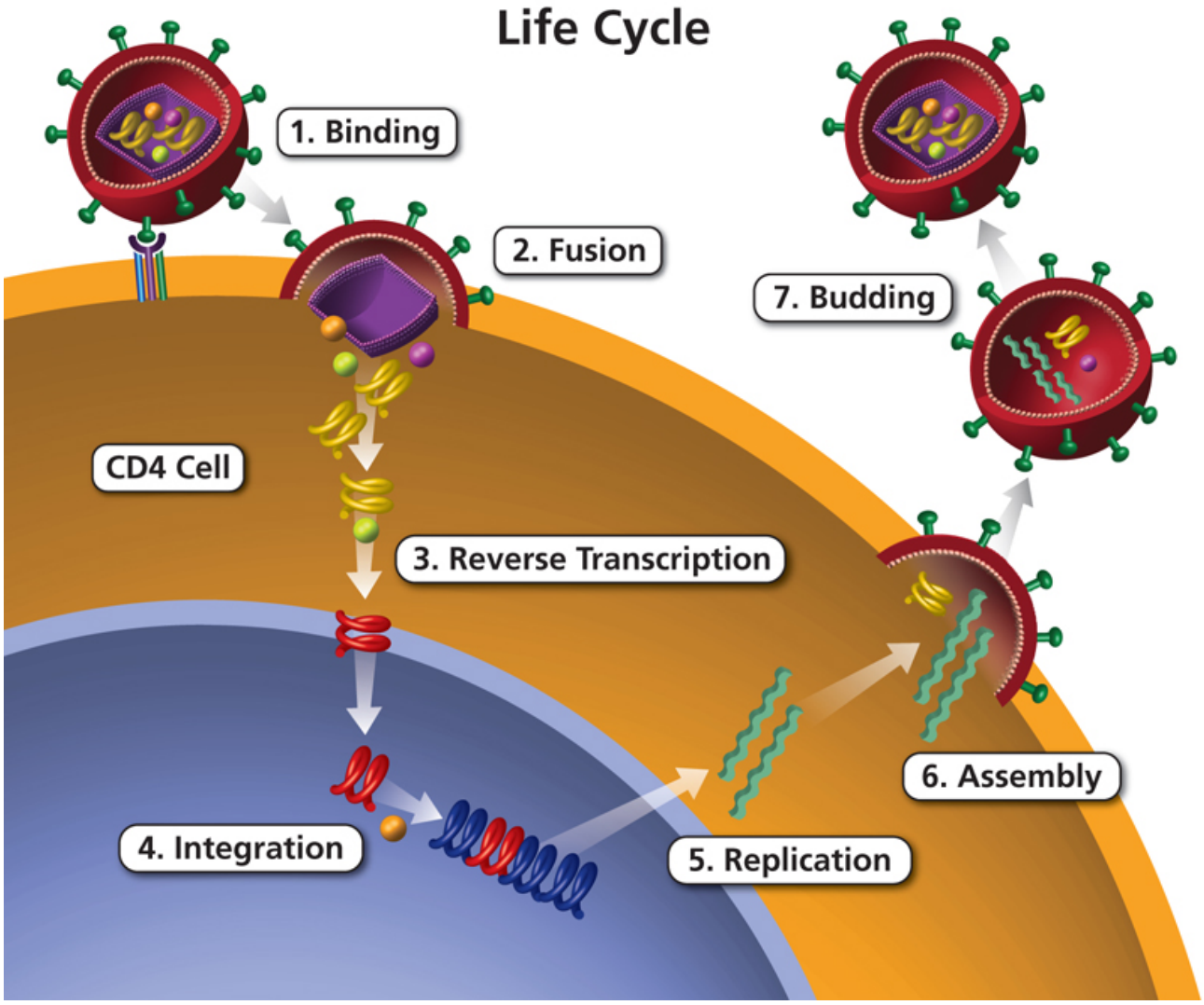
Protein Synthesis Diagram





The central dogma of molecular biology describes how proteins are synthesized. First double-stranded DNA is transcribed into single-stranded RNA. Second, single-stranded RNA is translated into a protein. For retroviruses like HIV, RNA can be reverse-transcribed back in double-stranded DNA. Diagram copied from a previous Bard Prison Initiative Citizen Science Anthology. Caption written by Marta Shocket.

HIV Replication Diagram 1



The series of steps that HIV follows to multiply in the body. The process begins when HIV encounters a CD4 cell. The seven steps in the HIV life cycle are: 1) binding; 2) fusion; 3) reverse transcription; 4) integration; 5) replication; 6) assembly; and 7) budding. Diagram from NIH's Office of AIDS Research. Accessed from https://clinicalinfo.hiv.gov/en/glossary/life-cycle.

HIV Replication Diagram 2

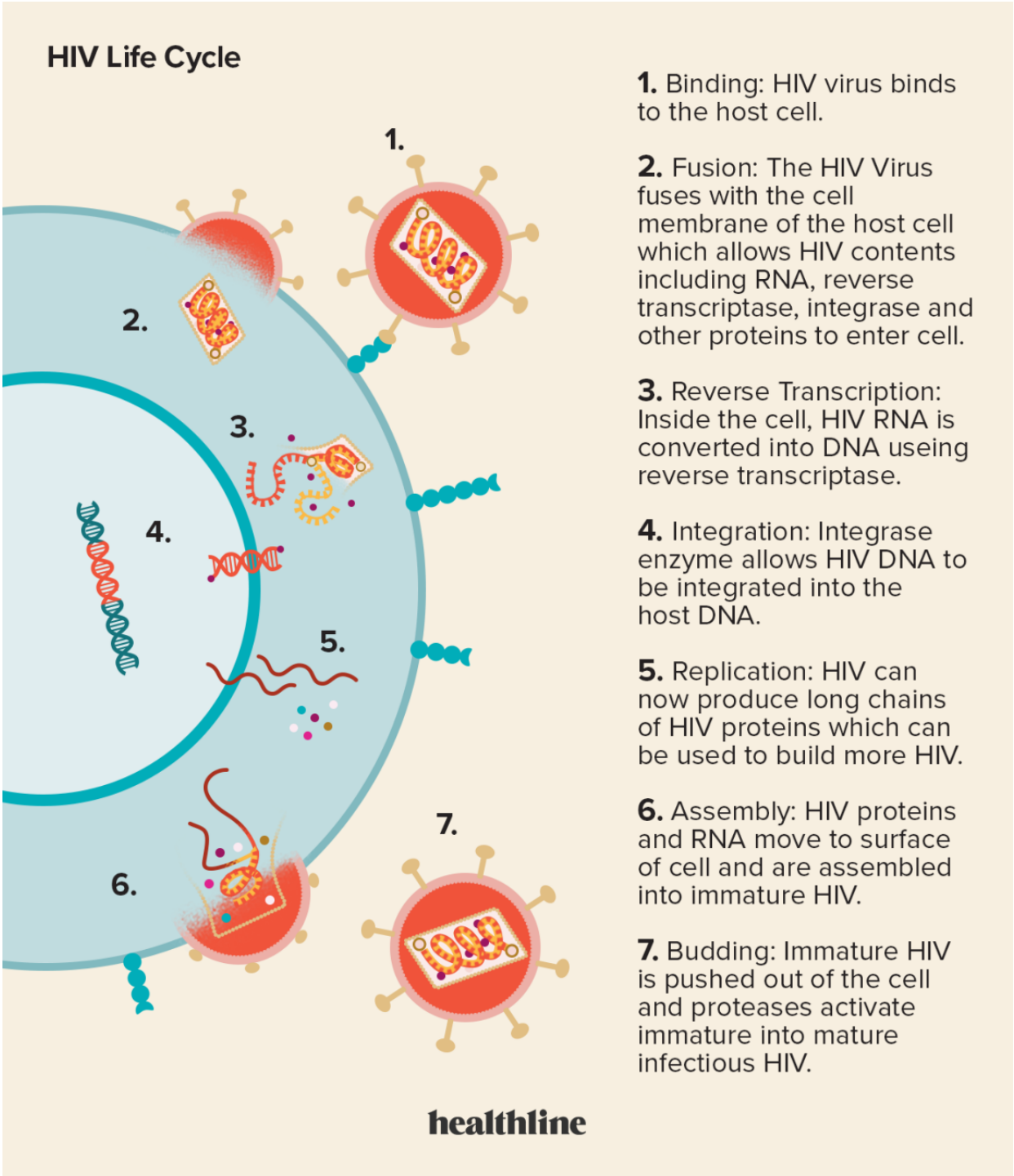
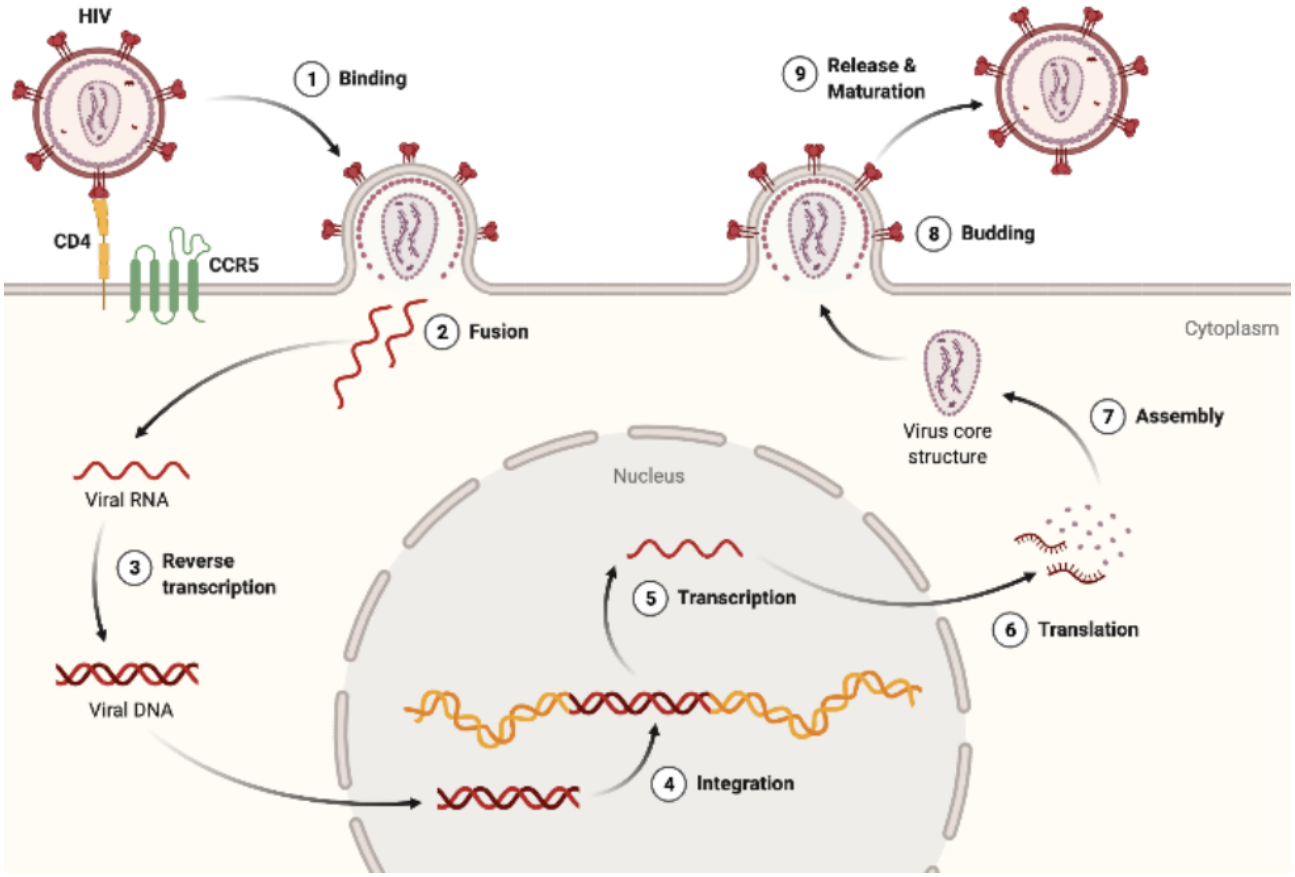


Diagram from Healthline's 7 Stages of the HIV Life Cycle. Accessed from https://www.healthline.com/health/hiv-life-cycle.

HIV Replication Diagram 3



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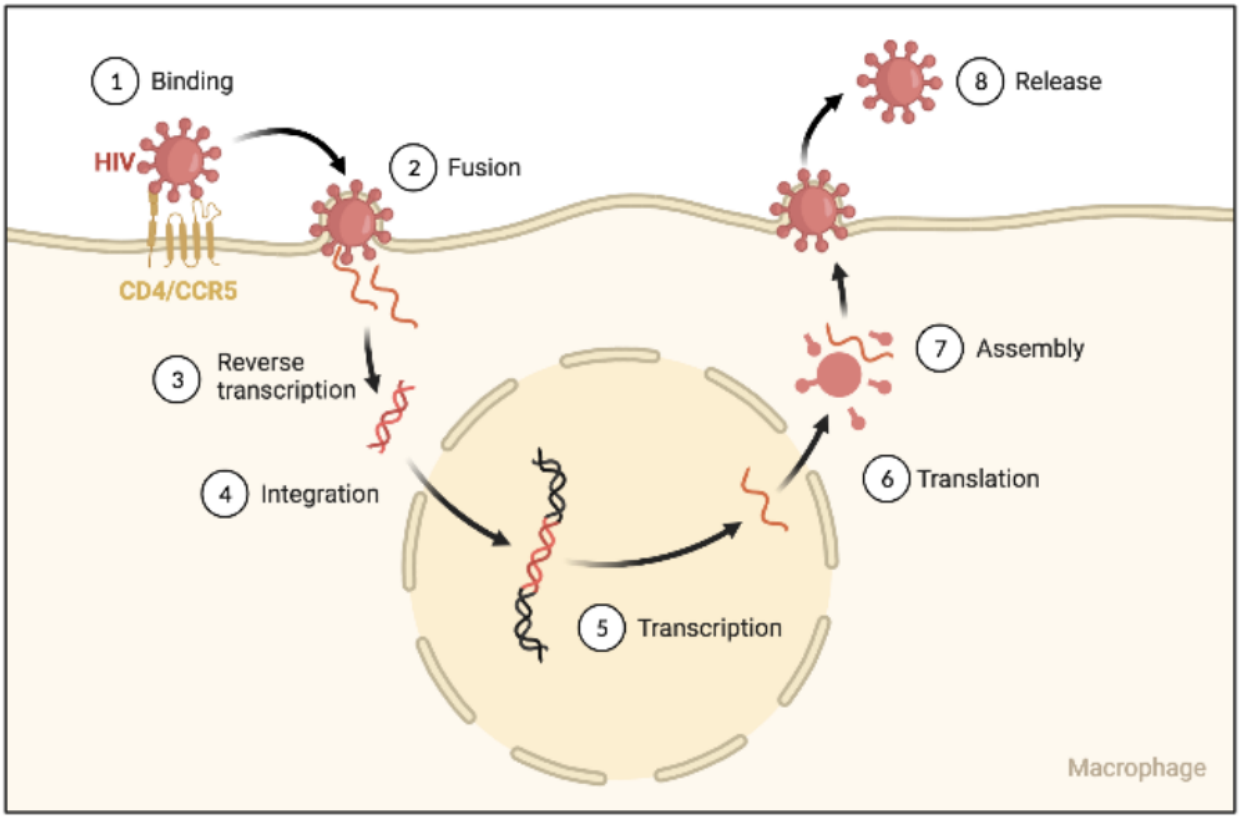
HIV Replication Diagram 4



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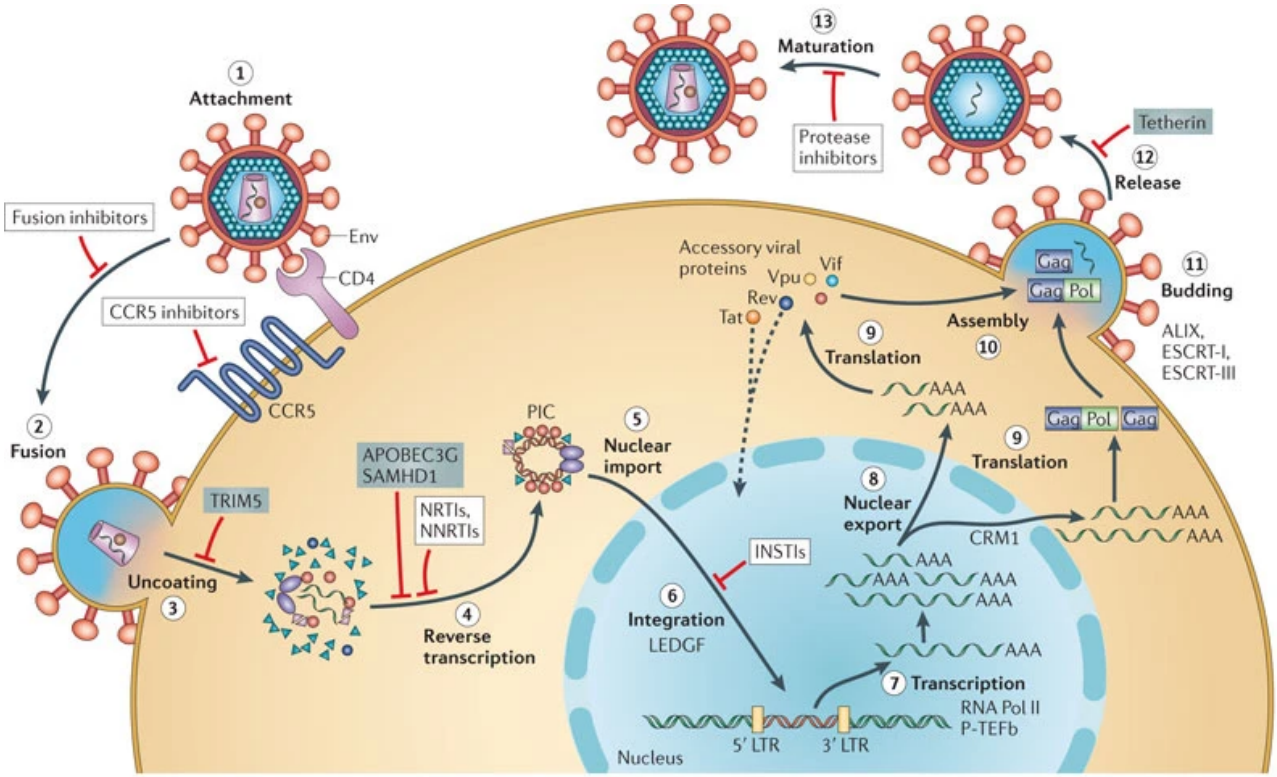
HIV Replication Diagram 4



Those host proteins that have a role in the replication cycle and are discussed in the text are indicated. The infection begins when the envelope (Env) glycoprotein spikes engage the receptor CD4 and the membrane-spanning co-receptor CC-chemokine receptor 5 (CCR5) (step 1), leading to fusion of the viral and cellular membranes and entry of the viral particle into the cell (step 2). Partial core shell uncoating (step 3) facilitates reverse transcription (step 4), which in turn yields the pre-integration complex (PIC). Following import into the cell nucleus (step 5), PIC-associated integrase orchestrates the formation of the integrated provirus, aided by the host chromatin-binding protein lens epithelium-derived growth factor (LEDGF) (step 6). Proviral transcription (step 7), mediated by host RNA polymerase II (RNA Pol II) and positive transcription elongation factor b (P-TEFb), yields viral mRNAs of different sizes, the larger of which require energy-dependent export to leave the nucleus via host protein CRM1 (step 8). mRNAs serve as templates for protein production (step 9), and genome-length RNA is incorporated into viral particles with protein components (step 10). Viral-particle budding (step 11) and release (step 12) from the cell is mediated by ESCRT (endosomal sorting complex required for transport) complexes and ALIX and is accompanied or soon followed by protease-mediated maturation (step 13) to create an infectious viral particle. Each step in the HIV-1 life cycle is a potential target for antiviral intervention165; the sites of action of clinical inhibitors (white boxes) and cellular restriction factors (blue boxes) are indicated. INSTI, integrase strand transfer inhibitor; LTR, long terminal repeat; NNRTI, non-nucleoside reverse transcriptase inhibitor; NRTI, nucleoside reverse transcriptase inhibitor. Figure 1 from Engelman, A., & Cherepanov, P. (2012). The structural biology of HIV-1: mechanistic and therapeutic insights. Nature Reviews Microbiology, 10(4), 279-290.

A Beginner's Guide to Scientific Method

FOURTH EDITION

STEPHEN S. CAREY
Portland Community College

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Carey

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novel or *proposed* explanations or something similar. Explanations which are well established, like some theories, we may simply characterize as *received*, *established*, *generally accepted*, etc.

CAUSATION

One way to explain how or why something has occurred is to give an account of the events leading up to it. Why, for example, when we were small children, did teeth, carefully tucked under our pillows, vanish only to be replaced by money? Because while we were sleeping our parents removed the teeth and replaced them with money. Why is there a circular crater several miles in the diameter in the Arizona desert? Because a large meteor survived its trip through Earth's atmosphere intact; its crash produced the crater. Why is smoking on the increase among young adults? In part, because the tobacco industry targets this segment of the population in much of its advertising. In each of these cases, a cause for a particular effect is identified, and with each we understand something of why the phenomenon in question is the case.

Causal explanations are common in our daily lives. Imagine I've arrived late for a lunch engagement. "Sorry I'm late. The traffic was horrendous," I say. My excuse is to the effect that something out of my control caused me to be late. Or suppose the street out front of the restaurant where we are meeting is flooded. You venture the guess that all of the drains are clogged with leaves. Your guess involves a causal explanation. The leaves covering the drains have caused the street to flood. Causal relationships are not always simple or straightforward. Consider some of the complexities we must face in thinking about causes and their effects.

First, effects can be the result of a combination of causes. It may be, for example, that my lateness was in part caused by a traffic jam. But suppose that while hung up in traffic I ran low on gas and so had to stop and fill up. Suppose also that neither event, alone, would have made me late. My being late has been caused by a combination of events.

Second, both causes and effects can be about groups rather than individual facts or events. To claim, for example, that cigarette smoking causes lung cancer is to claim that lung cancer will occur with greater frequency among the group of people who smoke than among those who do not.

Third, effects may result from several distinct causes. We know that cigarette smoking causes lung cancer. But other things—exposure to asbestos and genetic abnormalities, for example—can cause lung cancer as well. In some cases, a series of discrete causes will be responsible for an overall effect, though each factor will be responsible for only part of the effect. In the early 1990s, violent crime rates in the United States fell precipitously after 15 years of constant increase. As it turns out, several factors were responsible for the decline, though each was responsible for only part of the overall decline. Among the more pronounced causal factors were: increased use of capital punishment, increased rates of imprisonment, increased number of police, changes in the

illegal drug market, and the legalization of abortion approximately 20 years earlier.[1] A rough estimate is that the hiring of additional police accounted for roughly 10% of the 1990s crime drop and that decreased demand for crack cocaine was responsible for another 15%.

Fourth, effects need not invariably be associated with a given causal factor. Though cigarette smoking is indeed a cause of lung cancer, many cigarette smokers will neither contract nor die of lung cancer. There is today a good deal of evidence that children who drink fluoridated water will have fewer problems with tooth decay than children who do not drink fluoridated water. Though there is clearly a causal link between fluoride and tooth decay, it does not follow that children who drink fluoridated water will be completely free of decay problems.

Fifth, causal explanations can be negative, as in our last example. Fluoridation of the water supply prevents tooth decay. Similarly, many people believe there is a causal link between vitamin C and the common cold. Regular doses of vitamin C, it is claimed, will decrease your chances of contracting a cold.

Finally, causal explanations can involve a sequence of linked events. If, say, A causes B which in turn causes C, A is often referred to as a *proximate* cause of B and a *remote* cause of C. B in turn is a proximate cause of C. So for example, if I trip and bump into the table where you are seated, causing your water glass to spill into your lap, my tripping is the proximate cause of the movement of the table and the remote cause of the mess in your lap.

CORRELATION

Closely related to the notion of a causal explanation is that of a correlation. Indeed, people often assume that if two things are correlated they are causally linked. But this assumption is often wrong. A correlation is nothing more than a comparison between a pair of characteristics within a population. Those characteristics are correlated if they display some regular, measurable variance. The simplest sort of correlation involves the comparison of two groups, one having a given characteristic and the other lacking it. If a second characteristic occurs at different frequencies in the two groups, it is correlated with one of the two. Suppose, for example, that we compared two groups of people, all between ages 30 and 49. The first group all have completed at least four years of college, while the second have less than four years. Suppose also that we were able to look at the average annual income of the two groups and were to find that the income of the first group is, on average, 20% higher than that of the second group. This means there is a correlation between education and income in the groups of people we have considered.

Correlations can be positive or negative. If a characteristic occurs at a greater frequency in one group than in the other, it is positively correlated with the first group; if it occurs at a lesser frequency, the correlation is negative. By contrast, if the characteristic occurs at roughly the same frequency in both groups, there is no correlation between the characteristic and either group. In our example, we

have uncovered a positive correlation between education and income. Suppo instead we had found that the income of those having four or more years c college was actually lower than that of people with less education. This findin would suggest a negative correlation between the two factors. Had we found n real difference in levels of income, we would have had to conclude that, insof as we can tell, there is no correlation between level of education and incom (This does not mean there is no such correlation. All we can conclude is that ou quick check of the data available shows no correlation!)

Correlations can also hold between pairs of characteristics within a singl group. Within a group, if two measurable characteristics vary in a somewh regular and predictable fashion, they are correlated. Suppose, for example, w had at our disposal a large amount of information about the freshman class at small local college. Examining the data we find what appears to be an interestin relationship between first-semester grade point averages (GPA) and Scholasti Aptitude Test (SAT) scores. About 100 students completed the first semester. I most cases, say 75 or so, we find that GPA varies directly with SAT score. Th is, if we arrange these 75 students in order of ascending SAT score, we find corresponding increase in GPAs; the higher the SAT score, the higher the GP For the other 25 or so students, we find no regular variance. Some studen with relatively high SAT scores have relatively low GPAs and vice versa. Some wit average SAT scores have relatively high, some relatively low GPAs. Despit these exceptions, our findings suggest a positive correlation between SAT scor and GPA, at least in the group we have examined. Had we found just th reverse—had we found that for most students, GPA diminished when SA scores increased—we would have uncovered a negative correlation betwee SAT score and GPA. Suppose instead we were to discover no regular varianc between SAT scores and GPAs; many students with relatively high SAT scor had average or low GPAs, while many with relatively low SAT scores ha average or high GPAs. This would suggest that no correlation exists betwee SAT score and GPA in the freshman class of the college.

As our last examples suggest, correlation is seldom an all-or-nothing matte A perfect correlation between two characteristics would require a one-to-on correspondence between changes in the two. (In our example, increases in SA score would need to be accompanied by increases in GPA in all 100 cases t establish a perfect correlation.) But particularly when groups of subjects ar large, the fact that a correlation is somewhat less than perfect does not underc its potential significance, perhaps as a predictor of one characteristic in case where we know something about the breakdown of the other. Presuming, i our example, that we have uncovered a fairly consistent positive correlatio between SAT score and first semester GPA, we may be able to predict somethin about a new college student's chances of success, based on his or her SAT scor But here we need to introduce a crucial note of caution. Any inference we dra about an individual, based on the evidence of a correlation, assumes a caus connection between the correlated characteristics. And this assumption is nc always warranted. The fact that two things are correlated does not, by itsel indicate that the two are causally linked.

Why this is so can be seen in the following examples. If we were to examine a group of similar people, say, members of a single trade or profession, we could probably unearth a number of correlations. We might find, for example, a correlation between age and income, established either by showing a regular variance between age and income for the whole group, or by showing that people above and below a certain age have, on average, different income levels. We would probably also find a correlation between age and the use of reading glasses. Given these correlations, it is likely we will also find a correlation between income and the use of reading glasses! Now, none of these correlations seems to be a coincidence. There seems to be a clear link between age and the need for reading glasses. But the link in the other two cases is much more tenuous. Advancing age does not cause one's income level to rise, nor does income have any bearing on the need for reading glasses. The link in these two cases is undoubtedly explained by some other factor or series of factors. For example, in most trades or professions, the longer one works at a job, the more one generally makes. This, then, accounts for the correlation between age and income.

To make matters worse, a correlation may be evidence of nothing more than coincidence, a "mere correlation." This is because unrelated things can vary in regular, measurable ways. For a number of years now, two things have regularly increased: the sale of Burger King Whoppers and the number of minutes per day that children watch television. Come to think of it, recent increases in Whopper sales are correlated, negatively, with a gradual but regular decrease, in the same period, in the number of people who go bowling! And since we are an aging population, I suspect we could also dredge up a correlation between Whopper sales and the purchase of reading glasses. These new correlations, of course, suggest nothing more than the fact that lots of things, many of them not causally related, vary over time in somewhat regular ways.

All of this is not to say that the search for correlations is not an important component of causal research. Indeed, if two things are causally linked, they will be correlated, and so evidence of a correlation may provide some initial evidence for a causal link. But the simple fact that two things are correlated is, by itself, not evidence of a causal link. In Chapter 5 we will look closely at the ways in which claims about causal links and their attendant correlations are tested. For now, it is enough to keep in mind that correlations do not necessarily indicate causal links and, for this reason, are of less explanatory value than are facts about causal links.

Though causal explanation plays a central role in science, there are several other ways of explaining, all of which have a distinct role to play in scientific investigation. Consider another pair of examples. Why do our eyelids blink open and shut several times every minute? To keep the surface of the eye moist. Why does a gun "kick" as it is discharged? Because of a well established physical law: for every action there is an equal and opposite reaction. Neither of these explanations involves a cause, at least in any straightforward sense. We normally think of causes as events that precede the things they bring about. Physical laws do not cause things to happen in this sense. Nor is the blinking of an eyelid caused by the fact that it thereby keeps the eye moist.

An explanation may focus on the function or role a thing plays in some larger enterprise or on a law that accounts for the behavior in question. These

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Carey

QUICK REVIEW 3.1 Causation and Correlation

Causation
Two things are causally linked if one proceeds and is responsible for the other. Suppose your car won't start because its battery is dead. The dead battery is the cause and your car's failure to start, the effect. Effects can have more than a single cause, and there may be many causes for similar effects. Several causal factors are responsible for the behavior of the stock market and a market decline can be caused by a variety of factors. Causal relationships can hold between individual events or between large classes of events as in the claim that megadoses of vitamin C can reduce occurrences of the common cold. If events are causally linked they will be correlated, but correlations do not necessarily indicate causal links.

Positive Correlation
In two populations, P and Q are positively correlated if a greater percentage of Ps than non-Ps have Q. Suppose that nationwide, people with cell phones have, on average, a higher income than people without cell phones. Cell phone ownership and income are positively correlated.

In a single population, if a regular increase in one trait, P, is accompanied by a regular increase in another, Q, then the two are positively correlated. Suppose worker productivity at a plant increases as pay increases, though with some exceptions. Worker productivity is positively correlated with income.

Negative Correlation
In the two populations, P and Q are negatively correlated if a smaller percentage of Ps than non-Ps have Q. Suppose regular users of the local public library (once or more a month) watch, on average, much less TV than sporadic or nonusers of the library. TV-watching and library use are negatively correlated for the group in question. In a single population, P and Q are negatively correlated if a regular increase in P is accompanied by a regular decrease in Q. Suppose that the number of visits to the library per month increases as the average number of hours watching TV decreases. Library use and TV watching are negatively correlated.

No Correlation
In two populations, P and Q are not correlated if there is no difference in levels of Q in P and not-P. If equal percentages of males and females are left-handed, there is no correlation between left-handedness and gender. In a single population, two traits are not correlated if there is no regular variance between the occurrence of the two. Suppose we were to record both the number of checks written and the number of soft drinks consumed per month by a randomly chosen group of people. We would probably find no evidence that variation in one trait is a predictor of a variation in the other. This suggests there is no correlation between the two.

Perfect Correlation
An invariant relation between two traits; for every change in one trait there is a consistent change in the other. In most species of trees, age in years is perfectly correlated with the number of rings in the tree's trunk; the older the tree the greater the number of rings, without exception.

strategies were used in the examples just above. Explanations can also make reference to underlying processes and causal mechanisms, techniques often used to enrich causal explanations. Since each of these ways of explaining plays an important role in scientific inquiry, let's take a closer look at what each involves.

CAUSAL MECHANISMS

Earlier we noted that a causal explanation can involve a series of linked events. One cause can be more remotely connected to its effect than another, more proximate cause. A causal mechanism is nothing more than a series of proximate causes that intervene between a remote cause and its effect. Researchers often comment that though they have evidence for a causal link, they lack a clear understanding of the mechanism involved. This tells us that the sequence of causes which have led to the effect has not been fully fleshed in. Cigarette smoking, for example, is known to be linked to lung cancer. Yet despite the fact that we are quite confident there is a link between smoking and lung cancer, little is know about the mechanism—the physiological process—by which the carcinogens ("carcinogen" just means "cancer-causing agent") in cigarette smoke lead to uncontrolled cell growth in the lungs of the smoker.

A recent study revealed an apparent causal connection between aspirin consumption and the risk of heart attack. According to the study, men who take a single buffered aspirin every other day have a 50% lower chance of having a heart attack than do men who do not take aspirin. Here the connection between aspirin consumption and risk of heart attack seems to be fairly well documented. As it turns out, the causal mechanism by which aspirin reduces the risk of heart attack is also well understood. Aspirin interferes with the first stage of the blood's clotting process. Now, many heart attacks are caused by blood clots in damaged arteries. It seems that when the thin inner wall of an artery is damaged, aspirin inhibits the tendency of minute blood platelets to clot over the damaged area. Thus, aspirin reduces the clotting effect that can lead to serious heart attack.

To take a very different example, one more closely related to every day life, imagine the following.[2] A friend applied for a job she really wanted to get. Yet now she tells us she finds the job utterly uninteresting and probably wouldn't accept it even if it were offered to her. Why the change in attitude? We discover subsequently that our friend learned she had no chance of getting the job. But how, if at all, did this bring about her change in attitude about the job? The answer may well lie in a causal mechanism, often called cognitive dissonance reduction, that makes people cease desiring that which they cannot get; you may be familiar with this mechanism under its more common name, sour grapes. Having learned she wouldn't get the job, our friend adjusted her desires thereby reducing the dissonance caused by wanting something she could not have. No doubt, the notion of cognitive dissonance reduction is a bit less precise than is the mechanism invoked to explain the connection between aspirin and heart disease, and for that reason it would be more difficult to test. But such psychological mechanisms nonetheless play an important role in our attempts at explaining why people behave as they do

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Fallacies in the Name of Science

WHAT IS A FALLACY?

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The faith of most people in the credibility of science is nearly unshakable. When we read in the newspaper or see on television that there is "scientific evidence for" or that "scientists have discovered" something new and interesting, our tendency is to assume that the evidence is impeccable. Certainly, the material we have covered in the previous chapters suggests that careful scientific investigation is perhaps the most powerful tool we have for getting at the truth of things. Unfortunately, scientific method can, and as we shall see, often is, misapplied.

In this chapter we will examine a number of fallacies committed in attempting to employ the methods introduced in the last four chapters. In logic, a fallacy is a mistake in reasoning. Thus, if I conclude that because (1) Morris is a mammal and (2) dolphins are mammals then (3) Morris must be a dolphin, I have committed a fallacy. The conclusion I have drawn (3) does not follow from (1) and (2), even if (1) and (2) are true. Similarly, the fallacies we will examine in this chapter all involve drawing conclusions that are logically suspect, in the process of applying some aspect of scientific method.

We must keep in mind here the difference between fallacious reasoning, on the one hand, and mistaken belief, on the other. Many ideas in the history of science have turned out to be mistaken, but the mistakes they involve are usually not the product of fallacious reasoning. Prior to the mid-eighteenth century, for example, scientists believed in the existence of something called phlogiston, sometimes called the "fiery substance."[1] Phlogiston, it was thought, was the stuff

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responsible for a number of observable reactions in matter: among other things, it was thought to be the stuff released rapidly into the atmosphere during combustion and slowly, as metals decay. Now, as it turns out, there is no such thing as phlogiston; the scientists of the time were mistaken. However, the theory of phlogiston reactions was well supported by a large body of experimental evidence; indeed, the best evidence available at the time. Among other things, the formulas by which metals were produced from ores derived from phlogiston theory. Subsequent experimentation revealed a better explanation for reactions than phlogiston theory, one involving a new chemical element later to be identified as oxygen. The point here is that both the work which established and ultimately overturned phlogiston theory involved correct applications of the methods we have discussed in previous chapters. Careful observations were made, experiments run, and bits and pieces of the overall theory were modified and finally rejected in light of new experimental results. By contrast, a fallacy occurs when the methods of science are illicitly applied. Fallacious applications of the methods of science lead only to a false impression that something has been established with great care and rigor. Indeed, many of the fallacies we shall consider involve ways of lending the appearance of scientific evidence where there is little or none.

One well-known fallacy in informal logic is called *argumentum ad hominem*: attacking the person rather than his or her argument. If, for example, I argue that every student ought to know something about science and so ought to read this book, you might reply that I receive a royalty from the sale of copies of the book. If your point is to mount an objection to my argument, you are guilty of an *ad hominem* fallacy. Even though what you say is true, the point you make is not relevant to the argument I have given. By pointing out that I stand to profit if students buy this book, you attack my motives for arguing as I have but you have not shown that my argument is flawed.

At the risk of committing an *ad hominem* fallacy, let me propose the following. Most, though certainly not all, of the fallacies we will discuss are committed typically by people on the fringes of science, not by mainstream scientists.[2] By "people on the fringes of science," I mean people who engage in fallacious scientific reasoning for one (or both) of two reasons. First, people commit fallacies because they have little knowledge of what rigorous scientific inquiry involves but nonetheless believe they are capable of undertaking such inquiry. Second, fallacies are committed by people who may well know a great deal about science but who are trying to create the impression that there is some real measure of scientific evidence for something when in fact there is very little. Thus, errors of the sort we will discuss are sometimes committed inadvertently, sometimes intentionally. But no matter what the motives of their authors, such mistakes are instances of what is generally called *pseudoscience*. The distinction between genuine science and pseudoscience is one about which we will have more to say later in this chapter. But for now let's begin by taking a look at several common fallacies, all committed in the name of science.

FALSE ANOMALIES

Were we to do a quick search of an internet book store we would turn up a large number of entries on just about every extraordinary claim we have discussed in previous chapters. The literature on ESP, UFOs, ghosts, crop circles, alternative medical cures, and so on is nearly endless. A small sample of such books would quickly reveal a common theme. The author(s) would get our attention by laying out a series of apparently well-documented anomalies, and then in the body of the book go on to offer new and revolutionary suggestions as to what their explanation might be. At some point a theme will emerge: the scientific community is embarrassed because they can't explain these anomalies and so can be expected to ignore the author's findings. All too often, however, the air of mystery surrounding the cases and events which have drawn us in will be no more than a carefully contrived illusion, a false anomaly.

One way to make something appear mysterious is to omit certain facts in describing the phenomenon, facts which suggest that the phenomenon may not be all that anomalous. In Chapter 2 we mentioned an apparent anomaly, crop circles. Large, symmetrical geometric figures, circular and otherwise, mysteriously appeared in wheat and corn fields in Southern England and have since been observed in many other countries, including the United States. We also noted that the circles are relatively easy to explain away given that there are tractor indentations near most of them and that several debunkers have demonstrated how easily and quickly an intricate crop figure can be constructed. Yet most books on this phenomenon conveniently omit these facts. Similarly, the six or so major books on the Bermuda Triangle, another example from Chapter 2, omit much well-documented information suggesting that their favored anomalies are the result of accidents, inclement weather, and inexperienced crews.

Another way to create a sense of mystery is to subtly distort the content of a factual description. For example, much research has been done in recent years on "near-death experiences." Some researchers claim that people who have been near death but have been revived, typically during a medical emergency, have reported a remarkable experience. Here is an account of that experience from one of the best known books on the subject, *Life After Life*, by Raymond Moody:

> A man ... begins to hear an uncomfortable noise, a loud ringing or buzzing, and at the same time feels himself moving very rapidly through a long dark tunnel. After this he suddenly finds himself outside of his own physical body, but still in the immediate physical environment, and he sees his body from a distance, as though he is a spectator ... after a while, he collects himself and becomes more accustomed to his odd condition.... soon other things begin to happen. He glimpses the spirits of relatives and friends who have already died, and a loving warm spirit of a kind he has never encountered before—a being of light—appears before him.... at some point he finds himself approaching some sort of barrier or border, apparently representing the limit between earthly life and the next life. Yet he finds that he must go back to earth, that the time for death has not yet come.[3]

Now, if this precise experience were reported by many people, we would have quite a remarkable phenomenon on our hands. In fact, the description provided in this passage is based on the reports of hundreds of people. But no two reports are precisely the same. The description we have just read combines elements from many varied experiences. Moreover, no single element in this description occurs in all reports and no single subject has given precisely this description. Though Moody quite openly admits all of this, many people who argue that near-death experiences provide evidence of life after death accept this artificial account as an accurate description of the strange experiences people report when near death. The fact that people are liable to report any of a number of things, that reports are frequently at odds with one another and that many people when near death report no such experience, all suggest that there may be a more mundane explanation for the things people report when near death. At any rate the appearance of a great mystery here is heightened by the subtle fabrication of an experience that, strictly speaking, no one has ever had.

The use of distortion and omission to create false anomalies is nowhere more in evidence that in the many conspiratorial theories surrounding the events of 9/11. The basic idea behind these theories is that many things happened on that tragic day that cannot be explained by the more or less standard account of what transpired. Moreover, those who know the real explanation for these anomalous events are engaged in a conspiracy to keep the public in the dark about what really went on. (We will have more to say about fallacious conspiracy theories later in this chapter.) Here are just a few of those claimed anomalies along with the facts that are omitted or distorted in their fabrication.[4]

(1) The American Airlines Boeing 757 that struck the Pentagon left suspiciously little wreckage, none of which was clearly from a 757. Omitted in this account is the fact that a small piece of the fuselage with the American Airlines logo visible was found and photographed on the lawn in front of the Pentagon.

(2) *Early coverage on 9/11 by CNN reported that no plane hit the Pentagon.* In fact, CNN reporter Jamie McIntyre did say "There's no evidence of a plane having crashed anywhere near the Pentagon." But Flight 77 did not crash "near" the Pentagon. It crashed into the Pentagon.

(3) *The Air Force could have scrambled fighter planes in plenty of time to intercept Flight 77. In 1999 golfer Payne Stewart's private jet was not responding to radio calls. Within 20 minutes fighter planes were alongside Stewart's plane.* Indeed, air controllers lost contact with Stewart's jet at 9:30 a.m. and the intercept did occur at 9:52 a.m. However, contact was lost at 9:30 *Eastern* Daylight Time and the interception was at 9:52 *Central* Daylight Time. The intercept took one hour and 22 minutes, not 22 minutes.

(4) *The impact of a commercial jet alone could not bring down either of the twin towers. In 1945 the Empire State Building was hit by a B-25 bomber and certainly did not collapse.* Like most skyscrapers of the time, the Empire State Building was stiffly constructed with reinforced concrete columns and a thin masonry

exterior. Its weight was 38 pounds per cubic foot. The World Trade Center, by contrast, was constructed with a much thinner exterior shell fabricated from steel plates. Its density was less than 10 pounds per cubic foot. The bomber that hit the Empire State Building was traveling at roughly half the speed of the 767s that hit the twin towers, carried one-tenth as much fuel and weighed less than one-tenth the weight of a 767.

One final way to create the appearance of an anomaly is by over-reliance on anecdotal evidence, a technique commonly found in works about revolutionary medical cures. For example, there are hundreds of books available on homeopathy, a type of medical practice discovered in the 19th century. According to homeopathic theory, a person can be cured of an ailment by being given minute doses of whatever substance creates its symptoms in a healthy person. Moreover, the smaller the dosage, the greater will be its effects. Precisely how and why homeopathy should work is unclear and is often chalked up to an "unknown mechanism." But does it work? The way to answer this question, of course, is to undertake a series of carefully controlled causal studies of the sort discussed in Chapter 5. Most of the books on homeopathy acknowledge that little rigorous scientific evidence is currently available. For a variety of reasons, few such studies have been done. Lack of funding and skepticism on the part of the mainstream medical community are often cited. Most authors make their case for the efficacy of homeopathy by citing numerous anecdotes, remarkable stories of actual people who have been cured by homeopathic remedies. Yet such anecdotal evidence is of little scientific value. It is estimated that about 50% to 60% of all the ailments for which people seek medical help will, if left untreated, go away within 90 days. Thus, the fact that someone has a problem, submits to homeopathic treatment, and gets better is not evidence that their improvement is due to the treatment! The fact that many ailments will disappear without treatment is almost always ignored, as authors set forth their amazing stories of homeopathic cures.

A good piece of advice when confronted with evidence that is wholly anecdotal is to ask yourself, "What is missing, what haven't we been told?" A well known medium, John Edwards, claims to be able to communicate with dead relatives and friends of people in the audience for his television program, *Crossing Over*. On a typical episode Edwards will tell audience members things about their dead loved ones that he would have no way of knowing unless he were somehow in psychic contact with them. The program, of course, is carefully edited so that we are not privy to much of what he communicates that turns out to be wrong.

QUESTIONABLE ARGUMENTS BY ELIMINATION

Suppose we know that either A or B must be true and subsequently discover that B is false. Logically we can conclude that A must be true. This pattern of reasoning is sometimes called *argument by elimination*, for it involves establishing

one alternative, A, by eliminating the possibility of the other. An argument by elimination is fallacious when it ignores other likely possibilities in the process of arguing for one of the given alternatives. Imagine that I want to establish a particular explanation. First I list possible rival explanations and then proceed to show that none of the rivals are likely to be correct. Have I established my favored explanation? For two reasons, our answer here must be "no." First, there may be other possible explanations I have failed to consider. Second, even if I succeed in ruling out all the rival candidates we can think of, the failure of these rival explanations only entitles us to conclude that the phenomenon in question needs explaining, not that my favored explanation is correct.

A common strategy in ESP research is to claim that an explanation involving some sort of extrasensory mechanism can be established by showing that experimental subjects can achieve results in an ESP experiment that would be highly unlikely by chance alone. For example, a study might claim that a particular experimental subject has the gift of mental telepathy (the ability to read the mind of another) because he or she is able to guess the playing card an experimenter is thinking about more frequently than chance would suggest. Implicit in this claim is a fallacious argument by elimination. That the subject is telepathic follows only if we assume there are only two possibilities—telepathy or sheer luck—and if we can effectively rule out luck or chance under tightly controlled experimental conditions. Yet this assumption is flawed. First, there may be other possible explanations. Maybe an invisible imp peeks at the cards and whispers the right answer in the subject's ear. As wild as this "explanation" seems, it would appear to be as well supported by the experimental outcome as is the telepathy hypothesis. (What experimental outcome would support telepathy and rule out imps, or vice versa?) Second, even in the absence of rival explanations, the outcome of this experiment does not confirm the claim that the subject has telepathy. The only conclusion we are warranted in drawing, based on the results of this experiment, is that something quite interesting, something we do not fully understand, is going on. What we are conspicuously not entitled to conclude is that we have evidence for any particular explanation.

Conspiracy theorists often fall prey to a subtle version of this fallacy. As we have noted in the case of various 9/11 conspiracies, they begin by citing a number of apparent anomalies. The conclusion that these anomalies are evidence for some sort of conspiratorial explanation assumes there are only two possibilities. If the anomalies cannot be completely explained in more or less conventional ways, then there must be a conspiracy lurking in the shadows. But even if it could be shown that some events have yet to be explained, it does not follow that their explanation must involve conspiracy.

ILLICIT CAUSAL INFERENCES

People all too often draw conclusions about causal links based on evidence that is all too sketchy. In most cases the inference of a causal link seems plausible only because rival explanations are overlooked or ignored. Conclusions about a causal

link between A and B are often drawn on the basis of a number of specific kinds of evidence, none of which, taken alone, is sufficient to support a claim of causal connectedness. The most prominent of these are:

1. A simple correlation between A and B
2. A concomitant variation between A and B
3. The fact that A precedes B

Let's look at an example or two of each and the plausible rival explanations our examples fail to take into consideration.

A simple correlation between A and B. In Chapter 3 we noted that the simplest sort of correlation is a claim about the levels of a characteristic in two groups, only one of which has another characteristic. Thus, A is correlated with B if more As than non-As have B. This does not necessarily mean that A and B are causally linked but people frequently make the illicit inference that they are.

Imagine we were to read the results of a study which purported to show a link between a person's astrological sign and his or her profession. Reading further, we discover that the birth dates of a large group of lawyers were examined and that it was discovered that more were born under the sign of Leo than under any other sign. Clearly, there is a positive correlation between being a lawyer and being a Leo. Now, this may suggest that there is a causal link between the two factors. However, there seem to be at least two plausible explanations for the data—explanations that do not involve any sort of causal link between profession and astrological sign. The first is that the correlation is just a *coincidence*. If we look at a number of groups by profession, we may now and then find one where there is a significantly greater number of people born under a particular sign, particularly if we restrict our investigation to groups that are none too large. Imagine we were to do a study of plumbers and astrological sign. If we restrict our sample to one or two dozen subjects, chances are quite high we will not find an even distribution under all signs. What we will find is some entirely predictable "clumping." Some signs will have more subjects than others. From here it is but a short step to a claim about a remarkable correlation between being born under a few astrological signs and becoming a plumber!

The fact that our study only cites one profession and one correlation suggests another possible explanation. It may be that the researchers who undertook the study have presented us with only one small part of their overall data, the part that appears to confirm the possibility of a causal link. Or it may be that, convinced of the truth of astrology, they have inadvertently pruned away just enough data—say, by excluding certain subjects—to lend support to the idea of a correlation.

The explanation for a correlation need not be coincidence or even fudging, inadvertent or otherwise. Frequently, correlations are explained by some third factor which suggests a possible indirect link between the correlated factors. Suppose, for example, that we discover—from careful observation of a number of classes—that students who sit near the front of the classroom tend to achieve higher grades than do students who sit near the rear. It may be that this is a

coincidence. At any rate it hardly seems likely that I can improve my grade simply by moving to the front of the classroom. What seems a more likely explanation is that students who want to do well are enthusiastic and want to sit "where the action is," namely near the front of the classroom. Thus, it may be that some additional motivational factor accounts for the correlation between the two factors in question.

Several recent medical studies have suggested that there may be a link between church attendance and health. In one study, 21,000 subjects were tracked for eight years. During this time 2,016 died. The researchers discovered that those who regularly attended church were much less likely to have died in that eight-year period. Though it is possible there is a direct link between church attendance and health, it is entirely likely that this effect is due to a third factor. Unhealthy people are less likely to lead an active life and so less likely to attend church.[5]

A concomitant variation between A and B. Concomitant variation[6] is a convenient name for the second sort of correlation discussed in Chapter 3. Concomitant variation occurs when a variation in one factor, A, is accompanied by a variation in another factor, B. It is quite tempting to conclude that there must be some connection between A and B if changes in the level of one are regularly accompanied by changes in the level of the other. The problem with such a conclusion is that an enormous number of entirely unrelated things tend to vary in very regular sorts of ways. Over the past ten years there has been a dramatic increase in the popularity of country-western music. At the same time there has been a corresponding increase in the cost of a loaf of bread. What is the explanation here? A genuinely baffling causal link? Some overlooked third factor? The most likely explanation is that we have managed to pick two completely unrelated trends that happen to be going in the same direction at the same time.

The fact that A occurs prior to B. In most circumstances, we would not automatically assume that because one event precedes another, the two are causally linked. But the inclination to infer a link increases dramatically when something out of the ordinary is preceded by something equally unusual. Our thinking seems to be that one remarkable thing must have an equally remarkable cause; if two remarkable things happen in close proximity, they must be connected. We have all had experiences like this before: just as you think of someone, the phone rings, and it is the person you were thinking about. ESP? Perhaps. But a more likely explanation is coincidence. Consider the number of times you have thought of that person and they haven't called as well as the number of times they have called though you were not thinking about them. That the two events should occur in close proximity every so often seems not all that unusual.

Recently, an electrician fixed my furnace. A few days later, I noticed that the clock on the thermostat that controls the furnace wasn't working. It seems natural to conclude that something the electrician did caused the clock to stop. In such cases, the fact that one event precedes another is probably best explained as nothing more than a coincidence. What would be required to discount the possibility of coincidence would be some sort of independent evidence linking the work of the electrician and the behavior of the thermostat.

UNSUPPORTED ANALOGIES AND SIMILARITIES

In attempting to explain something puzzling, it is sometimes useful to consider something similar but whose explanation is well understood. Thus, for example, in the late 19th century, physicists hypothesized about the existence of what was then called the luminiferous ether, the medium in which light waves are propagated. They arrived at this notion by thinking of certain similarities between light and sound. Both appear to be wave phenomena and sound waves are propagated in a medium, our atmosphere, much as the waves created by dropping a pebble in a pond are propagated out of the surrounding water. Thus, physicists reasoned, there must exist a medium for the transmission of light waves as well, a luminiferous ether. Subsequent experimentation, however, demonstrated that there is no such stuff, and so physicists went on to consider other possible explanations for the propagation of light waves. Interestingly enough, physicists next thought about light in terms of another well-understood phenomenon, electro-magnetic fields.

This example illustrates the way in which thinking about a puzzle in terms of something similar but better understood can lead to possible explanations. But it also illustrates the need for independent testing of the explanation arrived at in this way. Analogies and similarities are fallaciously exploited when the fact that an explanation works in one case is given as evidence for the correctness of a similar explanation in another case. At the very most, a well-chosen similarity guides us to a possible explanation; it should not be thought to provide evidence that the explanation is correct. Only careful testing can provide such evidence.

Consider one explanation often proposed by astrologers. Grant, for the moment, that there may be something to astrology and that, indeed, the position of the stars and planets at the time of our birth can influence our personalities or even our choices of profession. What is the explanation? How is it that the stars and planets influence our lives? Astrologers are likely to give something like the following explanation:

> Much as the moon influences the tides and sun spot activity can disturb radio transmissions, so do the positions of the planets have an important influence on formation of the human personality. Modern science is constantly confirming the interconnectedness of all things. Is it any surprise that distant events, like the movement of the planets and the decisions people make, should be connected?

So the stars and planets affect our lives much in the way the moon influences the tides, etc. Of course, there is no claim here that the relation between the stars and our lives is precisely the same as between the moon and the tides or the sun and radio transmissions. What we have, then, is the barest suggestion that an explanation may be possible for astrological effects and that it may somehow be similar to whatever it is that explains the relation between moon and tides, sun and radio transmissions. What we do not have is any of the details of what that explanation might be. Nonetheless, by appealing to something that is understood and suggesting that the explanation for something

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else must be similar, our astrologer has managed to create the impression that something like an explanation has been given.

UNTESTABLE EXPLANATIONS AND PREDICTIONS

To test an explanation we begin by devising a set of experimental conditions under which we predict that something will occur if the explanation is correct. If the predicted result fails to occur, we conclude that the explanation is probably wrong. What this means is that an explanation, to be subject to scientific testing, must, in principle, be falsifiable. Don't confuse falsifiability with falsehood. To be falsifiable is simply to be testable. By contrast, an unfalsifiable explanation would be one whose falsity could not be detected by any conceivable test. It may seem that an unfalsifiable explanation is simply true, but this is not so. An explanation that is in principle unfalsifiable is not a scientific explanation at all. Precisely why this should be so can best be explained by way of an example or two.

I cashed a large check yesterday and today discover that it bounced. Looking over my checkbook register, I discover a glaring error in addition; I had much less money in my checking account than I thought. My miscalculation, then, explains why my check bounced. Had I not miscalculated, I would not have written a bad check. Imagine instead I gave this as the explanation for my bad check: "It must have been fate. What happens, happens." But what if my check had not bounced? Once again fate, I say, is the real culprit. Now it may be that fate determines what we do and do not do. But insofar as the notion of fate is consistent with everything that happens, it cannot be invoked to explain why a particular thing and not something else happened. Maybe fate determined I would bounce a check, maybe not. But by invoking the notion of fate I do not thereby explain why my check bounced as opposed to not bouncing.

A group of people, calling themselves "special creationists," claim that there is "scientific evidence" that the universe was created by God. Some believe creation occurred only a few thousand years ago while others believe it may have occurred billions of years in the past. Both groups claim however that the processes by which God created the world are "special" in the sense of no longer operating in the natural world; the "laws of nature" by which God created are different from those we currently observe. Well, this is all very interesting. But what prediction about the world could we make, provided this claim is true? The processes by which God created so quickly and completely are no longer in existence, so we should not expect to find evidence of their continuing operation. And for precisely the same reason we should expect to find no evidence against the theory of special creation. It would seem, then, that the creationist explanation is consistent with everything that is happening or could conceivably happen, and so could not possibly be falsified.

But this means that the creationist account of how things began is not an explanation at all! To explain something is to try to make clear how or why it and

not something else happened. A proposed explanation that is consistent with what happened and anything else that could have happened instead explains nothing. Perhaps God created all things and did so in a very short time using special processes no longer in operation. But by venturing this scenario, the creationist has not explained why things are as they are and not some other way; the creationist scenario is consistent with anything that could conceivably happen. Though the creationist's account is interesting it is not a scientific account of things. Does this mean the creationist is wrong? No. What it does mean, however, is that special creationism does not constitute a scientific explanation.

If we find that an apparent explanation cannot be falsified, we have uncovered a compelling reason to reject it as an instance of genuine scientific explanation. As a rule of thumb, it is always a good idea to ask of any proposed explanation: "Under what conditions would we be willing to set aside the explanation on the grounds that it is false?" If no such conditions can be imagined, we are dealing with something that is at best fascinating speculation, perhaps even an article of faith, but not a genuine scientific explanation.

Predictions made by psychics, tarot readers, astrologers, and others claiming the ability to foresee the future are often couched in terms that render them unfalsifiable. "A big career move awaits you," a psychic tells us. Just how big and how soon we are not told. What would falsify this prediction? A few months pass and no new job is on the horizon. Is the prediction false? Well, the big career move may not involve a job change and whatever is to occur may still await us. As you can see, it would be hard to imagine anything that might prove such a vague prediction to be false. Astrologers are fond of cautioning their clients that the stars "impel, they don't compel." Presumably, what this means is that anything the astrologer predicts cannot be false since it may be about a future path the client will choose not to take.

Many conspiracy theories seem attractive and plausible largely because they are immune to falsification. Imagine, for example, that I claim to understand why gasoline prices continue to rise at a much greater rate than the cost of living. There is, sorry to say, a plot, a conspiracy, among the major oil companies to insure that just enough gasoline is refined to keep demand slightly ahead of supply. Might I be wrong, you ask? After all, there have been many congressional investigations of the oil industry and none has yet turned up evidence for such a plot. Well, what do you expect, I reply. The one thing we can be sure of in a conspiracy of this magnitude is that the conspirators are going to do everything necessary to cover their tracks, even if this requires buying the services of a few congressmen. Note here how I have attempted to turn the lack of any evidence against my theory into evidence that it is so. Thus, far from viewing its inability to be falsified as evidence that my theory is not scientific, I take this to be evidence that it must be correct. 9/11 conspiracy theorists are fond of calling their detractors "sheeple." Presumably any criticism of the theory can be discounted on the ground that it has been fabricated to throw us off the track. Nothing, it seems, can count against the theory.

Conspiracy theories, as we have noted, are often designed so that nothing can count against them. Remarkably, many such theories retain an air of

Box 6.1

People who are attracted to conspiracy theories usually make a series of assumptions:

A. *Nothing happens by accident.* Events that appear to be coincidental are intended to appear that way.

B. *Everything is connected precisely because nothing is accidental.* The web of connections underlying seemingly unconnected events is, of course, hidden.

C. *Nothing is as it seems.* Appearances are deceptive because conspirators wish to deceive in order to disguise their activities or their identities.

D. *Most information flowing from mainstream institutions such as the government and the mass media is suspect.* Such institutions are frequently seen either as participants in conspiratorial activities or as the victims of such. By contrast, obscure sources, little known Internet sites, periodicals, newsletters, and unverifiable personal testimony are generally regarded as more reliable than mainstream information.

Adopted from *A Culture of Conspiracy*, by Michael Barkun. (Berkeley: University of California Press, 2003.)

plausibility in the eyes of their supporters despite a complete lack of evidence. This is due to another misapplication of scientific method. The claims such theories are invoked to explain are then treated as evidence they are true. Earlier we discussed several apparent anomalies associated with the events of 9/11. The explanation, we are told, is that a powerful group of conspirators, probably involving our government and others, planned and executed the attacks. What evidence is there for this conspiratorial explanation? The long list of events that occurred on 9/11 which nobody seems able to explain away. As you can see, this kind of thinking is like a dog chasing its tail. A series of anomalies is introduced. An explanation is proposed. Its subsequent vindication involves nothing more than a rehash of the anomalies that gave rise to the explanation in the first place. The appearance of a body of independent evidence has been cleverly insinuated where in fact there is none!

EMPTY JARGON

The language of the sciences is notoriously jargon-laden. Scientists often deal with ideas that are not part and parcel of the ordinary world and so must resort to terminology that is for the most part unfamiliar to the layman. Astronomers speak of pulsars, quasars, Doppler shifts and dark matter, physicists of leptons, fermions, strong and weak interactions and geneticists of genes, chromosomes, alleles, DNA, and the double helix. One way to make a claim appear to be scientific is to appropriate the jargon of the scientists. All too often, however, claims made by stringing together bits of jargon tell us nothing even though they have the look and sound of real science. Psychokinesis is the ability to

manipulate objects by sheer mind power. Presuming such a thing is possible, you might wonder how it works. "Photon radiation from the brain of the sender," I tell you, "destabilizes the wave function of the light nuclei in the object being manipulated." Sounds impressive and very scientific. But what have I actually said? I must admit, I don't really know, for I've just strung together bits of jargon.

This sort of misappropriation of scientific jargon can be quite effective. Deepak Chopra, a well known medical doctor and writer on alternative medicine, claims that illness can be banished by the power of the mind. He believes that the explanation is to be found in modern quantum physics. Commenting on cases of cancer remission, Chopra explains: "Such patients apparently jump to a new level of consciousness that prohibits the existence of cancer ... that is a quantum jump from one level of functioning to a higher level."[7] In physics, quantum "jumps" occur when electrons instantaneously move from one discrete position to another. What is not clear is that this idea makes sense when applied to anything other than the behavior of electrons and a few other sorts of sub-atomic particles. Chopra's "explanation," then, sounds good but in the end tells us nothing about cancer remission and its causes.

We've examined several cases involving ESP of one sort or another. But the acronym, ESP, has become a bit shopworn. Many of its practitioners have been caught engaging in fraudulent activities and little progress has been made in making sense of what ESP might involve. Recently, paranormal researchers have come up with a new name for ESP. They're now calling it *anomalous cognition*. This phrase certainly sounds scientific and does manage to avoid the bad publicity associated with ESP. But it is just another name for the same old thing.

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AD HOC RESCUES

Imagine we have conducted an experiment but that the results are negative. As we found in our discussion of experimental design in Chapter 4, we need not immediately dismiss the claim at issue. The test may have overlooked something that compromised the results. An initial test that fails to get the results expected can be modified and redone. But this sort of holding maneuver can only take us so far. If numerous modifications continue to yield negative results, there is a point at which we must admit that our initial expectations were wrong. To persist in defending a claim in the light of repeated experimental failures is to engage in what is called an ad hoc rescue. Such a move is not intended to find new and better ways to test a claim nor even to provide grounds for modifying the claim. Rather, the aim of an ad hoc rescue is simply to save the claim in the face of mounting evidence that it is wrong. To argue, for example, that some unknown factor must be confounding the results of a test is, thus, to engage in an ad hoc rescue.

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As we have noted, there is nothing fallacious about rethinking and modifying an experiment when the initial results are inconsistent with

expectations, particularly when those expectations have some measure of independent support. Such maneuvers are part and parcel of the way science is done. The discovery of the planet, Neptune, provides a good example. In the early 1800s, six of the seven known planets in our solar system seemed to obey laws set forth by Kepler and Newton: the planets trace out elliptical orbits at precisely predictable rates unless their motion is affected by other gravitating objects. But the outermost planet, Uranus, did not square with these laws. Now, one possibility was that the laws in question were a special case, only capable of explaining the motions of some of the planets. But astronomers were not ready to give up on prevailing theory, given its effectiveness at accounting for the behavior of all other objects then known to make up our solar system. In the mid-1800s they speculated that the peculiar movement of Uranus could be explained in a way consistent with Newton and Kepler if another planet were to exist out beyond the orbit of Uranus that was affecting its movement by gravitational attraction. Now, at this point in the story, we must regard the proposed new planet with some suspicion. With no evidence for its existence, it seems like an ad hoc rescue intended to save prevailing theory. Fortunately, however, astronomers were able to predict just where the new planet should be in order to exert the postulated gravitational influence on Uranus and shortly thereafter Neptune was discovered precisely where predicted.

By way of contrast, consider the following. Imagine that a psychic has agreed to be tested and further agrees that he can perform under the experimental conditions we have set up. Alas, our psychic fails. Nevertheless, claims our psychic, this does not show that he cannot do the things in question. For psychic abilities are subject to something called the "shyness effect"; psychic abilities ebb and flow and frequently seem to ebb just when we want them to flow. It is almost, adds our psychic, as though they don't want to be tested. It would seem that the psychic's appeal to the shyness effect is calculated not to help us rethink our experiment, particularly if there is no independent way of testing for its presence or absence. It is rather nothing more than an attempt to make sure that, no matter how carefully we design our experimental test, no conceivable result need be taken as repudiating the psychic's claimed ability. Unlike the planet Neptune, the "shyness effect" cannot be verified. Our psychic's maneuver seems clearly to constitute an ad hoc rescue. The only redeeming feature of the "shyness effect" is that, if true, it would save our psychic in the face of his failure to perform under controlled conditions.

EXPLOITING UNCERTAINTY

Uncertainty is a fact of life in science. As we saw in Chapter 4, experimental results stand only on the assumption that unforeseen factors have not been overlooked. Causal studies, like those in Chapter 5, typically yield conclusions that are highly probable but not a certainty. When scientists publish their results, they take great pains to make clear the probability that their findings are correct and to outline any considerations that might suggest otherwise.

The careful manner in which scientific findings are set forth can be exploited to make highly questionable views appear to be considerably less so. Here, in a nutshell, is how the argument goes: *If scientists are unsure of the truth of their favored view, there is a reasonable chance they are mistaken and that a rival view may be true.* If, in addition, a few "experts" can be found to defend the rival view, it can be made to seem even more respectable.

The Shroud of Turin is a large piece of linen cloth that bears the indistinct, full-length image of a bearded man who, some say, appears to have been crucified. Is it the burial cloth of Christ? In 1987, the Vatican—the official owner of the Shroud—agreed to have samples from the Shroud tested by carbon dating.[8] The results were published in a major scientific journal, *Nature*. They indicated that the material from which the Shroud was woven had been harvested sometime between 1260 and 1320 A.D. though it was possible that it could have been harvested as late as 1390 A.D. The Shroud, it seems, is not nearly old enough to be Christ's burial cloth.

Nevertheless, controversy continues to this day about the authenticity of the Shroud. Believers point out that scientists are not really certain of the exact date when the material was harvested, so it is possible that their estimate is wrong. They go on to point out that it is at least possible that the samples from the Shroud were contaminated with material from other sources and that experts in carbon dating admit this. What they often fail to mention is that three independent laboratories—picked by the Vatican—tested Shroud samples and all three arrived at dates for the Shroud that were very close to one another. Moreover, all three agreed that though a precise date could not be fixed, chances were exceedingly high that the material was harvested somewhere between 1260 and 1320 A.D. What little uncertainty results from the estimated dates or from that small possibility of contaminated samples, then, does not make it reasonable to assume the Shroud is old enough to be Christ's burial cloth.

Much of what controversy remains about whether human activity contributes to global warming involves another twist on this fallacy. By now the vast majority of scientists in fields that study global climate accept as fact the notion that human-caused CO_2 in the atmosphere is responsible for a significant part of the greenhouse effect. The precise amount that is human-caused can only be estimated. Moreover, a clear picture of what will happen to the environment in the near future if nothing is done to curtail CO_2 production remains somewhat murky. What is a near certainty, however, is that human activity contributes to global climate change. The few remaining, but persistent, global warming skeptics tend to exploit uncertainty—in current measurements and about the precise details of what is going to happen—while ignoring the overwhelming consensus that human activity is responsible for a large part of global warming. You've probably figured out their argument by now. *If scientists are unsure about the extent of global warming and about how much of it is due to natural causes as opposed to human causes, and if a few reputable scientists have doubts about the conventional view, it may well be that the very idea that human activity causes global warming is wrong.* Needless to say, scientific uncertainty about the precise level of the human contribution to global warming does not translate into uncertainty about the larger picture.

SCIENCE AND PSEUDOSCIENCE

Our discussion of fallacious applications of scientific method provides a first clue as to how to distinguish genuine from pseudoscience. Genuine science involves the rigorous testing of new ideas; as such, the results of a genuine scientific investigation will reflect the methods introduced in Chapter 2 through Chapter 5. Pseudoscientific ideas will frequently be supported by arguments and evidence that depend on one or more of the fallacies discussed in this chapter. Though adherence to the methods of science is at the heart of the distinction between genuine and pseudoscience, there are a number of other important differences between the two, as well as a number of mistaken ideas about what the distinction involves.

Science cannot be distinguished from pseudoscience simply on the basis of the results each produces. In science, at any rate, ideas earn their respectability not because they are right but because they are developed and tested in the right sort of way. At one point in the history of Western thought, the best-informed scientific view was that the earth is at the center of the universe. Though this view was ultimately shown to be wrong, it nonetheless constituted the best science of the time. Though Ptolemy and his followers were mistaken, their view of the cosmos provided a coherent, testable explanation for a wide variety of phenomena. Our discussion earlier in this chapter of phlogiston theory and the luminiferous ether provides striking examples of genuine—though ultimately mistaken—science.

Though much of pseudoscience is simply false or incoherent, it is possible that some claim will turn out to be of scientific value even though the evidence for it now appears to be entirely pseudoscientific. Acupuncture theory claims that the human body is covered with channels of energy, called *chi*, that intersect at numerous "meridians." Today there is no scientific evidence for the existence of chi. Its existence is confirmed only by a multitude of anecdotal evidence in the form of satisfied customers. But even if it turns out that something in acupuncture theory is right or even on the right track, the theory will remain an artifact of pseudoscientific thinking until it can be confirmed, modified, or rejected on the basis of controlled experimentation.

The distinction between science and pseudoscience cannot be drawn along lines of scientific discipline. We cannot say, for example, that astronomy is a science while astrology is not, that psychology is, but parapsychology isn't. This is not to say that astronomy or psychology does not deserve to be called a science. But the notion of a science, or scientific discipline, is much too broad for our purposes. My dictionary defines astronomy as "the science which treats of the heavenly bodies—stars, planets, satellites, and comets," and I suppose this is as good a definition as any. But within this broad discipline we sometimes encounter instances of pseudoscience as well as of genuine science.

For example, in the 1950s a self-proclaimed astronomer and archaeologist, Immanuel Velikovsky, hypothesized that the planet Venus was created out of an enormous volcanic eruption on Jupiter. Velikovsky speculated that as the newly formed planet hurtled toward the sun, it passed by Earth, causing several cataclysmic events, and eventually settled down to become the second planet in

our solar system. Yet careful examination of Velikovsky's work has shown that this sort of cosmic ping-pong is quite impossible, and that Velikovsky either ignored or was unaware of certain physical constraints which his hypothesis violated. One of Velikovsky's most glaring mistakes involves a well-known law of motion: if one body exerts a force on a second body, then the second exerts a force that is equal in strength and opposite in direction. An explosion of sufficient magnitude to allow an object the size of Venus to overcome the gravitational attraction of Jupiter would simultaneously send Jupiter off in the opposite direction, despite Jupiter's great mass. Yet in Velikovsky's theory, the orbit of Jupiter remains unaffected by this most cataclysmic of events. Here, then, we have an example of pseudoscience, yet one which we can certainly classify under the broad heading of astronomy.

Similarly, early in the 20th century, the British psychologist, Sir Cyril Burt, claimed to have decisive evidence that heredity, not environment, plays the dominant role in determining intelligence. As it turned out, much of Burt's work was based on fictional or distorted data. Burt invented experimental subjects and altered test results to conform to his expectations, in the process of trying to make his findings appear to be scientific.

Disciplines we might tentatively classify as pseudoscientific can be subject to legitimate scientific investigation. Many of the extraordinary claims discussed in Chapters 2 and 4 come from disciplines such as astrology, special creationism, and parapsychology, disciplines generally not regarded as legitimate sciences. Nonetheless, such claims can be tested in rigorous scientific ways.

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The distinction between science and pseudoscience has nothing to do with the distinction between "hard" and "soft" sciences. The sciences that study human behavior—sociology, anthropology, psychology, political science, to name a few—are sometimes characterized as "soft" as opposed to the "hard" physical and biological sciences. Though in a number of respects the soft and hard sciences differ, none of the differences is sufficient to support the complaint, occasionally leveled against the soft disciplines, that they are pseudosciences. The hard sciences do not have to deal with the complexities posed by the human ability to choose what to do in their attempts at describing and understanding nature. It is sometimes said that only the hard sciences are "exact" and this is generally taken to mean that predictions about human behavior cannot hope to be as precise as, say, predictions about what will happen to a gas under a specific set of conditions. Moreover, it is difficult to think of a single "soft" scientific theory that is as broad in scope as the theories of modern physics and chemistry. The law of gravity describes the behavior of all gravitating objects; it is hard to imagine a similar law describing a single aspect of the behavior of people, societies, and economic or political institutions.

Yet despite their obvious differences, the hard and soft sciences are all properly sciences. All aim at explaining phenomena of the natural world, be it the behavior of matter, plants, or animals (including humans). And both hard and soft sciences adhere to the methods we have discussed in Chapters 2 through 5 in advancing and testing their "hows" and "whys." Many philosophers argue that the social sciences will never produce the kinds of grand, unifying theories

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characteristic of the physical and biological sciences; it may be that the "soft" sciences will have to be satisfied with discrete bits of explanatory material, each of which is suited to a limited aspect of human behavior. But insofar as research in the social and behavioral sciences conforms to the more general methods of good scientific research, we have no reason to doubt their qualifications as disciplines capable of delivering genuine scientific insight.

Genuine science tends to be self-correcting; pseudoscience is not. We have examined a number of instances in which the results of scientific inquiry have been overturned. Yet in most cases, mistaken ideas have been rejected on the basis of further scientific inquiry. It is estimated that there are currently about 40,000 active scientific journals worldwide. These journals contain detailed synopses of research projects, generally written up by those who have done the research. An article reporting on new research will contain a description of the design and results of the experiment, discussion of the significance of the results and suggestions for future research. Most journals are peer reviewed: submitted articles will be reviewed by other scientists who will check to make sure the article is accurate and complete. The referees will finally decide whether the research described in the article is sufficiently interesting and important to merit publication. It is not unusual for a submitted manuscript to be returned to its author or authors for substantial revision. Thus the process by which journals decide what to accept and what reject serves to correct numerous potential errors.

This process is far from perfect. Given the sheer number of journals and articles, mistakes are bound to go unnoticed, some of them pretty spectacular. In the past few years, several instances have surfaced of published research that has involved fabricated data. Fortunately such incidents are fairly rare.[9] The fact that they have been discovered is itself a testimony to the self-correcting tendency of the process by which research is made public. When fraudulent research is detected, it is usually by other scientists, peers who have taken the time to look carefully at the published results.

Scientific journals serve another function as well. They provide a forum for critics of current research. Often journals will publish articles aimed at mounting objections to and uncovering flaws in previously reported research. Since the early 1980s, for example, an enormous amount of research has been directed at understanding AIDS and its cause or causes. The vast majority of AIDS research points to a retrovirus—Human Immunodeficiency Virus (HIV)—as the cause of AIDS. This contention has emerged from thousands of experiments and clinical trials—both on animals and humans—undertaken by medical doctors, biologists, geneticists, and specialists in other related disciplines. Yet a handful of AIDS researchers, notably, Peter Duesberg, a professor of molecular and cell biology, and Robert Root-Bernstein, a professor of physiology, have mounted serious objections to the mainstream view. Duesberg argues that a careful analysis of the evidence strongly suggests that AIDS is not caused by HIV; Root-Bernstein believes that HIV is but one of several cofactors that must be present for AIDS to develop. Both have suggested that much of the research into AIDS and its causes undertaken in the last 25 years has been largely misdirected. As you might suspect, the work of Duesberg and Root-Bernstein has met with a great deal of

resistance from the vast majority of AIDS researchers. In the last few years many articles have appeared in the scientific literature that are highly critical both of the methodology and the findings of Duesberg and Root-Bernstein.[10]

This episode illustrates several of the reasons why science stands a good chance of correcting its own mistakes. Note first that the research criticized by Duesberg and Root-Bernstein was readily available in the form of published articles in scientific journals. Second, Duesberg and Root-Bernstein are themselves credentialed, mainstream researchers. Third, the critiques produced by Duesberg and Root-Bernstein were taken sufficiently seriously to be published in reputable scientific journals. Duesberg's work has appeared, for example in both *Science* and *Nature*, two of the most visible and highly respected scientific journals. Finally, their criticisms were not simply dismissed out of hand, on the grounds that they were out of step with mainstream views. Other scientists have taken them sufficiently seriously to devote considerable time and space to rebuttals; again, in the forum provided by scientific publications.

Interestingly enough, most critical discussion of controversial pseudoscientific ideas comes from mainstream science as well. In recent years, for example, a new version of special creationism has emerged, calling itself "intelligent design" theory. The central ideal of this theory is that many biological entities are "irreducibly complex." What this means is that such entities could not have evolved by random mutation and natural selection. Rather, their existence must be the product of intervention by some intelligent entity. From here it is but a short step to the postulation of a supernatural intelligent designer. The notion that some natural systems are irreducibly complex has come under heavy attack; its central examples have been pretty much discredited. But discussion of difficulties facing its central idea has not come from within the intelligent design community. It has come, instead, in the writings of mainstream biologists, paleontologists, geneticists, and philosophers of science. Intelligent design theory, it would seem, is not self-correcting in the way crucial to the development of ideas in science.[11]

As a scientific discipline develops, it will gradually produce a maturing body of explanatory or theoretical findings; pseudoscience produces very little theory. One major aim of science, as we discussed in Chapter 1, is to "make sense" of nature by providing better and better and, often, more and more encompassing bodies of explanatory material. Think, for example, of all that is known about the mechanisms involved in the transmission of genetic information from one generation to the next, in contrast with what was known 150 years ago at the time of the birth of the science of genetics. Gregor Mendel, the founder of genetic research, introduced the somewhat vague and mysterious notion of a "genetic factor" in his attempts to explain the observable characteristics of some simple varieties of plants. Today, modern geneticists can provide us with the details of the explanation Mendel could only hint at, how those characteristics are encoded in DNA (a notion wholly unknown to Mendel).

By contrast, pseudoscientific research almost always produces spectacular claims for extraordinary abilities and events, but little else. Ideas tend not to develop and mature over time as they do in genuine science. As it turns out, ESP research began only a little later than did genetic research. Yet today we find

little more than an enormous body of controversial evidence that a few people have psychic ability and almost no theoretical understanding of how ESP might work. What little explanatory material emerges in many pseudoscientific endeavors is likely to be based on vague analogies and similarities drawn from some well-understood area of science. So, for example, a book on ESP published in the 1930s was entitled, *ESP: Mental Radio*; an interesting idea, but hardly a reliable explanation. Today's ESP theorists exploit analogies with computers and quantum mechanical effects rather than the radio. Though the analogies are more up to date, little progress has been made at producing anything like a coherent theory for ESP.

The findings, theoretical and otherwise, of genuine science are always open to revision; rarely do pseudoscientific claims change much over time. It is hard to imagine a thriving scientific discipline today wherein much of what was believed one hundred or even fifty years ago has not been supplanted by a more accurate picture of things. Fifty years ago, particle physics provided us with a picture of the world in which the most fundamental particles were the electron, the proton, and the neutron. A few stray experimental results were in conflict with this picture, but few physicists questioned its rough fit with reality. Today physics provides a more comprehensive picture in which protons and neutrons are composites built out of more fundamental particles, quarks. The landscape of particle physics has changed dramatically in a brief period of time. The openness of science to revision does not mean that scientific results cannot achieve a kind of permanence. Many of the findings of science will doubtless not be repudiated by new research. Science will not discover that water molecules are composed of something other than two atoms of hydrogen and one of oxygen; no one doubts that Newton was correct in seeing that gravitational attraction is directly proportional to mass and inversely proportional to distance. The changes we can anticipate in well-established areas of science will generally occur at the level of underlying explanation. Why do gravitating objects behave in the way Newton discovered? What is the internal structure of "stuff" of water? And just how—if at all—are the forces at work inside the atom connected to the force responsible for gravity?

By contrast, it is interesting to look at the work of modern astrologers. If you were to have a competent astrologer draw a detailed horoscope, his or her work would be based on classic astrological texts, written over two thousand years ago. Pseudoscientists often claim the long history of their ideas to be evidence for their correctness. Thus, an astrologer might boast that his or her techniques are derived from the discoveries of ancient Babylonian and Egyptian astronomers. In and of itself, this is not reason to classify astrology as a pseudoscience. But at the level of underlying explanation, astrology remains today in much the position it was at its inception. After more than two thousand years, astrologers have conspicuously failed to produce even the beginnings of a plausible explanation for its purported effects. Conspicuously missing in the history of astrological research is any evidence of the kind of proposing, testing, modifying, and revising of new ideas that typifies scientific progress.

Genuine science embraces skepticism; pseudoscience tends to view skepticism as a sign of narrow-mindedness. The first reaction of a competent scientist, when faced with

something new and unusual, is to try to explain the phenomenon away by fitting it into what is already known. Many people who engage in pseudoscience see this as the worst sort of skepticism; the fact that one's initial reaction is to try to rob something of its mystery is taken to be a sign that one is unwilling to entertain new ideas. It is perhaps this attitude toward scientific skepticism more than anything else that contributes to the tendency in pseudoscience to accept claims in the absence of solid scientific evidence.

The question of whether a piece of "scientific" research is genuine or bogus is not always easy to answer. Though the contrasts we have drawn can provide some initial sense of the presence of pseudoscience, we should not wield them dogmatically. If someone purports to have "scientific evidence" for something, we should not dismiss their work simply because, for example, they refuse to countenance serious criticism, complain that their critics lack an open mind, or proclaim the longevity of their ideas. Rather, such moves should only be taken as a sign that something may well be seriously amiss. The fundamental difference between genuine science and bogus science is really a difference in method. The results of genuine scientific inquiry are the product of open and honest applications of the methods we have discussed in previous chapters. Pseudoscientific results, by contrast, are produced with little regard for these methods.

A person claims to have "scientific evidence" for X. Are we confronted with genuine science or pseudoscience? To answer this question there is no substitute for taking a careful, critical look at the methods employed in establishing X.

CONCEPT QUIZ

The following questions will test your understanding of the basic ideas introduced in this chapter. Your answers can serve as a brief summary of the chapter.

1. Give a brief description of each of the fallacies listed below and make up an example of each.
   a. False anomalies
   b. Questionable arguments by elimination
   c. Illicit causal inference
   d. Unsupported analogies and similarities
   e. Untestable explanations and predictions
   f. Empty jargon
   g. Ad hoc rescue
   h. Exploiting uncertainty
2. What are the six basic ways in which pseudoscience differs from genuine science?

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The Reader's Presence

1. Gordon contrasts immigrant and mainstream American experiences, although nearly all present-day Americans have immigrant ancestry. How does she define *immigrant*? What imagery does she attach to the immigrant experience? How is this imagery made vivid for the reader? How do you think Gordon would wish a reader like herself to experience the essay? How do you think she would wish a mainstream American to experience the essay?
2. Gordon reveals little-known facts about the Statue of Liberty and Ellis Island. What symbolic meaning do these facts convey in terms of America's reception of immigrants? Ellis Island has since been refashioned into an impressive museum celebrating the history of immigrants in America. Does this development undercut or reinforce Gordon's opposition of official and hidden history?
3. Gordon's description of immigrants' contributions to American culture recalls Ralph Ellison's essay "What America Would Be Like without Blacks" (page 390). What sorts of contributions does Gordon credit immigrants with? In what ways are the two writers' visions of America as a "melting pot" similar? How do they differ?

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Gould, Stephen Jay. "Sex, Drugs, Disasters, and the Extinction of Dinosaurs." *In The Flamingo's Smile: Reflections in Natural History*, 448-455. New York: W. W. Norton, 1984.

Stephen Jay Gould

Sex, Drugs, Disasters, and the Extinction of Dinosaurs

Stephen Jay Gould (1941–2002) was professor of geology and zoology at Harvard and curator of invertebrate paleontology at Harvard's Museum of Comparative Zoology. He published widely on evolution and other topics and earned a reputation for making technical subjects readily comprehensible to lay readers without trivializing the material. His The Panda's Thumb *(1980) won the American Book Award, and* The Mismeasure of Man *(1981) won the National Book Critics Circle Award. Gould published more than one hundred articles in scientific journals, and he contributed to national magazines as well. "Sex, Drugs, Disasters, and the Extinction of Dinosaurs" appeared in* Discover *magazine in 1984. More recently, Gould wrote* Questioning the Millennium: A Rationalist's Guide to a Precisely Arbitrary Countdown *(1997),* Leonardo's Mountain of Clams and the Diet of Worms: Essays on Natural History *(1998),* Rocks of Ages: Science & Religion in the Fullness of Life *(1999),* The Lying Stones of Marrakesh *(2001), and* The Structure of Evolutionary Theory *(2001). Among many other honors and awards, he was a fellow of the National Science Foundation and the MacArthur Foundation. In 1999 Gould became president of the American Association for the Advancement of Science. John Updike comments that "Gould, in his scrupulous explication of [other scientists'] carefully wrought half-truths, abolishes the unnecessary distinction between the humanities and science, and honors the latter as a branch of humanistic thought, fallible and poetic."*

When asked if he found it difficult to write about complex scientific concepts in language that is accessible to general readers, Gould replied, "I don't see why it should be that difficult. . . . Every field has its jargon. I think scientists hide behind theirs perhaps more than people in other professions do—it's part of our mythology—but I don't think the concepts of science are intrinsically more difficult than the professional notions in any other field."

Science, in its most fundamental definition, is a fruitful mode of inquiry, not a list of enticing conclusions. The conclusions are the consequence, not the essence.

My greatest unhappiness with most popular presentations of science concerns their failure to separate fascinating claims from the methods that scientists use to establish the facts of nature. Journalists, and the public, thrive on controversial and stunning statements. But science is, basically, a way of knowing—in P. B. Medawar's apt words, "the art of the soluble." If the growing corps of popular science writers would focus on *how* scientists develop and defend those fascinating claims, they would make their greatest possible contribution to public understanding.

Consider three ideas, proposed in perfect seriousness to explain that greatest of all titillating puzzles—the extinction of dinosaurs. Since these three notions invoke the primally fascinating themes of our culture—sex, drugs, and violence—they surely reside in the category of fascinating claims. I want to show why two of them rank as silly speculation, while the other represents science at its grandest and most useful.

Science works with the testable proposals. If, after much compilation and scrutiny of data, new information continues to affirm a hypothesis, we may accept it provisionally and gain confidence as further evidence mounts. We can never be completely sure that a hypothesis is right, though we may be able to show with confidence that it is wrong. The best scientific hypotheses are also generous and expansive: They suggest extensions and implications that enlighten related, and even far distant, subjects. Simply consider how the idea of evolution has influenced virtually every intellectual field.

Useless speculation, on the other hand, is restrictive. It generates no testable hypothesis, and offers no way to obtain potentially refuting evidence. Please note that I am not speaking of truth or falsity. The speculation may well be true; still, if it provides, in principle, no material for

affirmation or rejection, we can make nothing of it. It must simply stand forever as an intriguing idea. Useless speculation turns in on itself and leads nowhere; good science, containing both seeds for its potential refutation and implications for more and different testable knowledge, reaches out. But, enough preaching. Let's move on to dinosaurs, and the three proposals for their extinction.

1. *Sex:* Testes function only in a narrow range of temperature (those of mammals hang externally in a scrotal sac because internal body temperatures are too high for their proper function). A worldwide rise in temperature at the close of the Cretaceous period caused the testes of dinosaurs to stop functioning and led to their extinction by sterilization of males.
2. *Drugs:* Angiosperms (flowering plants) first evolved toward the end of the dinosaurs' reign. Many of these plants contain psychoactive agents, avoided by mammals today as a result of their bitter taste. Dinosaurs had neither means to taste the bitterness nor livers effective enough to detoxify the substances. They died of massive overdoses.
3. *Disasters:* A large comet or asteroid struck the earth some 65 million years ago, lofting a cloud of dust into the sky and blocking sunlight, thereby suppressing photosynthesis and so drastically lowering world temperatures that dinosaurs and hosts of other creatures became extinct.

Before analyzing these three tantalizing statements, we must establish a basic ground rule often violated in proposals for the dinosaurs' demise. *There is no separate problem of the extinction of dinosaurs.* Too often we divorce specific events from their wider contexts and systems of cause and effect. The fundamental fact of dinosaur extinction is its synchrony with the demise of so many other groups across a wide range of habitats, from terrestrial to marine.

The history of life has been punctuated by brief episodes of mass extinction. A recent analysis by University of Chicago paleontologists Jack Sepkoski and Dave Raup, based on the best and most exhaustive tabulation of data ever assembled, shows clearly that five episodes of mass dying stand well above the "background" extinctions of normal times (when we consider all mass extinctions, large and small, they seem to fall in a regular 26-million-year cycle). The Cretaceous debacle, occurring 65 million years ago and separating the Mesozoic and Cenozoic eras of our geological time scale, ranks prominently among the five. Nearly all the marine plankton (single-celled floating creatures) died with geological suddenness; among marine invertebrates, nearly 15 percent of all families perished, including many previously dominant groups, especially the ammonites (relatives of squids in coiled shells). On land, the dinosaurs disappeared after more than 100 million years of unchallenged domination.

In this context, speculations limited to dinosaurs alone ignore the larger phenomenon. We need a coordinated explanation for a system of events that includes the extinction of dinosaurs as one component. Thus it makes little sense, though it may fuel our desire to view mammals as inevitable inheritors of the earth, to guess that dinosaurs died because small mammals ate their eggs (a perennial favorite among untestable speculations). It seems most unlikely that some disaster peculiar to dinosaurs befell these massive beasts—and that the debacle happened to strike just when one of history's five great dyings had enveloped the earth for completely different reasons.

The testicular theory, an old favorite from the 1940s, had its root in an interesting and thoroughly respectable study of temperature tolerances in the American alligator, published in the staid *Bulletin of the American Museum of Natural History* in 1946 by three experts on living and fossil reptiles—E. H. Colbert, my own first teacher in paleontology; R. B. Cowles; and C. M. Bogert.

The first sentence of their summary reveals a purpose beyond alligators: "This report describes an attempt to infer the reactions of extinct reptiles, especially the dinosaurs, to high temperatures as based upon reactions observed in the modern alligator." They studied, by rectal thermometry, the body temperatures of alligators under changing conditions of heating and cooling. (Well, let's face it, you wouldn't want to try sticking a thermometer under a 'gator's tongue.) The predictions under test go way back to an old theory first stated by Galileo in the 1630s—the unequal scaling of surfaces and volumes. As an animal, or an object, grows (provided its shape doesn't change), surface areas must increase more slowly than volumes—since surfaces get larger as length squared, while volumes increase much more rapidly, as length cubed. Therefore, small animals have high ratios of surface to volume, while large animals cover themselves with relatively little surface.

Among cold-blooded animals lacking any physiological mechanism for keeping their temperatures constant, small creatures have a hell of a time keeping warm—because they lose so much heat through their relatively large surfaces. On the other hand, large animals, with their relatively small surfaces, may lose heat so slowly that, once warm, they may maintain effectively constant temperatures against ordinary fluctuations of climate. (In fact, the resolution of the "hot-blooded dinosaur" controversy that burned so brightly a few years back may simply be that, while large dinosaurs possessed no physiological mechanism for constant temperature, and were not therefore warm-blooded in the technical sense, their large size and relatively small surface area kept them warm.)

Colbert, Cowles, and Bogert compared the warming rates of small and large alligators. As predicted, the small fellows heated up (and cooled down) more quickly. When exposed to a warm sun, a tiny 50-gram (1.76-ounce) alligator heated up one degree Celsius every minute and a half, while a large alligator, 260 times bigger at 13,000 grams (28.7 pounds), took seven and a half minutes to gain a degree. Extrapolating up to an adult 10-ton dinosaur,

they concluded that a one-degree rise in body temperature would take eighty-six hours. If large animals absorb heat so slowly (through their relatively small surfaces), they will also be unable to shed any excess heat gained when temperatures rise above a favorable level.

The authors then guessed that large dinosaurs lived at or near their optimum temperatures; Cowles suggested that a rise in global temperatures just before the Cretaceous extinction caused the dinosaurs to heat up beyond their optimal tolerance—and, being so large, they couldn't shed the unwanted heat. (In a most unusual statement within a scientific paper, Colbert and Bogert then explicitly disavowed this speculative extension of their empirical work on alligators.) Cowles conceded that this excess heat probably wasn't enough to kill or even to enervate the great beasts, but since testes often function only within a narrow range of temperature, he proposed that this global rise might have sterilized all the males, causing extinction by natural contraception.

The overdose theory has recently been supported by UCLA psychiatrist Ronald K. Siegel. Siegel has gathered, he claims, more than 2,000 records of animals who, when given access, administer various drugs to themselves—from a mere swig of alcohol to massive doses of the big H. Elephants will swill the equivalent of twenty beers at a time, but do not like alcohol in concentrations greater than 7 percent. In a silly bit of anthropocentric speculation, Siegel states that "elephants drink, perhaps, to forget . . . the anxiety produced by shrinking rangeland and the competition for food."

Since fertile imaginations can apply almost any hot idea to the extinction of dinosaurs, Siegel found a way. Flowering plants did not evolve until late in the dinosaurs' reign. These plants also produced an array of aromatic, amino-acid-based alkaloids—the major group of psychoactive agents. Most mammals are "smart" enough to avoid these potential poisons. The alkaloids simply don't taste good (they are bitter); in any case, we mammals have livers happily supplied with the capacity to detoxify them. But, Siegel speculates, perhaps dinosaurs could neither taste the bitterness nor detoxify the substances once ingested. He recently told members of the American Psychological Association: "I'm not suggesting that all dinosaurs OD'd on plant drugs, but it certainly was a factor." He also argued that death by overdose may help explain why so many dinosaur fossils are found in contorted positions. (Do not go gentle into that good night.)

Extraterrestrial catastrophes have long pedigrees in the popular literature of extinction, but the subject exploded again in 1979, after a long lull, when the father-son, physicist-geologist team of Luis and Walter Alvarez proposed that an asteroid, some 10 km in diameter, struck the earth 65 million years ago (comets, rather than asteroids, have since gained favor. Good science is self-corrective).

The force of such a collision would be immense, greater by far than the megatonnage of all the world's nuclear weapons. In trying to reconstruct a scenario that would explain the simultaneous dying of dinosaurs on land

and so many creatures in the sea, the Alvarezes proposed that a gigantic dust cloud, generated by particles blown aloft in the impact, would so darken the earth that photosynthesis would cease and temperatures drop precipitously. (Rage, rage against the dying of the light.) The single-celled photosynthetic oceanic plankton, with life cycles measured in weeks, would perish outright, but land plants might survive through the dormancy of their seeds (land plants were not much affected by the Cretaceous extinction, and any adequate theory must account for the curious pattern of differential survival). Dinosaurs would die by starvation and freezing; small, warm-blooded mammals, with more modest requirements for food and better regulation of body temperature, would squeak through. "Let the bastards freeze in the dark," as bumper stickers of our chauvinistic neighbors in sunbelt states proclaimed several years ago during the Northeast's winter oil crisis.

All three theories, testicular malfunction, psychoactive overdosing, and asteroidal zapping, grab our attention mightily. As pure phenomenology, they rank about equally high on any hit parade of primal fascination. Yet one represents expansive science, the others restrictive and untestable speculation. The proper criterion lies in evidence and methodology; we must probe behind the superficial fascination of particular claims.

How could we possibly decide whether the hypothesis of testicular frying is right or wrong? We would have to know things that the fossil record cannot provide. What temperatures were optimal for dinosaurs? Could they avoid the absorption of excess heat by staying in the shade, or in caves? At what temperatures did their testicles cease to function? Were late Cretaceous climates ever warm enough to drive the internal temperatures of dinosaurs close to this ceiling? Testicles simply don't fossilize, and how could we infer their temperature tolerances even if they did? In short, Cowles's hypothesis is only an intriguing speculation leading nowhere. The most damning statement against it appeared right in the conclusion of Colbert, Cowles, and Bogert's paper, when they admitted: "It is difficult to advance any definite arguments against the hypothesis." My statement may seem paradoxical—isn't a hypothesis really good if you can't devise any arguments against it? Quite the contrary. It is simply untestable and unusable.

Siegel's overdosing has even less going for it. At least Cowles extrapolated his conclusion from some good data on alligators. And he didn't completely violate the primary guideline of siting dinosaur extinction in the context of a general mass dying—for rise in temperature could be the root cause of a general catastrophe, zapping dinosaurs by testicular malfunction and different groups for other reasons. But Siegel's speculation cannot touch the extinction of ammonites or oceanic plankton (diatoms make their own food with good sweet sunlight; they don't OD on the chemicals of terrestrial plants). It is simply a gratuitous, attention-grabbing guess. It cannot be tested, for how can we know what dinosaurs tasted and what their livers could do? Livers don't fossilize any better than testicles.

The hypothesis doesn't even make any sense in its own context. Angiosperms were in full flower ten million years before dinosaurs went the

way of all flesh. Why did it take so long? As for the pains of a chemical death recorded in contortions of fossils, I regret to say (or rather I'm pleased to note for the dinosaurs' sake) that Siegel's knowledge of geology must be a bit deficient: muscles contract after death and geological strata rise and fall with motions of the earth's crust after burial—more than enough reason to distort a fossil's pristine appearance.

The impact story, on the other hand, has a sound basis in evidence. It can be tested, extended, refined, and, if wrong, disproved. The Alvarezes did not just construct an arresting guess for public consumption. They proposed their hypothesis after laborious geochemical studies with Frank Asaro and Helen Michael had revealed a massive increase of iridium in rocks deposited right at the time of extinction. Iridium, a rare metal of the platinum group, is virtually absent from indigenous rocks of the earth's crust; most of our iridium arrives on extraterrestrial objects that strike the earth.

The Alverez hypothesis bore immediate fruit. Based originally on evidence from two European localities, it led geochemists throughout the world to examine other sediments of the same age. They found abnormally high amounts of iridium everywhere—from continental rocks of the western United States to deep sea cores from the South Atlantic.

Cowles proposed his testicular hypothesis in the mid-1940s. Where has it gone since then? Absolutely nowhere, because scientists can do nothing with it. The hypothesis must stand as a curious appendage to a solid study of alligators. Siegel's overdose scenario will also win a few press notices and fade into oblivion. The Alvarezes' asteroid falls into a different category altogether, and much of the popular commentary has missed this essential distinction by focusing on the impact and its attendant results, and forgetting what really matters to a scientist—the iridium. If you talk just about asteroids, dust, and darkness, you tell stories no better and no more entertaining than fried testicles or terminal trips. It is the iridium—the source of testable evidence—that counts and forges the crucial distinction between speculation and science.

The proof, to twist a phrase, lies in the doing. Cowles's hypothesis has generated nothing in thirty-five years. Since its proposal in 1979, the Alvarez hypothesis has spawned hundreds of studies, a major conference, and attendant publications. Geologists are fired up. They are looking for iridium at all other extinction boundaries. Every week exposes a new wrinkle in the scientific press. Further evidence that the Cretaceous iridium represents extraterrestrial impact and not indigenous volcanism continues to accumulate. As I revise this essay in November 1984 (this paragraph will be out of date when the book is published),[1] new data include chemical "signatures" of other isotopes indicating unearthly provenance, glass spherules of a size and sort produced by impact and not by volcanic eruptions, and high-pressure varieties of silica formed (so far as we know) only under the tremendous shock of impact.

[1]*The Flamingo's Smile* (1985), in which Gould collected this essay.—Eds.

My point is simply this: Whatever the eventual outcome (I suspect it will be positive), the Alvarez hypothesis is exciting, fruitful science because it generates tests, provides us with things to do, and expands outward. We are having fun, battling back and forth, moving toward a resolution, and extending the hypothesis beyond its original scope.

As just one example of the unexpected, distant cross-fertilization that good science engenders, the Alvarez hypothesis made a major contribution to a theme that has riveted public attention in the past few months—so-called nuclear winter. In a speech delivered in April 1982, Luis Alvarez calculated the energy that a ten-kilometer asteroid would release on impact. He compared such an explosion with a full nuclear exchange and implied that all-out atomic war might unleash similar consequences.

This theme of impact leading to massive dust clouds and falling temperatures formed an important input to the decision of Carl Sagan and a group of colleagues to model the climatic consequences of nuclear holocaust. Full nuclear exchange would probably generate the same kind of dust cloud and darkening that may have wiped out the dinosaurs. Temperatures would drop precipitously and agriculture might become impossible. Avoidance of nuclear war is fundamentally an ethical and political imperative, but we must know the factual consequences to make firm judgments. I am heartened by a final link across disciplines and deep concerns—another criterion, by the way, of science at its best.[2] A recognition of the very phenomenon that made our evolution possible by exterminating the previously dominant dinosaurs and clearing a way for the evolution of large mammals, including us, might actually help to save us from joining those magnificent beasts in contorted poses among the strata of the earth.

The Reader's Presence

1. Although the title of Gould's essay focuses on the extinction of dinosaurs, his overriding interest is in demonstrating the way science works, and his purpose is to make that process fully accessible and understandable to the general public. Where does he lay out this central claim, and how does he demonstrate, clarify, and complicate it as his essay proceeds?
2. Reread Gould's essay, with special attention to his use of tone, diction, syntax, and metaphor. How does he use these compositional strategies to make information accessible to his readers? Point to passages where Gould uses the diction and syntax of a serious scientist. When—and with what effects—does his prose sound

[2]This quirky connection so tickles my fancy that I break my own strict rule about eliminating redundancies from [this essay]. . . .

The Validation of Continental Drift - Stephen Gould

As the new Darwinian orthodox' swept through Europe, its most brilliant opponent, the aging embryologist Karl Ernst von Baer, remarked with bitter irony that every triumphant theory passes through three stages: first it is dismissed as untrue; then it is rejected as contrary to religion; finally, it is accepted as dogma and each scientist claims that he had long appreciated its truth.

I first met the theory of continental drift when it labored under the inquisition of stage two. Kenneth Caster, the only major American paleontologist who dared to support it openly, came to lecture at my alma mater, Antioch College. We were scarcely known as a bastion of entrenched conservatism, but most of us dismissed his thoughts as just this side of sane. (Since I am now in von Baer's third stage, I have the distinct memory that Caster sowed substantial seeds of doubt in my own mind.) A few years later, as a graduate student at Columbia University, I remember the a priori derision of my distinguished stratigraphy professor toward a visiting Australian drifter. He nearly orchestrated the chorus of Bronx cheers from a sycophantic crowd of loyal students. (Again, from my vantage point in the third stage, I recall this episode as amusing, but distasteful.) As a tribute to my professor, I must record that he experienced a rapid conversion just two years later and spent his remaining years joyously redoing his life's work.

Today, just ten years later, my own students would dismiss with even more derision anyone who denied the evident truth of continental drift-a prophetic madman is at least amusing; superannuated fuddy-duddy is merely pitiful. Why has such profound change occurred in the short space of a decade?

Most scientists maintain-or at least argue for public consumption-that their profession marches toward truth by accumulating more and more data, under the guidance of an infallible procedure called "the scientific method." If this were true, my question would have an easy answer. The facts, as known ten years ago, spoke against continental drift; since then, we have learned more and revised our opinions accordingly. I will argue, however, that this scenario is both inapplicable in general and utterly inaccurate in this case.

During the period of nearly universal rejection, direct evidence for continental drift-that is, the data gathered from rocks exposed on our continents-was every bit as good as it is today. It was dismissed because no one had devised a physical mechanism that would permit continents to plow through an apparently solid oceanic floor. In the absence of a plausible mechanism, the idea of continental drift

was rejected as absurd. The data that seemed to support it could always be explained away. If these explanations sounded contrived or forced, they were not half so improbable as the alternative-accepting continental drift. During the past ten years, we have collected a new set of data, this time from the ocean basins. With these data, a heavy dose of creative imagination, and a better understanding of the earth's interior, we have fashioned a new theory of planetary dynamics. Under this theory of plate tectonics, continental drift is an inescapable consequence. The old data from continental rocks, once soundly rejected, have been exhumed and exalted as conclusive proof of drift. In short, we now accept continental drift because it is the expectation of a new orthodoxy.

I regard this tale as typical of scientific progress. New facts, collected in old ways under the guidance of old theories, rarely lead to any substantial revision of thought. Facts do not "speak for themselves"; they are read in the light of theory. Creative thought, in science as much as in the arts, is the motor of changing opinion. Science is a quintessentially human activity, not a mechanized, robotlike accumulation of objective information, leading by laws of logic to inescapable interpretation. I will try to illustrate this thesis with two examples drawn from the "classical" data for continental drift. Both are old tales that had to be undermined while drift remained unpopular.

I. The late Paleozoic glaciation. About 240 million years ago, glaciers covered parts of what is now South America, Antarctica, India, Africa, and Australia. If continents are stable, this distribution presents some apparently insuperable difficulties:

A. The orientation of striae in eastern South America indicates that glaciers moved onto the continent from what is now the Atlantic Ocean (striae are scratches on bedrock made by rocks frozen into glacier bottoms as they pass over a surface). The world's oceans form a single system, and transport of heat from tropical areas guarantees that no major part of the open ocean can freeze.
B. African glaciers covered what are now tropical areas.
C. Indian glaciers must have grown in semitropical regions of the Northern hemisphere; moreover, their striae indicate a source in tropical waters of the Indian Ocean.
D. There were no glaciers on any of the northern continents. If the earth got cold enough to freeze tropical Africa, why were there no glaciers in northern Canada or Siberia?

All these difficulties evaporate if the southern continents (including India) were joined together during this glacial period, and located farther south, covering the South Pole; the South American glaciers moved from Africa, not an open ocean; "tropical" Africa and "semitropical" India were near the South Pole; the North Pole lay in the middle of a major ocean, and glaciers could not develop in the Northern Hemisphere. Sounds good for drift; indeed, no one doubts it today.

II. The distribution of Cambrian trilobites -(fossil arthropods living 500 to 600 million years ago). The Cambrian trilobites of Europe and North America divided themselves into two rather different faunas with the following peculiar distribution on modem maps. "Atlantic" province trilobites lived all over Europe and in a few very local areas on the far eastern border of North America--eastern (but not western) Newfoundland and southeastern Massachusetts, for example. "Pacific" province trilobites lived all over America and in a few local areas on the extreme western coast of Europe - northern Scotland and northwestern Norway, for example. It is devilishly difficult to make any sense of this distribution if the two continents always stood 3,000 miles apart.

But continental drift suggests a striking resolution. In Cambrian times, Europe and North America were separated: Atlantic trilobites lived in waters around Europe; Pacific trilobites in waters around America. The continents (now including sediments with entombed trilobites) then drifted toward each other and finally joined together. Later, they split again, but not precisely along the line of their previous junction. Scattered bits of ancient Europe, carrying Atlantic trilobites, remained at the easternmost border of North America, while a few pieces of old North America stuck to the westernmost edge of Europe.

Both examples are widely cited as "proofs" of drift today, but they were soundly rejected in previous years, not because their data were any less complete but only because no one had devised an adequate mechanism to move continents. All the original drifters imagined that continents plow their way through a static ocean floor. Alfred Wegener, the father of continental drift, argued early in our century that gravity alone could put continents in motion. Continents drift slowly westward, for example, because attractive forces of the sun and moon hold them up as the earth rotates underneath them. Physicists responded with derision and showed mathematically that gravitational forces are far too weak to power such a monumental peregrination. So Alexis du Toit, Wegener's South African champion, tried a different tack. He argued for a local, radioactive melting of oceanic floor at continental borders, permitting the continents to glide through. This ad hoc hypothesis added no increment of plausibility to Wegener's speculation. Since drift seemed absurd in the absence of a mechanism, orthodox geologists set out to render the impressive evidence for it as a series of unconnected coincidences.

In 1932, the famous American geologist Bailey Willis strove to make the evidence of glaciation compatible with static continents. He invoked the deus ex machina of "isthmian links"-narrow land bridges flung with daring abandon across 3,000 miles of ocean. He placed one between eastern Brazil and western Africa,

another from Africa all the way to India via the Malagasy Republic, and a third from Vietnam through Borneo and New Guinea to Australia. His colleague, Yale professor Charles Schuchert, added one from Australia to Antarctica and another from Antarctica to South America, thus completing the isolation of a southern ocean from the rest of the world's waters. Such an isolated ocean might freeze along its southern margin, permitting glaciers to flow across into eastern South America. Its cold waters would also nourish the glaciers of southern Africa. The Indian glaciers, located above the equator 3,000 miles north of any southern ice, demanded a separate explanation. Willis wrote: "No direct connection between the occurrences can reasonably be assumed. The case must be considered on the basis of a general cause and the local geographic and topographic conditions." Willis's inventive mind was equal to the task: he simply postulated a topography so elevated that warm, wet southern waters precipitated their product as snow. For the absence of ice in temperate and arctic zones of the Northern Hemisphere, Willis reconstructed a system of ocean currents that permitted him to postulate "a warm, subsurface current flowing northward beneath cooler surface waters and rising in the Arctic as a warm-water heating system." Schuchert was delighted with the resolution provided by isthmian links:

Grant the biogeographer Holarctis, a land bridge from northern Africa to Brazil, another from South America to Antarctis (it almost exists today), still another from this polar land to Australia and from the latter across the Arafura Sea to Borneo and Sumatra and so on to Asia, plus the accepted means of dispersal along shelf seas and by wind and water currents and migratory birds, and he has all the possibilities needed to explain the life dispersion and the land and ocean realms throughout geological time on the basis of the present arrangement of the continents.

The only common property shared by all these land bridges was their utterly hypothetical status; not an iota of direct evidence supported any one of them. Yet, lest the saga of isthmian links be read as a warped fairy tale invented by dogmatists to support an untenable orthodoxy, I point out that to Willis, Schuchert, and any right-thinking geologist of the 1930s, one thing legitimately seemed ten times as absurd as imaginary land bridges thousands of miles long-continental drift itself.

In the light of such highly fertile imaginations, the Cambrian trilobites could present no insuperable problem. The Atlantic and Pacific provinces were interpreted as different environments, rather than different places-shallow water for the Pacific, deeper for the Atlantic. With a freedom to invent nearly any hypothetical geometry for Cambrian ocean basins, geologists drew their maps and hewed to their orthodoxy.

When continental drift came into fashion during the late 1960s, the classical data from continental rocks played no role at all: drift rode in on the coattails of a new theory, supported by new types of evidence. The physical absurdities of Wegener's theory rested on his conviction that continents cut their way through the ocean floor. But how else could drift occur? The ocean floor, the crust of the earth, must be stable. After all, where could it go, if it moved in pieces, without leaving gaping holes in the earth? Nothing could be clearer. Or could it?

"Impossible" is usually defined by our theories, not given by nature. Revolutionary theories trade in the unexpected. If continents must plow through oceans, then drift will not occur; suppose, however, that continents are frozen into the oceanic crust and move passively as pieces of crust shift about. But we just stated that the crust cannot move without leaving holes. Here, we reach an impasse that must be bridged by creative imagination, not just by another field season in the folded Appalachians-we must model the earth in a fundamentally different way.

We can avoid the problem of holes with a daring postulate that seems to be valid. If two pieces of ocean floor move away from each other, they will leave no hole if material rises from the earth's interior to fill the gap. We can go further by reversing the causal implications of this statement: the rise of new material from the earth's interior may be the driving force that moves old sea floor away. But since the earth is not expanding, we must also have regions where old sea floor founders into the earth's interior, thus preserving a balance between creation and destruction.

Indeed, the earth's surface seems to be broken into fewer than ten major "plates," bounded on all sides by narrow zones of creation (oceanic ridges) and destruction (trenches). Continents are frozen into these plates, moving with them as the sea floor spreads away from zones of creation at oceanic ridges. Continental drift is no longer a proud theory in its own right; it has become a passive consequence of our new orthodoxy-plate tectonics.

We now have a new, mobilist orthodoxy, as definite and uncompromising as the staticism it replaced. In its light, the classical data for drift have been exhumed and proclaimed as proof positive. Yet these data played no role in validating the notion of wandering continents; drift triumphed only when it became the necessary consequence of a new theory.

The new orthodoxy colors our vision of all data; there are no "pure facts" in our complex world. About five years ago, paleontologists found on Antarctica a fossil reptile named Lystrosaurus. It also lived in South Africa, and probably in South America as well (rocks of the appropriate age have not been found in South America).

If anyone had floated such an argument for drift in the presence of Willis and Schuchert, he would have been howled down-and quite correctly. For Antarctica and South America are almost joined today by a string of islands, and they were certainly connected by a land bridge at various times in the past (a minor lowering of sea level would produce such a land bridge today). Lystrosaurus may well have walked in comfort, on a rather short journey at that. Yet the New York Times wrote an editorial proclaiming, on this basis alone, that continental drift had been proved.

Many readers may be disturbed by my argument for the primacy of theory. Does it not lead to dogmatism and disrespect for fact? It can, of course, but it need not. The lesson of history holds that theories are overthrown by rival theories, not that orthodoxies are unshakable. In the meantime, I am not distressed by the crusading zeal of plate tectonics, for two reasons. My intuition, culturally bound to be sure, tells me that it is basically true. My guts tell me that it's damned exciting-more than enough to show that conventional science can be twice as interesting as anything invented by all the von Danikens and in all the Bermuda triangles of this and previous ages of human gullibility.

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Hans Sloane collected this specimen of cacao in Jamaica in the 1680s. Sloane often collected on or near slave plantations, taking advantage of slavery's infrastructure to advance his science. NHM IMAGES

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Historians expose early scientists' debt to the slave trade

By Sam Kean | Apr. 4, 2019 , 10:00 AM

At the dawn of the 1700s, European science seemed poised to conquer all of nature. Isaac Newton had recently published his monumental theory of gravity. Telescopes were opening up the heavens to study, and Robert Hooke and Antonie van Leeuwenhoek's

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microscopes were doing the same for the miniature world. Fantastic new plants and animals were pouring in from Asia and the Americas. But one of the most important scientists alive then was someone few people have ever heard of, an apothecary and naturalist named James Petiver. And he was important for a startling reason: He had good connections within the slave trade.

Although he rarely left London, Petiver ran a global network of dozens of ship surgeons and captains who collected animal and plant specimens for him in far-flung colonies. Petiver set up a museum and research center with those specimens, and he and visiting scientists wrote papers that other naturalists (including Carl Linnaeus, the father of taxonomy) drew on. Between one-quarter and one-third of Petiver's collectors worked in the slave trade, largely because he had no other options: Few ships outside the slave trade traveled to key points in Africa and Latin America. Petiver eventually amassed the largest natural history collection in the world, and it never would have happened without slavery.

Petiver wasn't unique. By examining scientific papers, correspondence between naturalists, and the records of slaving companies, historians are now seeing new connections between science and slavery and piecing together just how deeply intertwined they were. "The biggest surprise is, for a topic that has been ignored for so long, how much there was once I started digging," says Kathleen Murphy, a science historian at California Polytechnic State University in San Luis Obispo who's writing a book about the topic. She adds, "There's a tendency to think about the history of science in this —I don't want to say triumphant, but—progressive way, that it's always a force for good. We tend to forget the ways in which that isn't the case."

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James Delbourgo, a historian at Rutgers University in New Brunswick, New Jersey, who has written extensively about slavery and science, agrees. He argues that the belief in the progressive nature of science has made historians reluctant to take a critical look at its past. "This is a hard story for us to deal with," he says. He adds that academic specialization also prevented many people from seeing what, in retrospect, seem like obvious connections: "Slave trade historians don't know about science, and vice versa."

> **"There's a tendency to think about the history of science in this—I don't want to say triumphant, but—progressive way, that it's always a force for good. We tend to forget the ways in which that isn't the case."**
>
> *Kathleen Murphy, California Polytechnic State University*

Those connections aren't just ancient history. Thousands of specimens collected through the slave trade still reside in places such as the Natural History Museum in London, and they're still used in genetic and taxonomic research. Yet few people using the collections know of their origins.

All of which casts an uncomfortable shadow on what's often viewed as a heroic era in science. "We do not often think of the wretched, miserable, and inhuman spaces of slave ships as simultaneously being spaces of natural history," Murphy writes in *The William and Mary Quarterly*. "Yet Petiver's museum suggests that this is exactly what they were."

Compromises to gain access to distant lands

Slavery is as old as civilization, but the transatlantic slave trade between the 1500s and 1800s was particularly brutal. Estimates vary, but at least 10 million Africans were

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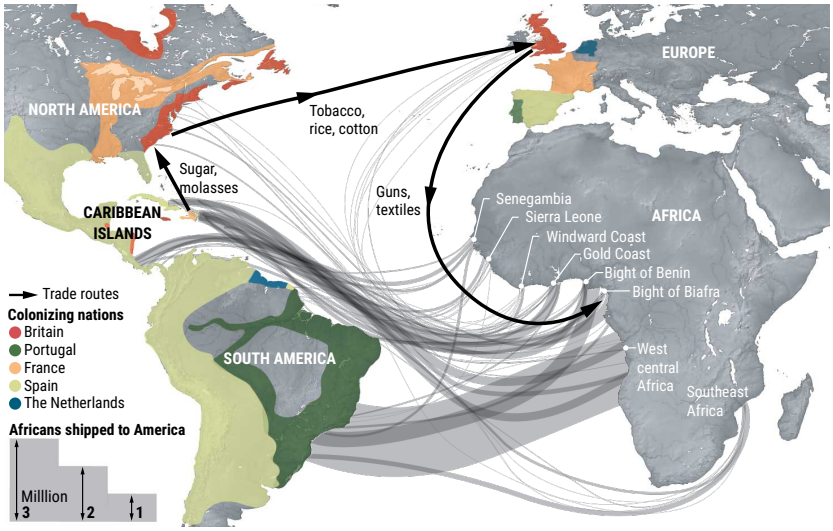
enslaved, with roughly half dying on the way to slave ports or on voyages across the ocean. Statistics alone can't capture the cruelty and squalor of slave ships, though. Men and women were chained up for weeks in hot, filthy holds, where diseases ran rampant and punishment for disobedience was harsh. Sharks reportedly followed ships on journeys, having learned that a slave or two would probably be tossed overboard—or commit suicide—at some point.

Why did scientists align themselves with that horror? Access. European governments did sometimes sponsor scientific expeditions, but most ships visiting Africa and the Americas were private vessels engaged in the "triangular trade." That three-way exchange sent guns and manufactured goods to Africa; slaves to the Americas; and dyes, drugs, and sugar back to Europe. To gain access to Africa and the Americas, scientists had to hitch rides on slave ships. Upon arrival, the naturalists also relied on slavers for food, shelter, mail, equipment, and local transport.

France, Portugal, and the Netherlands captured and sold slaves, Murphy notes. But most historians studying science and slavery focus on Great Britain, which in the 1700s boasted the world's biggest and most powerful fleets, had adventurous scientists and collectors, and was a major participant in the slave trade. Spain controlled most of South and Central America then, but it lacked colonies in Africa and therefore couldn't import slaves directly. So it contracted that job out to various groups, including the British in the early 1700s, buying up to 4800 Africans per year.

When people were traded like goods

In the "triangular trade" of the 16th through 19th centuries, millions of people were shipped to the Americas as slaves, raw materials were transported to Europe, and manufactured goods went to Africa. The three-way trade provided European collectors access to specimens from Africa and the Americas.



(MAP) AFRICAN SLAVE TRADE, 1500–1870/PEARSON EDUCATION, INC., ADAPTED BY N. DESAI/*SCIENCE*; (DATA) TRANS-ATLANTIC SLAVE TRADE DATABASE/EMORY CENTER FOR DIGITAL SCHOLARSHIP

When British slave ships arrived in Latin America, the crews had strict orders to stay at port and not poke around, mostly because Spain wanted to protect its monopoly on certain lucrative natural resources. But naturalists such as Petiver knew Spain had no way to enforce that rule—the territories had too little oversight. So they cultivated crew members to collect specimens on the sly.

Murphy's research shows Petiver employed mostly ship surgeons, who cared for slaves on the voyage across the ocean. The surgeons were scientifically educated, she says, and

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had plenty of free time at ports such as Cartagena, in modern Colombia, and Portobelo, in modern Panama, while their fellow crew members sold slaves and provisioned the ships. Petiver usually supplied recruits with kits that included jars for insects and brown paper for pressing plants. Compensation included books, medicines, and cash.

Strikingly, some naturalists also instructed their contacts abroad to train slaves as collectors. Slaves often knew about specimens that Europeans didn't and visited areas that Europeans wouldn't. Those slaves virtually never got credit for their work, though Petiver did offer to pay them a half-crown ($18 today) for every dozen insects or 12 pence ($7) for every dozen plants.

Petiver never collected overseas himself, but some scientists did, and they often found themselves in morally compromising positions. Henry Smeathman, an idealistic English naturalist, sailed for a slave colony in Sierra Leone in December 1771 and collected for the likes of Joseph Banks, an adviser to King George and longtime president of the Royal Society. Among other activities, Smeathman studied the massive termite mounds in western Africa, which stand up to 4 meters high. He had rollicking adventures breaking the mounds open and fending off attacks from angry, biting termite soldiers.

As detailed in the 2018 book *Henry Smeathman, the Flycatcher: Natural History, Slavery, and Empire in the Late Eighteenth Century*, by historian Deirdre Coleman of the University of Melbourne in Australia, Smeathman began his journey as a foe of slavery, vowing to tell the truth about "those little-known and much misrepresented people, the Negroes." And as a scientist, he considered himself superior to the ignorant, crude slavers he encountered in Sierra Leone. (For their part, the slavers thought him barmy for coming all the way to Africa to hunt for bugs and weeds.)

European scientists in South America often relied on black or native people to collect for them. In an illustration from 1806, three Africans in Suriname kill and flay a gigantic snake while a European scientist stands back and directs. THE JOHN CARTER BROWN LIBRARY AT BROWN UNIVERSITY

But Smeathman was utterly dependent on those men for food, protection, and transportation. He also got lonely and started to socialize with them, playing whist and backgammon and even golf on a rugged, two-hole course on an offshore island. Soon he was hunting goats and enjoying grog-soaked feasts on the beach with the slavers. By 1774, he was working for a slaving company based in Liverpool because it greased the wheels for shipping specimens; he even started to trade slaves in exchange for supplies for his expeditions. Bit by bit, compromise by compromise, Smeathman became part of the system he once despised.

Smeathman and others also relied on slavers to haul their precious specimens to Great Britain, packing them onto the same ships as enslaved Africans. (Few ships sailed straight back to Europe from Africa, so most specimens reached England via the Caribbean.) Perhaps not surprisingly, given how they treated their human cargo, the ships' crews had a spotty record in caring for fragile bugs, plants, and animal skins. If the sunlight, heat, humidity, and saltwater didn't destroy the specimens, the worms, ants, and rodents onboard usually did. Careless sailors might also smash the specimens by accident or for sport.

Of the items that arrived safely in England, naturalists were most excited about exotic finds such as ostrich eggs, Goliath beetles, butterflies, sloths, and armadillos. But the real treasures, Murphy writes, were drugs such as cinchona bark, which contains quinine, and dyes such as deep-blue indigo and bright-red cochineal. The latter, which is extracted from beetles, was worth more per ounce than silver.

Scientific studies of drugs and dyes often opened new opportunities for slave traders. Merchants eagerly sought natural resources to exploit abroad and consulted scientists about the best way to hunt for and cultivate them. Quinine and other drugs gleaned from tropical locales, Murphy notes, also helped Europeans survive there. And the safer and more profitable a colony was, the more its commercial activity, including slavery, thrived, creating new demand for slaves. Scientific research, then, not only depended on colonial slavery, but enabled it and helped expand its reach.

The tainted origins of many cabinets of curiosity

Of all the scientific fields, natural history benefited most from the slave trade, especially botany and entomology. One disciple of Linnaeus reported collecting three species new to science within 15 minutes on his first excursion in Sierra Leone. The bounty of plants astounded him.

Doctors affiliated with slavery also collected human remains. "The trade in natural curiosities was widespread, and body parts were definitely part of that," says Carolyn Roberts, a historian of science and assistant professor of African American studies at Yale University who's writing a book about the slave trade and medicine. "Doctors would send things to Britain, especially if they had a case they found interesting." Examples of interesting items included polyps cut from the hands of slaves, patches of dried skin, a fetus taken after a miscarriage, and, according to one old catalog, "stones extracted from the vagina of a negro African girle."

Those bugs and plants and bits of human beings often ended up in wealthy gentlemen's "cabinets of curiosity," jammed next to Roman coins and gems and whatever else tickled their fancy. Other specimens landed in universities or scholarly institutes.

> **"Newton himself, who's really the paradigm figure of an isolated, nontraveling, sitting-at-his-desk genius, had access to numbers he wouldn't have had access to without the Atlantic slave trade."**
>
> *James Delbourgo, Rutgers University*

Some historians now refer to those private and institutional collections as the "big science" of their day. Scholars studied those centralized repositories and then circulated accounts of their research to other scientists. Linnaeus drew on such accounts when putting together *Systema Naturae* in 1735, the book that introduced his famous binomial naming system for flora and fauna.

A few physical sciences also piggybacked on the slave trade. Slave labor built the first major observatory in the Southern Hemisphere, in Cape Town, South Africa. Astronomers such as Edmond Halley solicited observations of the moon and stars from slave ports, and geologists collected rocks and minerals there.

Even a field as rarefied as celestial mechanics benefited from slavery. When developing his theory of gravity, Newton studied ocean tides, knowing that the gravitational tug of the moon causes them. Newton needed tide readings from all over the globe, and one crucial set of readings came from French slave ports in Martinique. Delbourgo says, "Newton himself, who's really the paradigm figure of an isolated, nontraveling, sitting-at-his-desk genius, had access to numbers he wouldn't have had access to without the Atlantic slave trade."

Museums grapple with the past

Many natural history specimens with ties to the slave trade eventually ended up in museums. When Petiver died in 1718, a fellow naturalist in London named Hans Sloane snapped up his collection. Sloane had collected on slave plantations in Jamaica, and he married into a slaving family whose money enabled more collecting. In 1727, he succeeded Newton as president of the Royal Society (which itself invested in slaving companies).

When Sloane died in 1753, he willed his collection, including Petiver's goods, to the British government, and it became the foundation of the British Museum in London. The museum later split into several entities. Many of Sloane's specimens went to the Natural History Museum, where they remain today. Specimens collected through the slave trade also ended up at the Oxford University Herbaria, Royal Society, and Chelsea Physic Garden, among other places, Murphy reports.

Representatives for those institutes say it's difficult to put numbers on how many of their specimens have ties to slavery. In some cases, they haven't gone through and digitized the records yet, and many old specimens have vague or fragmentary records anyway, making their provenance obscure. But documents from the 18th and 19th centuries attest to thousands upon thousands of items pouring into Europe. Smeathman alone sent 600 species of plants and 710 species of insects back to England, often with several individuals per species. (One of Smeathman's patrons complained about the glut of bugs, writing that Smeathman had sent too many to unpack: "My House could not possibly contain one half.") And although many old specimens have either disintegrated or been lost, at least some with ties to slavery probably survive in almost every institute in Europe with natural history collections dating back a few centuries.

In addition to his own collecting, Hans Sloane (pictured) bought up the collections of other naturalists, many of whom used slave ships to reach far-flung places. When Sloane died in 1753, his specimens became the founding collection of the British Museum. They later ended up in London's Natural History Museum. NHM IMAGES

Those collections aren't just antiquarian curiosities. Scientists still consult them to construct phylogenies and do taxonomic work: Many of the collections contain type specimens, the first described individual of a species against which all other individuals are compared. The collections are also invaluable for studying plant domestication, historic climate change, and shifts in geographical distributions of species. Scientists have even extracted DNA from specimens to study how plants and animals have evolved across the centuries.

Most scientists, however, remain unaware of the origins of the collections. "Very few

people think about how [specimens] were collected, whether they were collected through slave trade routes or otherwise," says Stephen Harris, a curator at the Oxford University Herbaria, which houses some of Sloane's goods. "They're simply data points."

In an email, Mark Carine, a curator at the Natural History Museum, noted that institutions such as his have a broader role than just preserving specimens. "As curators, we have a responsibility not only to care for our collections and make them available for research but also to facilitate an understanding of their significance and relevance today." He adds that Sloane's collection "is not simply a biological record; it is also a resource for understanding the social and historical context within which science developed, and we are certainly keen to continue working with researchers across disciplines to better understand this."

Still, Murphy and Delbourgo say that even some curators are oblivious to the histories of their collections, and Murphy encountered one who dismissed her work outright. Delbourgo emphasizes that his historical research "isn't an attack on museums" and that he knows museum staff are often "under-resourced and overworked." But, he adds, "Museums have been bad" about acknowledging the dubious origins of many items. "They have dragged their feet enormously."

Now that the link between early science and slavery has come to light, an important question remains: What should scientists do about it?

Historians say acknowledgment is a start: In research papers, scientists should mention how specimens were gathered. Taking the origin of specimens into account can also improve the research itself, especially given the paucity of collecting records in some cases. For example, Murphy mentions that the slave trade can help explain the geographic distributions of certain specimens. African plants, for instance, wouldn't have been collected from all over the continent, but from specific points along the coast—the ports where countries were shipping slaves.

"From a scientific point of view, your specimen is essentially a piece of evidence," Harris adds, "and the more you know about the provenance of that piece of evidence and the better understanding you have … the better you can use it within your analyses."

The connections between science and the slave trade could also feed into ongoing debates about reparations and the historical legacies of slavery. Like some U.K. organizations, U.S. universities such as Yale, Georgetown, and Brown have acknowledged how they benefited from slavery. For the most part, Murphy says, those conversations are framed "in terms of just dollars and cents, pounds and pence. Yet [the profits] can also clearly be measured in specimens collected and papers published."

Overall, she says, "Modern science and the transatlantic slave trade were two of the most important factors in the shaping of the modern world." Historians are finally recognizing that they shaped each other as well. As Delbourgo says, "We've been so negligent in bringing these histories [of slavery and science] together. We've missed that they are in fact the same history."

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Sam Kean

Sam Kean is a science journalist in Washington, D.C.

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Twitter Thread on Kean 2019 *Science* Article

Rae Wynn-Grant (@RaeWynnGrant)

April 10th, 2019

1 Background

On April 4th, 2019, *Science* magazine published an article by White science journalist Sam Kean titled "Historians expose early scientists' debt to the slave trade." [1] On April 10th, 2019, Black wildlife biologist and National Geographic Research Fellow Dr. Rae Wynn-Grant wrote thread on Twitter [2] responding to the article. The thread has been reproduced below, unmodified except for the addition of numbers denoting each Tweet in sequence and clarifying changes for primary versus secondary quotation marks.

2 Twitter Thread

1. Ok, ok. Deep breath. @sam_kean wrote a piece for @sciencemagazine about how European science was largely made possible by the #slavetrade. Sure. But the LANGUAGE IN THIS PIECE is irresponsible and it hurts!!! A thread...

2. "At the dawn of the 1700s, European science seemed poised to conquer all of nature." Opening sentence. What?! All of nature? 1700s? What about all of the science that had been done for the thousands of years before that by non-Europeans? What does "conquer all of nature" mean?

3. "Fantastic new plants and animals were pouring in from Asia and the Americas." WHAT? No mention of HOW this was happening? BECAUSE OF RAMPANT BLOODY WHITE-SUPREMACY-BASED VIOLENCE. oh, but we're supposed to call it "exploration"

4. "But one of the most important scientists alive then was someone few people have ever heard of, an apothecary and naturalist named James Petiver" - one of the most important to whom? The majority of the world who are non-european? no. the most important scientist to EUROPEANS

5. "Between one-quarter and one-third of Petiver's collectors worked in the slave trade, largely because he had no other options" - nope. No. trust me, he had plenty of options. One option is to not participate or support the slave trade. Try that idea on.

6. "Petiver eventually amassed the largest natural history collection in the world, and it never would have happened without slavery." This is NOT the way to write these words. It implies a sigh of relief that slavery, in fact, did some good amongst the harm.

7. NO! If Europeans couldn't get their hands on plants and animals from non-European places THAT IS FINE BECAUSE IT IS NOT NECESSARY FOR EUROPEANS IN THE 1700S TO BE THE DICTATORS OF NATURAL HISTORY. Guess what existed before Europeans "found" African plants - AFRICAN PLANTS

[1] https://www.sciencemag.org/news/2019/04/historians-expose-early-scientists-debt-slave-trade
[2] https://twitter.com/RaeWynnGrant/status/1116076320188981250

8. “historians are now seeing new connections between science and slavery and piecing together just how deeply intertwined they were” - oh, and as a result they are rejecting the validity of all science that has been created from slavery bc it was done at the expense of black lives?

9. I HARDLY DOUBT IT!!!! Are we talking about reparations? Are we talking about anyone who is the descendent of a slave now gets a full scholarship to study science because WE ENABLED EUROPEAN SCIENCE IN THE FIRST PLACE? No, instead “historians are SEEING connections” and that’s it

10. “There’s a tendency to think about the history of science in this—I don’t want to say triumphant, but—progressive way, that it’s always a force for good. We tend to forget the ways in which that isn’t the case.” WHO IS “WE”? Blk and brn ppl never “forgot” & WE ARE SCIENTISTS TOO

11. “This is a hard story for us to deal with” - AGAIN WHO IS THIS “US” you write of? Why are people of color - the people whose ancestors lived through the slave trade erased from this picture of who scientists are today? This “us” refers to Europeans and descendents of Europeans!

12. “Thousands of specimens collected through the slave trade still reside in places such as the Natural History Museum in London...” don’t even get me started on museum collections - are even ANY of them built from inclusionary, non-violent, equitable, and participatory methods?

13. “All of which casts an uncomfortable shadow on what’s often viewed as a heroic era in science” - it takes A LOT OF PRIVILEGE to think of this as “uncomfortable.” A lot. I can only imagine being able to opt-in or opt-out of feeling “uncomfortable.” How about generational trauma?

14. Who views this as a heroic era in science? You know what I view as a heroic era of science? THE FUTURE, when black and brown people are well funded and leaders in scientific thought and exploration. When anti-racist & decolonized science is at the core of our fields

15. “We do not often think of the wretched, miserable, and inhuman spaces of slave ships as simultaneously being spaces of natural history” - YIKES. This sentence is attempting to create a balancing act between human suffering and euro-scientific advancement. THIS IS OFFENSIVE

16. “Slavery is as old as civilization, but the transatlantic slave trade between the 1500s and 1800s was particularly brutal” - history lesson: racially-based forced labor systems are not as old as civilization/the American slave trade was different and you MUST acknowledge race

17. “Why did scientists align themselves with that horror? Access” - I might actually just die before I even finish this thread. WHO ARE SCIENTISTS TO YOU? White people only? Ever occur to you that scientists were also the people being enslaved? WHITE PEOPLE ALIGNED THEMSELVES...

18. ...with slavery because they believed in white supremacy and were delighted to perpetuate racism. FULL STOP. They didn’t just say “well, it’s worth it for access to plants and animals,” they said “We are superior to black people.” THESE SCIENTISTS WERE RACIST - SAY IT

19. @sam_kean this sentence is particularly offensive “To gain access to Africa and the Americas, scientists had to hitch rides on slave ships.” HAD TO? did they now? They had to support slave ships in order to do their science. It’s just a normal everyday trade-off?

20. This writing makes me cry, shake, and want to scream. The THOUSANDS of black scientists whose ancestors survived slavery (long enough to give birth) are owed better. The perspective that scientists are white and were the apologetic observers of how slavery could go right is awful

21. “some naturalists also instructed their contacts abroad to train slaves as collectors” - this is a note for museums globally: CREDIT THE SOURCES OF THE COLLECTIONS (also, provide reparations)

22. “Slaves often knew about specimens that Europeans didn’t” - oh, you don’t say! If this is to be written, it needs to be followed by some sort of acknowledgement that white people were out of line - if you want to know about a fucking plant, just ask the person who knows.

23. This is written as if it is a benefit of slavery. Saying “but the slaves came with a lot of knowledge” is such staunch white-supremacist prose I can’t even stand it.

24. “Petiver never collected overseas himself, but some scientists did, and they often found themselves in morally compromising positions” NO THEY DID NOT. There is only one right way to do this - DON’T PARTICIPATE IN THE SLAVE TRADE. Don’t try to evoke sympathy for the people who...

25. ...became rich and famous scientists at the expense of black life and dignity. Don’t you f-ing dare

26. “Bit by bit, compromise by compromise, Smeathman became part of the system he once despised” - I rewrote this part for you: “Smeathman never believed in human equality, and was racist and violent from the beginning to the end”

27. “given how they treated their human cargo, the ships’ crews had a spotty record in caring for fragile bugs, plants, and animal skins” - DO NOT PUT BLACK PEOPLE ON THE SAME PLANE AS INSECTS. NO! This is offensive! This is harsh! This is dehumanizing!

28. “Of the items that arrived safely in England, naturalists were most excited about exotic finds such as ostrich eggs, Goliath beetles, butterflies, sloths, and armadillos” - and naturalists were least concerned about black human beings. Still are, apparently.

29. “Quinine and other drugs gleaned from tropical locales, Murphy notes, also helped Europeans survive there” - responsible journalism would add to this “so they could continue with colonial rule, violence, rape, and enslavement”

30. “And the safer and more profitable a colony was, the more its commercial activity, including slavery, thrived, creating new demand for slaves” YOU MUST BE KIDDING ME!!! SAFE FOR WHOM? Slaves = enslaved black people. SAFE FOR WHOM?!?

31. “Scientific research, then, not only depended on colonial slavery, but enabled it and helped expand its reach” NO! Scientific research was not dependent on slavery. NO! White scientists saw an easy, lazy way to get what they wanted and no white people were hurt in the process

32. This is a horrible excuse for the participation of white scientists in the slave trade. THERE WAS NO DEPENDENCY. It seems like the other option at the time was for white people to do natural history work only in Europe without hurting people, and apparently that wasn’t acceptable

33. “Of all the scientific fields, natural history benefited most from the slave trade, especially botany and entomology” - AND WHAT TF ARE folks gonna do about this injustice? WE ARE ALL EARS (see what i did there? with “we”)

34. “One disciple of Linnaeus reported collecting three species new to science within 15 minutes on his first excursion in Sierra Leone” - again with responsible journalism...“new to science” is not even close to accurate. You mean “new to scientists from europe”

35. “Examples of interesting items included polyps cut from the hands of slaves, patches of dried skin, a fetus taken after a miscarriage, and, according to one old catalog, ‘stones extracted from the vagina of a negro African girle.’”

36. Why was this quote not followed DIRECTLY with something, ANYTHING, that could lesson the blow? THE TRAUMA READING THIS

37. “Those bugs and plants and bits of human beings often ended up in wealthy gentlemen’s ‘cabinets of curiosity,’ ALSO THIS sentence needs to be followed up with ANYTHING that acknowledges the absolute horror of this experience for the thousands of people who suffered it

38. “Some historians now refer to those private and institutional collections as the ‘big science’ of their day” - DO NOT WRITE THIS, IT IS HARMFUL. Who are these historians? Why are they not booted out of their institutions for dismissing this violence as “big science”

39. I, personally, do not want to be a scientist if *WE* accept “big science” as just this upsetting thing from the past. IT IS NOT SCIENCE, IT IS MURDER

40. “Astronomers such as Edmond Halley solicited observations of the moon and stars from slave ports” - AH! And another place for which I expect to see some SERIOUS reparations flowing from!

41. “Even a field as rarefied as celestial mechanics benefited from slavery” - newsflash for the author - the entire western economy was built on slavery, so obviously obscure scientific fields were too

42. “Newton himself, who’s really the paradigm figure of an isolated, nontraveling, sitting-at-his-desk genius, had access to numbers he wouldn’t have had access to without the Atlantic slave trade.” - YES BECAUSE THESE MEN WERE COMPLICIT!!!

43. “Representatives for those institutes say it’s difficult to put numbers on how many of their specimens have ties to slavery” - that is because we are not DEMANDING they put numbers on how many. Journalists need to call these people out for not cooperating!

44. “The collections are also invaluable for studying plant domestication, historic climate change, and shifts in geographical distributions of species” - oh, are they now? INVALUABLE?!?!?! WHAT ABOUT THE VALUE OF BLACK LIFE

45. “Most scientists, however, remain unaware of the origins of the collections” - dear author, do you really believe this? Or are you just uncomfortable writing the truth that many scientists choose to ignore the origins of their collections

46. “Very few people think about how [specimens] were collected, whether they were collected through slave trade routes or otherwise,” says Stephen Harris, a curator at the Oxford University Herbaria, which houses some of Sloane’s goods. “They’re simply data points.”...

47. really? well, I’ll give you ONE GUESS of which type of scientist thinks about the origins of specimens from Africa CONSTANTLY

48. “institutions such as his have a broader role than just preserving specimens” - does this broader role include advocating for racial justice and equity in science? DOES IT? CAN ANY MUSEUM INSTITUTION CLAIM THATS WHAT THEY DO?

49. “‘Museums have been bad’ about acknowledging the dubious origins of many items” - WHY IS THE WORD COMPLICIT NOT A PART OF THIS ARTICLE

50. “Now that the link between early science and slavery has come to light, an important question remains: What should scientists do about it?” -Come to light for whom? This article is written from start to finish as if scientists are only white people who don’t know about slavery

51. “Historians say acknowledgment is a start: In research papers, scientists should mention how specimens were gathered” - i am desperate to know which historians said this. Where is critical thought, action, and a commitment to equity mentioned? Anywhere???

52. “Murphy mentions that the slave trade can help explain the geographic distributions of certain specimens” - I

53. “The connections between science and the slave trade could also feed into ongoing debates about reparations and the historical legacies of slavery” - the author should have taken the time to find interviewees who could speak to this and provide ideas. It is dropped and left alone

54. “We’ve been so negligent in bringing these histories [of slavery and science] together. We’ve missed that they are in fact the same history” - this is the last sentence of the piece, which brings a feeling of harmony and closure....

55. ...a piece that was about how black bodies were brutalized and we’re sad about it, but at least it expanded European science. Oh, and some scientists felt bad the whole time they benefitted from it. THERE ARE SO MANY PARALLELS TODAY

56. Responsible journalism would have included the descendents of slaves in this piece! Scientists who work every day with collections that were gathered on the backs of our ancestors. It should have suggest we respect these awful, violent scientists LESS OR NOT AT ALL

57. Slavery wasn’t just people on boats in chains, it was murder, rape, torture over and over for 400+ years. It was a European-sponsored black killing machine, with lingering impacts for centuries....

58. ...and if we’re going to write about how science benefitted, one must write with EXTREME responsibility and WITHOUT an apologetic tone and an attempt at a balancing act. BETTER IDEA IS TO HAVE A SLAVE DESCENDENT WRITE IT - WE ARE HERE - WE ARE SCIENTISTS - we have survived.

59. I write this from my desk at @NatGeo, an institution that has acknowledged its role in perpetuating racist stereotypes. Black scientists, especially naturalists, are SURROUNDED by the legacy of white supremacy, and often face social and professional consequences for speaking out

60. I’m done with this thread. I’m going home to cuddle my sweet black 3 year old daughter and pray she gets to enter her chosen field at a time of TRUE equity and inclusion. Peace, y’all

The black-footed ferret has benefited from the U.S. Endangered Species Act.

PHOTO: LAURA ROMIN & LARRY DALTON/ALAMY STOCK PHOTO

Edited by **Jennifer Sills**

Solve the biodiversity crisis with funding

The recent Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) Global Assessment (*1*) is the most comprehensive synthesis of the status and trends of biodiversity to date, and it offers a bleak outlook: up to 1 million species at risk of extinction, with tangible harm for human societies. The U.S. Endangered Species Act (ESA) is widely considered the strongest law in the world for conserving imperiled wildlife (*2*), protecting species from extinction and providing tools for species recovery. Successes of the ESA are well documented, placing species like the California condor, black-footed ferret, and snail darter on the path to recovery (*3*).

However, decades of severe underfunding have prevented the ESA from achieving its potential. While the vast majority of listed species are still with us today, upwards of half of listed species have not progressed towards recovery (*3*, *4*). Data also show that less than 25% of the funding needed just for species recovery has been provided overall (*5*). The U.S. Fish and Wildlife Service, a lead agency for ESA implementation, receives less than half of the $486 million that it needs each year (*6*). And although conserving listed species should be a shared effort, expenditures by other federal agencies are inadequate, and states have provided an average of just 5% of total funds (*7*).

As scientists (*8*), we call on the U.S. Congress to fully fund wildlife conservation programs to protect biodiversity from severe and growing threats. The effort to conserve threatened and endangered species must be prioritized to protect our national heritage and safeguard human well-being. In light of the unprecedented global biodiversity crisis identified by the IPBES, we urge the United States to join governments around the world in immediate action. The data are clear and consistent: Our leaders must invest today to protect biodiversity in perpetuity.

Jacob Malcom[1], Mark W. Schwartz[2], Megan Evansen[1], William J. Ripple[3], Stephen Polasky[4], Leah R. Gerber[5], Thomas E. Lovejoy[6], Lee M. Talbot[6], Jennifer R. B. Miller[1]*, and 1648 signatories

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SUPPLEMENTARY MATERIALS

science.sciencemag.org/content/365/6459/1256.1/suppl/DC1
List of Initial Signatories

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On reporting scientific and racial history

In his News Feature "Science's debt to the slave trade" (5 April, p. 16), S. Kean discusses the role of the slave trade in 18th-century European science with an unfortunate lack of sensitivity (*1*). Scholars quoted in the article use "we" and "us" when talking about people who are surprised by scientists' connection to the slave trade. This in-group construction (*2*) suggests an underlying assumption that neither the Africans and African-Americans enslaved nor their descendants, who experienced and survived 400+ years of the transatlantic slave trade, were scientists then or are scientists today. Although the author and editors may have intended to raise awareness about white scientists' problematic involvement in the slave trade—a worthy goal—the language used in the article serves as an example of how inclusion is one of the wider science community's biggest challenges.

An opening sentence is typical of the article's flawed perspective: "Petiver eventually amassed the largest natural history collection in the world, and it never would have happened without slavery." This passage can be read to suggest a worthiness of slavery,

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diminishing the means from which the collection came about. Dr. Carolyn Roberts, the only person of color interviewed, is given one quote in the piece, introducing non-consensual studies on enslaved Africans. Kean directly follows Dr. Roberts's quote by listing various ways black bodies were manipulated and pulled apart, but he does not offer the reader any guiding judgments. Without bringing the reader back to the role of institutionalized racism and power dynamics, the article does little to support its title—a "debt" that scientists need to repay.

Alarmingly, the suggestion that early Western scientists were wrong does not appear clearly in the piece. Although Kean briefly details the harsh nature of the slave trade, he never describes these men—scientists who are revered in a white-washed version of history—as complicit in the murder, torture, and brutal enslavement of black people. An estimated 12 million Africans were forced across the Atlantic Ocean, with variable rates of survival (*3*, *4*). To suggest, as the article does, that European scientists "had to hitch rides on slave ships," as if they were without options for their work other than to use (and profit from) this inhumane system, is to exonerate their insidious behavior and corrupt belief system. For them to participate in this institution, they had to believe science was more important than black life. Saying that they did it for "access" is eliminating their responsibility. Slave ships should always be conceptualized as sites of violence, torture, and brutality—without reconsideration—and should not be characterized, as one of the scholars quoted does, as sites of scientific discovery. To do otherwise is an affront to all of the descendants of those enslaved peoples who are today working within a Western scientific philosophy that was built on the backs of our ancestors (*5*).

The benefits of slavery to white scientists are explained in this story—the author describes scientists as real people with names, internal dialogue, and triumphs. Meanwhile, the destruction of families, communities, empires, identities, and souls goes unmentioned; enslaved people who endured this violence are "slaves" throughout the piece. The discussion in this article is squarely centered around white people, white conquest, white so-called discovery, and white profit, and has little concern for the black experience or for how the legacy of slavery has directly influenced the participation of black people in science today. If Western science has gained anything from the transatlantic slave trade, it has lost much more in terms of human capacity.

Historical facts, patterns, or commonalities that affected the way many people lived and died are plagued with moral and ethical violations that require thoughtful discussion. Although the term "white supremacy" is often equated with direct violence, it also encompasses language use and word choice that reinforce racial hierarchies. By using language and context (even unintentionally) that propagate the idea that white interests trump black liberation, this piece, at the utmost, upholds colonial science and white supremacy. At the minimum, this type of writing is a microaggression that can cause black people to feel unvalued and unwelcome in the scientific community. I implore *Science* magazine, Sam Kean, scientists, and journalists globally to put the experiences, values, and needs of people from oppressed backgrounds at the center of historical narratives to endow them with truth and transparency (*6*, *7*).

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Editor's Note

We thank Dr. Wynn-Grant for her thoughts, which have provoked useful discussions among our reporters and editors. We are sorry that our story's language was not as inclusive as we strive to be, and we've learned important lessons from her about such sensitivities. We do not think that, read as a whole, our article absolves the European scientists who benefited from the slave trade or suggests that their interests in any way justified the human costs of slavery. Dr. Wynn-Grant's points echo our goal in writing this story: to raise awareness about the immoral decisions of white scientists and their willing complicity in the transatlantic slave trade. However, we agree that we need to apply broader perspectives when telling difficult stories such as this one.

Tim Appenzeller
News Editor

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A new scientific agenda for Mexico

In his Editorial "Quo vadis, Mexican science?" (26 July, p. 301), A. Lazcano expressed concern about cuts to the budget of the Mexican National Council of Science and Technology (CONACYT) and questioned my leadership of the organization. The data summarized here should allay Lazcano's concerns.

In Mexico, the total budget for science, technology, and innovation (STI) in 2019 (77.3 billion MP, equivalent to 4.1 billion U.S. dollars) was the highest it has been in 7 years (*1–3*). Despite the 2.4 billion MP cut to CONACYT's funding in 2019, an efficient administration and coordination among federal sectors that receive STI resources have redirected other funds to support the scientific community more than ever (*1–3*).

During previous years, there was limited or no support for basic science, and many high-quality proposals went unfunded. In 2019, 1.6 billion MP have been assigned to be transferred to fund high-rated peer-reviewed basic science projects *(3)*. Calls for novel technological development and innovation approaches were recently announced. In addition, interdisciplinary projects geared toward the UN Sustainable Development Goals will be published soon; they address pressing challenges such as acute lymphoblastic leukemia, the most common cause of mortality in Mexican children *(4–6)*.

CONACYT allocated 5.65 billion MP to support Mexico's 27 public research centers in 2019 (*1–3*). By optimizing the use of such public resources, we are committed to improving conditions at these research centers. Additionally, all Mexican scientists are protected by the social health insurance system, and their private health insurance has been maintained in public universities.

Lazcano worries that our changes could "extinguish international collaborations…and fuel a brain drain." However, all students and scientists may continue to travel for scientific and educational goals as usual. Moreover, CONACYT has allocated more than 10 billion MP (41% of the total budget) to fund ongoing and new fellowships for Mexican graduate students and postgraduate researchers in national and international programs and to continue supporting international graduates and postgraduates to study in Mexico (*1–3*). Furthermore, 1.11 billion MP have been directed to support early career scientists. Finally, the National System of Researchers, administrated by CONACYT, complements the salary of over 30,000

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“Asters and Goldenrod” from *Braiding Sweetgrass*

by Robin Wall Kimmerer

https://commons.bluemountaincenter.org/goldenrod-and-asters-my-life-with-plants/

I like to imagine that they were the first flowers I saw, over my mother’s shoulder, as the pink blanket slipped away from my face and their colors flooded my consciousness. I’ve heard that early experience can attune the brain to certain stimuli, so that they are processed with greater speed and certainty, so that they can be used again and again, so that we remember. Love at first sight. Through cloudy newborn eyes their radiance formed the first botanical synapses in my wide- awake brain, which until then had encountered only the blurry gentleness of pink faces. I’m guessing all eyes were on me, a little round baby all swaddled in bunting, but mine were on goldenrod and asters. I was born to these flowers and they came back for my birthday every year, weaving me into our mutual celebration.

People flock to our hills for the fiery suite of October but they often miss the sublime prelude of September fields. As if harvest time were not enough—peaches, grapes, sweet corn, squash— the fields are also embroidered with drifts of golden yellow and pools of deepest purple, a masterpiece.

I wanted to make a good first impression. There were hardly any women at the forestry school in those days and certainly none who looked like me. For the freshman intake interview, I wore my new red plaid shirt, a hallmark of foresters, so I’d fit right in. My new faculty adviser peered at me over his glasses and said, “So, Miss Wall, why do you want to major in botany?” His pencil was poised over the registrar’s form, twitching, while portraits of Linneaus and Asa Gray looked on from his walls.

How could I answer, how could I tell him that I was born a botanist, that I had shoeboxes of seeds and piles of pressed leaves under my bed, that plants colored my dreams, that the plants had chosen me?

So I told him the truth. I was proud of my well- planned answer, its freshman sophistication apparent to anyone, revealing what I hoped was a deep knowledge of plants. I told him that I chose botany because I wanted to learn about why asters and goldenrod looked so beautiful together. I’m sure I was smiling then, in my new red plaid shirt.

But he was not. He laid down his pencil as if there was no need to record what I had said. “Miss Wall,” he said, fixing me with a disappointed smile, “I must tell you that that is not science. Beauty is not the sort of thing with which botanists concern themselves.” I tried again: I’d like to learn why plants make medicines, why willow bends for baskets and why strawberries are sweeter in the shade. “Also not science,” he said and he ought to know, sitting in his laboratory, a learned professor of botany. “And if you want to study beauty, you should go to art school.”

I had no rejoinder; I had made a mistake. I did not have the words for resistance, only embarrassment at my error. But he promised to put me right. “I’ll enroll you in General Botany so you can learn what it is.” And so it began.

I didn’t think about it at the time,the echo of my grandfather’s first day at the Carlisle Indian school, when he was ordered to leave everything—language, culture, family— behind. But they did not cut my hair.

If a fountain could jet bouquets of chrome yellow in dazzling arches of chrysanthemum fireworks, that would be Canada goldenrod. Each three- foot stem is a geyser of tiny gold daisies, ladylike in miniature, exuberant en masse. Where the soil is damp enough, they stand side by side with their perfect counterpart, New England asters. Not the pale domesticates of the perennial border, the weak sauce of lavender or sky blue, but full- on royal purple that would make a violet shrink. The daisy-like fringe of purple petals surrounds a disc as bright as the sun at high noon, a golden- orange pool, just a tantalizing shade darker than the surrounding goldenrod. Alone, each is a botanical superlative. Together, the visual effect is stunning. Purple and gold, the heraldic colors of the king and queen of the meadow, a regal procession in complementary colors. I just wanted to know why.

Why do they stand beside each other when they could grow alone? There are plenty of pinks and whites and blues dotting the fields, so is it only happenstance that the magnificence of purple and gold end up side by side? Einstein himself said that “God doesn’t play dice with the universe.” Why is the world so beautiful? It seemed like a good question to me.

In moving from a childhood in the woods to the university I had unknowingly shifted between worldviews, from a natural history of experience, in which I knew plants as teachers and companions into the realm of science. The questions scientists raised were not “Who are you?” but “What is it?” No one asked plants “What can you tell us?” The primary question was “How does it work?” The botany I was taught was reductionist, mechanistic. Plants were reduced to objects; they were no longer

subjects. The way botany was conceived and taught didn't seem to leave much room for a person who thought the way I did. The only way I could make sense of it was to conclude that the things I had always believed about plants must not be true after all.

That first plant science class was almost a disaster. I barely scraped by with a C and could not muster much enthusiasm for memorizing the concentrations of essential plant nutrients. There were times when I wanted to quit, but the more I learned, the more fascinated I became with the intricate structures that made up a leaf and the alchemy of photosynthesis. Companionship between asters and goldenrod was never mentioned, but I memorized botanical Latin as if it was poetry, eagerly tossing aside the name "goldenrod" for *Solidago canadensis*.

I scarcely doubted the primacy of scientific thought. Following the path of science trained me to separate, to distinguish perception from physical reality, to atomize complexity into its smallest components, to honor the chain of evidence and logic, to discern one thing from another, to savor the pleasure of precision. The more I did this, the better I got at it. A master's degree, a PhD followed. No doubt on the strength of the letter of recommendation from that freshman adviser, which read, "She's done remarkably well for an Indian girl."

I am grateful for the knowledge that was shared with me and deeply privileged to carry the powerful tools of science as a way of engaging the world. I remember feeling, as a new professor, as if I finally understood plants. I too began to teach the mechanics of botany, emulating the approach that I had been taught. And yet there was always something tapping at my shoulder, willing me to turn around.

To walk the science path I had stepped off the path of indigenous knowledge. But the world has a way of guiding your steps. Seemingly out of the blue came an invitation to a small gathering of Native elders, to talk about traditional knowledge of plants. One teacher I will never forget—a Navajo woman without a day of university botany training—spoke for hours and I hung on every word. One by one, name by name, she told of the plants in her valley. Where each one lived, when it bloomed, who it liked to live near and all its relationships, who ate it, who lined their nests with its fibers, what kind of medicine it offered. She also shared the stories held by those plants, their origin myths, how they got their names, and what they have to tell us. She spoke of beauty.

Her words were like smelling salts for me—I was suddenly newborn wide awake—and profoundly humbled in the shallowness of my own understanding. Her

knowledge was so much deeper and wider and engaged all the human ways of knowing. She could have explained asters and goldenrod. It was the beginning of my reclaiming that other way of knowing that I had helplessly let science supplant. I felt like a malnourished refugee invited to a feast, the dishes scented with the herbs of home.

I circled right back to where I had begun, to the question of beauty. Back to the questions that science does not ask, not because they aren't important, but because science as a way of knowing is too narrow for the task. Had my adviser been a better scholar, he would have celebrated my questions, not dismissed them. He offered me only the cliché that beauty is in the eye of the beholder, and since science separates the observer and the observed, by definition beauty could not be a valid scientific question. I should have been told that my questions were bigger than science could touch.

He was right about beauty being in the eye of the beholder, especially when it comes to purple and yellow. Color perception in humans relies on banks of specialized receptor cells, the rods and cones in the retina. The job of the cone cells is to absorb light of different wavelengths and pass it on to the brain's visual cortex, where it can be interpreted. The visible light spectrum, the rainbow of colors, is broad, so the most effective means of discerning color is not one generalized jack-of-all-trades cone cell, but rather an array of specialists, each perfectly tuned to absorb certain wavelengths. The human eye has three kinds. One type excels at detecting red and associated wavelengths. There is one for blue and the last one optimally perceives light of two colors: purple and yellow.

The human eye is superbly equipped to detect these colors and send a signal pulsing to the brain. This doesn't explain why I perceive them as beautiful, but it does explain why that combination gets my undivided attention. I asked my artist friends about the power of purple and gold, and they sent me right to the color wheel: these two are complementary colors, as different in nature as could be. In composing a palette, putting them together makes each more vivid; just a touch of one will bring out the other. Purple and yellow are a reciprocal pair.

Our eyes are so sensitive to these wavelengths that the cones can get over-saturated and the stimulus pours over onto the other cells. A printmaker I know showed me that if you stare for a long time at a block of yellow and then shift your gaze to a white sheet of paper, you will see it, for a moment, as violet. This phenomenon— the colored afterimage—occurs because there is energetic

reciprocity between purple and yellow pigments, which goldenrod and asters knew well before we did.

The real beholder whose eye they hope to catch is a bee bent on pollination. As it turns out, goldenrod and asters appear very similarly to bee eyes and human eyes. Their striking contrast when they grow together makes them the most attractive target in the whole meadow. Growing together, both receive more pollinator visits than they would if they were growing alone.

It's a testable hypothesis; it's a question of science, a question of art, and a question of beauty. Why are they beautiful together? It is a phenomenon simultaneously material and spiritual, for which we need all wavelengths of knowledge. When I stare too long at the world with science eyes, I see an afterimage of indigenous knowledge. Might science and traditional knowledge be purple and yellow to one another? We see the world more fully when we use both.

The question of goldenrod and asters was of course just emblematic of what I really wanted to know. It was an architecture of relationships that I yearned to understand. I wanted to see the shimmering threads that hold it all together why the most ordinary scrap of meadow can rock us back on our heels in awe. And I wanted to know why we love the world.

There was a time when I teetered precariously with an awkward foot in each of two worlds; the scientific and the indigenous. But then I learned to fly. It was the bees that showed me how to move between different flowers— to drink the nectar and gather pollen from both. It is this dance of cross- pollination that can produce a new species of knowledge, a new way of being in the world. After all, there aren't two worlds, there is just this one good green earth.

That September pairing of purple and gold is lived reciprocity; its wisdom is that the beauty of one is illuminated by the radiance of the other. Science and art, matter and spirit, indigenous knowledge and Western science— can they be goldenrod and asters for each other? When I am in their presence, their beauty asks me for reciprocity, to be the complementary color, to make something beautiful in response.

“*Mishkos Kenomagwen*: The Teachings of Grass”
from *Braiding Sweetgrass*
by Robin Wall Kimmerer

i. Introduction

You can smell it before you see it, a sweetgrass meadow on a summer day. The scent flickers on the breeze, you sniff like a dog on a scent, and then it’s gone, replaced by the boggy tang of wet ground. And then it’s back, the sweet vanilla fragrance, beckoning.

ii. Literature Review

Lena is not fooled easily, though. She wanders into the meadow with the certainty of her years, parting grasses with her slender form. A tiny, gray-haired elder, she is up to her waist in grass. She casts her gaze over all the other species and then makes a beeline to a patch that to the uninitiated looks like all the rest. She runs a ribbon of grass through the thumb and forefinger of her wrinkled brown hand. “See how glossy it is? It can hide from you among the others, but it wants to be found. That’s why it shines like this.” But she passes this patch by, letting it slide through her fingers. She obeys the teachings of her ancestors to never take the first plant that you see.

I follow behind her as her hands trail lovingly over the boneset and the goldenrod. She spies a gleam in the sward and her step quickens. “Ah, *Bozho*,” she says. Hello. From the pocket of her old nylon jacket she takes her pouch, deerskin with a beaded red edge, and shakes a little tobacco into the palm of her hand. Eyes closed, murmuring, she raises a hand to the four directions and then scatters the tobacco to the ground. “You know this,” she says, her eyebrows a question mark. “To always leave a gift for the plants, to ask if we might take them? It would be rude not to ask first.” Only then does she stoop and pinch off a grass stem at its base, careful not to disturb the roots. She parts the nearby clumps, finding another and another until she has gathered a thick sheaf of shining stems. A winding path marks her progress where the meadow canopy was opened by the trail of her passage.

She passes right by many dense patches, leaving them to sway in the breeze. “It’s our way,” she says, “to take only what we need. I’ve always been told that you never take more than half.” Sometimes she doesn’t take any at all, but just comes here to

check on the meadow, to see how the plants are doing. “Our teachings,” she says, “are very strong. They wouldn’t get handed on if they weren’t useful. The most important thing to remember is what my grandmother always said: ‘If we use a plant respectfully it will stay with us and flourish. If we ignore it, it will go away. If you don’t give it respect it will leave us.’” The plants themselves have shown us this—mishkos kenomagwen. As we leave the meadow for the path back through the woods, she twists a handful of timothy into a loose knot upon itself, beside the trail. “This tells other pickers that I’ve been here,” she says, “so that they know not to take any more. This place always gives good sweetgrass since we tend to it right. But other places it’s getting hard to find. I’m thinking that they might not be picking right. Some people, they’re in a hurry and they pull up the whole plant. Even the roots come up. That’s not the way I was taught.”

I’ve been with pickers who did that, yanking up a handful that left a little bare spot in the turf and a fuzz of broken roots on the uprooted stems. They too made offerings of tobacco and took only half, and they assured me that their method of picking was the correct one. They were defensive about the charges that their harvesting was depleting sweetgrass. I asked Lena about it and she just shrugged.

iii. Hypothesis

In many places, sweetgrass is disappearing from its historic locales, so the basket makers had a request for the botanists: to see if the different ways of harvesting might be the cause of sweetgrass’s leaving.

I want to help, but I’m a little wary. Sweetgrass is not an experimental unit for me; it’s a gift. There is a barrier of language and meaning between science and traditional knowledge, different ways of knowing, different ways of communicating. I’m not sure I want to force the teachings of grass into the tight uniform of scientific thinking and technical writing that is required of the academy: Introduction, Literature Review, Hypothesis, Methods, Results, Discussion, Conclusions, Acknowledgments, References Cited. But I’ve been asked on behalf of sweetgrass, and I know my responsibility.

To be heard, you must speak the language of the one you want to listen. So, back at school, I proposed the idea as a thesis project to my graduate student Laurie. Not content with purely academic questions, she had been looking for a research project

that would, as she said, “mean something to someone” instead of just sitting on the shelf.

iv. Methods

Laurie was eager to begin, but she hadn’t met Sweetgrass before. “It’s the grass that will teach you,” I advised, “so you have to get to know it.” I took her out to our restored sweetgrass meadows and it was love at first sniff. It didn’t take her long to recognize Sweetgrass after that. It was as if the plant wanted her to find it.

Together we designed experiments to compare the effects of the two harvesting methods the basket makers had explained. Laurie’s education so far was full of the scientific method, but I wanted her to live out a slightly different style of research. To me, an experiment is a kind of conversation with plants: I have a question for them, but since we don’t speak the same language, I can’t ask them directly and they won’t answer verbally. But plants can be eloquent in their physical responses and behaviors. Plants answer questions by the way they live, by their responses to change; you just need to learn how to ask. I smile when I hear my colleagues say “I discovered X.” That’s kind of like Columbus claiming to have discovered America. It was here all along, it’s just that he didn’t know it. Experiments are not about discovery but about listening and translating the knowledge of other beings.

My colleagues might scoff at the notion of basket makers as scientists, but when Lena and her daughters take 50 percent of the sweetgrass, observe the result, evaluate their findings, and then create management guidelines from them, that sounds a lot like experimental science to me. Generations of data collection and validation through time builds up to well-tested theories.

At my university, as at many others, graduate students must present their thesis ideas to a faculty committee. Laurie did a wonderful job of outlining the proposed experiment, ably describing multiple study sites, the many replicates, and intensive sampling techniques. But when she was through speaking there was an uneasy silence in the conference room. One professor shuffled through the proposal pages and pushed them aside dismissively. “I don’t see anything new here for science,” he said. “There’s not even a theoretical framework.”

A theory, to scientists, means something rather different from its popular use, which suggests something speculative or untested. A scientific theory is a cohesive body of knowledge, an explanation that is consistent among a range of cases and can

allow you to predict what might happen in unknown situations. Like this one. Our research was most definitely grounded in theory—Lena's, primarily —in the traditional ecological knowledge of indigenous peoples: If we use a plant respectfully, it will flourish. If we ignore it, it will go away. This is a theory generated from millennia of observations of plant response to harvest, subject to peer review by generations of practitioners, from basket makers to herbalists. Despite the weight of this truth, the committee could only struggle not to roll their eyes.

The dean looked over the glasses that had slid down his nose, fixing Laurie with a pointed stare and directing a sidelong glance toward me. "Anyone knows that harvesting a plant will damage the population. You're wasting your time. And I'm afraid I don't find this whole traditional knowledge thing very convincing." Like the former schoolteacher she was, Laurie was unfailingly calm and gracious as she explained further, but her eyes were steely.

Later, though, they were filled with tears. Mine, too. In the early years, no matter how carefully you prepared, this was nearly a rite of passage for women scientists—the condescension, the verbal smackdown from academic authorities, especially if you had the audacity to ground your work in the observations of old women who had probably not finished high school, and talked to plants to boot.

Getting scientists to consider the validity of indigenous knowledge is like swimming upstream in cold, cold water. They've been so conditioned to be skeptical of even the hardest of hard data that bending their minds toward theories that are verified without the expected graphs or equations is tough. Couple that with the unblinking assumption that science has cornered the market on truth and there's not much room for discussion.

Undeterred, we carried on. The basket makers had given us the prerequisites of the scientific method: observation, pattern, and a testable hypothesis. That sounded like science to me. So we began by setting up experimental plots in the meadows to ask the plants the question "Do these two different harvest methods contribute to decline?" And then we tried to detect their answer. We chose dense sweetgrass stands where the population had been restored rather than compromising native stands where pickers were active.

With incredible patience, Laurie did a census of the sweetgrass population in every plot to obtain precise measures of population density prior to harvest. She even marked individual stems of grass with colored plastic ties to keep track of them. When all had been tallied, she then began the harvest.

The plots were subject to one of the two harvest methods the basket makers had described. Laurie took half of the stems in each plot, pinching them off one by one carefully at the base in some plots and yanking up a tuft and leaving a small ragged gap in the sod in others. Experiments must have controls, of course, so she left an equal number of plots alone and did not harvest them at all. Pink flagging festooned the meadows to mark her study areas.

One day in the field we sat in the sun and talked about whether the method really duplicated the traditional harvest. “I know that it doesn’t,” she said, “because I’m not replicating the relationship. I don’t speak to the plants or make an offering.” She had wrestled with this but settled on excluding it: “I honor that traditional relationship, but I couldn’t ever do it as part of an experiment. It wouldn’t be right on any level—to add a variable that I don’t understand and that science can’t even attempt to measure. And besides, I’m not qualified to speak to sweetgrass.” Later, she admitted that it was hard to stay neutral in her research and avoid affection for the plants; after so many days among them, learning and listening, neutrality proved impossible. Eventually she was just careful to show them all her mindful respect, making her care a constant as well, so that she would not sway the results one way or the other. The sweetgrass she harvested was counted, weighed, and given away to basket makers.

Every few months, Laurie counted and marked all the grass in her plots: dead shoots, living ones, and brand-new shoots just pushing up from the ground. She charted the birth, the death, and the reproduction of all her grass stems. When the next July rolled around she harvested once more, just as women were doing in the native stands. For two years she harvested and measured the response of the grass along with a team of student interns. It was a little tough at first to recruit student helpers given that their task would be watching grass grow.

v. Results

Laurie observed carefully and filled her notebook with measurements, charting the vigor of each plot. She worried a little when the control plots were looking a little sickly. She was relying on these controls, the unharvested patches, to be the reference point for comparing the effects of harvesting in the other plots. We hoped they would perk up when spring came.

By the second year, Laurie was expecting her first child. The grass grew and grew, as did her belly. Bending and stooping became a little more difficult, to say nothing of lying in the grass to read plant tags. But she was faithful to her plants, sitting in the dirt among them, counting and marking. She said the quiet of fieldwork, the calm of sitting in a flower-strewn meadow with the smell of sweetgrass all around, was a good beginning for a baby. I think she was right.

As the summer wore on, it became a race to finish the research before the baby was born. Just weeks away from delivery, it became a team effort. When Laurie was done with a plot, she would call out for her field crew to help hoist her to her feet. This too was a rite of passage for women field biologists.

As her baby grew, Laurie came to believe with increasing conviction in the knowledge of her basket-making mentors, recognizing, as Western science often does not, the quality of observations from the women who had long had close relationships with plants and their habitats. They shared many of their teachings with her, and they knit many baby hats.

Baby Celia was born in the early fall, and a braid of sweetgrass was hung over her crib. While Celia slept nearby, Laurie put her data on the computer and began to make the comparisons between the harvesting methods. From the twist ties on every stem, Laurie could chart the births and deaths in the sample plots. Some plots were full of new young shoots that signaled a thriving population, and some were not.

Her statistical analyses were all sound and thorough, but she hardly needed graphs to tell the story. From across the field you could see the difference: some plots gleamed shiny golden green and some were dull and brown. The committee's criticism hovered in her mind: "Anyone knows that harvesting a plant will damage the population."

The surprise was that the failing plots were not the harvested ones, as predicted, but the unharvested controls. The sweetgrass that had not been picked or disturbed in any way was choked with dead stems while the harvested plots were thriving. Even though half of all stems had been harvested each year, they quickly grew back, completely replacing everything that had been gathered, in fact producing more shoots than were present before harvest. Picking sweetgrass seemed to actually stimulate growth. In the first year's harvest, the plants that grew the very best were the ones that had been yanked up in a handful. But, whether it was pinched singly or

pulled in a clump, the end result was nearly the same: it didn't seem to matter how the grass was harvested, only that it was.

Laurie's graduate committee had dismissed this possibility from the outset. They had been taught that harvesting causes decline. And yet the grasses themselves unequivocally argued the opposite point. After the grilling Laurie received over her research proposal, you might imagine she was dreading the thesis defense. But she had one thing skeptical scientists value most: data. While Celia slept in her proud father's arms, Laurie presented her graphs and tables to demonstrate that sweetgrass flourishes when it's harvested and declines when it is not. The doubting dean was silent. The basket makers smiled.

vi. Discussion

We are all the product of our worldviews—even scientists who claim pure objectivity. Their predictions for sweetgrass were consistent with their Western science worldview, which sets human beings outside of "nature" and judges their interactions with other species as largely negative. They had been schooled that the best way to protect a dwindling species was to leave it alone and keep people away. But the grassy meadows tell us that for sweetgrass, human beings are part of the system, a vital part. Laurie's findings might have been surprising to academic ecologists but were consistent with the theory voiced by our ancestors. "If we use a plant respectfully it will stay with us and flourish. If we ignore it, it will go away."

"Your experiment seems to demonstrate a significant effect," said the dean. "But how do you explain it? Are you implying that the grass that was unharvested had its feelings hurt by being ignored? What is the mechanism responsible for this?"

Laurie admitted that the scientific literature held no explanations for the relationship between basket makers and sweetgrass since such questions were not generally deemed worthy of scientific attention. She turned to studies of how grasses respond to other factors, such as fire or grazing. She discovered that the stimulated growth she had observed was well known to range scientists. After all, grasses are beautifully adapted to disturbance—it's why we plant lawns. When we mow them they multiply. Grasses carry their growing points just beneath the soil surface so that when their leaves are lost to a mower, a grazing animal, or a fire, they quickly recover.

She explained how harvesting thinned the population, allowing the remaining shoots to respond to the extra space and light by reproducing quickly. Even the pulling method was beneficial. The underground stem that connects the shoots is dotted with buds. When it's gently tugged, the stem breaks and all those buds produce thrifty young shoots to fill the gap.

Many grasses undergo a physiological change known as compensatory growth in which the plant compensates for loss of foliage by quickly growing more. It seems counterintuitive, but when a herd of buffalo grazes down a sward of fresh grass, it actually grows faster in response. This helps the plant recover, but also invites the buffalo back for dinner later in the season. It's even been discovered that there is an enzyme in the saliva of grazing buffalo that actually stimulates grass growth. To say nothing of the fertilizer produced by a passing herd. Grass gives to buffalo and buffalo give to grass.

The system is well balanced, but only if the herd uses the grass respectfully. Free-range buffalo graze and move on, not returning to the same place for many months. Thus they obey the rule of not taking more than half, of not overgrazing. Why shouldn't it also be true for people and sweetgrass? We are no more than the buffalo and no less, governed by the same natural laws.

With a long, long history of cultural use, sweetgrass has apparently become dependent on humans to create the "disturbance" that stimulates its compensatory growth. Humans participate in a symbiosis in which sweetgrass provides its fragrant blades to the people and people, by harvesting, create the conditions for sweetgrass to flourish.

It's intriguing to wonder whether the regional decline in sweetgrass might be due not to overharvesting but rather to underharvesting. Laurie and I pored over the map of historical locations for sweetgrass created by a former student, Daniela Shebitz. There were blue dots where sweetgrass used to be found but has since disappeared. Red dots marked the few places where sweetgrass was reported historically and where it is still thriving. These red dots are not randomly scattered. They are clustered around Native communities, particularly those known for their sweetgrass basketry. Sweetgrass thrives where it is used and disappears elsewhere.

Science and traditional knowledge may ask different questions and speak different languages, but they may converge when both truly listen to the plants. To relate the story the ancestors told us to the academics in the room, however, we needed to

use scientific explanations expressed in the language of mechanism and objectification: “If we remove 50 percent of the plant biomass, the stems are released from resource competition. The stimulus of compensatory growth causes an increase in population density and plant vigor. In the absence of disturbance, resource depletion and competition result in a loss of vigor and increased mortality.”

The scientists gave Laurie a warm round of applause. She had spoken their language and made a convincing case for the stimulatory effect of harvesters, indeed for the reciprocity between harvesters and sweetgrass. One even retracted his initial criticism that this research would “add nothing new to science.” The basket makers who sat at the table simply nodded their heads in agreement. Wasn’t this just as the elders have said?

The question was, how do we show respect? Sweetgrass told us the answer as we experimented: sustainable harvesting can be the way we treat a plant with respect, by respectfully receiving its gift.

Perhaps it is no coincidence that it is Sweetgrass that reveals this story. *Wiingaashk* was the first to be planted by Skywoman on the back of Turtle Island. The grass gives its fragrant self to us and we receive it with gratitude. In return, through the very act of accepting the gift, the pickers open some space, let the light come in, and with a gentle tug bestir the dormant buds that make new grass. Reciprocity is a matter of keeping the gift in motion through self- perpetuating cycles of giving and receiving.

Our elders taught that the relationship between plants and humans must be one of balance. People can take too much and exceed the capacity of the plants to share again. That’s the voice of hard experience that resonates in the teachings of “never take more than half.” And yet, they also teach that we can take too little. If we allow traditions to die, relationships to fade, the land will suffer. These laws are the product of hard experience, of past mistakes. And not all plants are the same; each has its own way of regenerating. Some, unlike sweetgrass, are easily harmed by harvest. Lena would say that the key is to know them well enough to respect the difference.

vii. Conclusions

With their tobacco and their thanks, our people say to the Sweetgrass, “I need you.” By its renewal after picking, the grass says to the people, “I need you, too.”

Mishkos kenomagwen. Isn't this the lesson of grass? Through reciprocity the gift is replenished. All of our flourishing is mutual.

viii. Acknowledgments

In a field of tall grass, with only the wind for company, there is a language that transcends the differences between scientific and traditional understandings, the data or the prayer. The wind moves through and carries the grass song. It sounds to me like *mishhhhkos*, over and over again on ripples of moving grass. After all it has taught us, I want to say thank you.

ix. References Cited

Wiingaashk, Buffalo, Lena, the Ancestors.

“Collateral Damage” from *Braiding Sweetgrass*

by Robin Wall Kimmerer

The headlights throw two beams through the fog from a long way off as the car winds toward us. The rise and fall of the lights has become our signal to dash into the road, grabbing up one soft black body in each hand. The beams appear and disappear in the dips and curves as we shuttle back and forth with flashlight beams speckling the pavement. When we hear the engine we know there is only time for one last run before the car crests the hill and bears down upon us.

Standing on the shoulder, I can see faces as the car draws near, greenish in the dashboard lights, looking right at us as the spray from the tires flies up. Our eyes meet and the brake lights flash red for just a heartbeat, lit up like momentary synapses in the driver’s brain. The light telegraphs a hint of thought for fellow humans in the rain on the side of a lonely country road. I’m waiting for them to roll down a window and ask if we need help, but they don’t stop. The driver looks back over his shoulder, brake lights dimming as he speeds away. If cars scarcely brake for *Homo sapiens*, what hope can we hold for *Ambystoma maculata*, our other neighbors who travel this road in the night?

Rain beats against my kitchen window in the falling dusk. I can hear geese outside, in low formation over the valley. Winter is letting go. Pausing by the stove with raincoats draped over my arm, I stop to stir a pot of pea soup, sending up clouds of steam that mist over the window. We’ll be glad for a warm cup during the night ahead.

The six o’clock news comes on while I am headfirst in the closet, rounding up flashlights. It has begun—bombs are falling on Baghdad tonight. I stop in the middle of the floor, listening, with my hands full of boots, a red pair and a black. Somewhere another woman looks out her window, but the formation of dark shapes in her sky is not a skein of spring geese returning. Skies billowing with smoke, homes alight, sirens wailing. CNN reports the number of sorties and tons of ordnance like box scores in a baseball game. The level of collateral damage, they say, is as yet unknown.

Collateral damage: shielding words to keep us from naming the consequences of a missile gone astray. The words ask us to turn our faces away, as if man-made destruction were an inescapable fact of nature. Collateral damage: measured in overturned soup pots and wailing children. Heavy with helplessness, I turn off the

radio and call my family to supper. When the dishes are done, we slip into raincoats then out into the night, driving the back roads to Labrador Hollow.

While it rains bombs on Baghdad, the first rain of spring falls on our valley. Soft and steady, it penetrates the forest floor, melting away the last of the ice crystals beneath the winter-weary blanket of leaves. The splatter and splash is a welcome sound after the long silence of snow. To a salamander beneath a log, the first heavy raindrops must sound like the knuckles of spring knocking hard on the door overhead. After six months of torpor, stiff limbs slowly flex, tails wiggle out of winter immobility, and within minutes, snouts nose upward and legs push away cold earth as the salamanders crawl up into the night. The rain washes away traces of clinging soil and polishes their smooth black skin. The land is waking up, rising to the call of rain.

After we pull off the road and get out of the car, the quiet is stunning in the wake of swishing windshield wipers and the defroster going full tilt. The warm rain on cold earth has raised a ground fog, wrapping around the bare trees. Our voices are muffled in the mist. Our flashlights diffuse into warm halos.

Here in upstate New York, flocks of geese mark the change of seasons, noisily making their way from winter safety to the breeding grounds of spring. Largely unseen, but equally dramatic, is the migration of salamanders from winter burrows to the vernal pools where they will meet their mates. The first warm rain of spring, a soaking rain coinciding with a temperature above forty-two degrees, sets the forest floor to rustling and stirring. En masse they rise from the hidden places, blink at the open air, and start on their way. This outpouring of animals is nearly invisible, unless you happen to be in a swamp on a rainy spring night. Salamanders move when darkness protects them from predators and rain keeps their skin moist. And they move by the thousands, like a herd of sluggish buffalo. Like the buffalo, too, their numbers diminish each year.

Like its nearby cousins, the Finger Lakes, Labrador Pond lies in the bottom of a V-shaped valley flanked by two steep hills left behind by the last glacier. The forested slopes curve around the pond like the sides of a bowl, funneling amphibians from the woods of the entire watershed straight to the water. But their route is interrupted by a road that snakes through the hollow. The pond and surrounding hills are protected as state forest, but the road is a free-for-all.

We walk down the deserted road, scanning our lights back and forth over the pavement. Salamanders aren’t the only ones on the move tonight: wood frogs, bullfrogs, green frogs, leopard frogs, and newts also hear the call and begin their

annual journey. There are toads, peepers, red efts, and legions of tree frogs all with mating on their minds. The road is a circus of jumps and leaps flashing in and out of our flashlights. My beam catches the glittering gold of an eye. The peeper freezes as I approach and then hops away. Ahead of us, the road is alive with frogs leaping across, two here in my light, three over there, bounding toward the pond. With their prodigious leaps they cross the road in just a few seconds. Not so the heavy-bodied salamanders, who belly their way across the road. Their journey takes about two minutes, and in two minutes anything can happen.

Spotting the lumbering forms among the frogs, we stop and pick them up one after the other, carefully setting them on the other side of the road. We walk back and forth between the passage of cars over the same small stretch, and each time we look there are more—the land seems to be releasing salamanders as numerous as the geese rising off a marsh.

I run my light across the road and the center line reflects bright yellow against the rain-black asphalt. In the corner of my eye, there is something darker than dark, a break in reflection off the pavement that draws my light back to that spot. The shadow resolves into a big spotted salamander, *Ambystoma maculata*, black and yellow like the road. The shape is so primitive, with right- angle limbs jutting from the side and moving with a jerky, mechanical motion across the road, dragging a thick tail in a sinuous side-to-side wave behind it. When it stops in the circle of my light, I reach out to touch its skin, blue-black, like night congealed. The body is splotched with opaque yellow like drops of paint on a wet surface, blurred at the edges. Its wedge-shaped head swings from side to side, blunt snout with eyes so dark they disappear into its face. By its size—about seven inches long—and its swollen sides, I'd guess this is a female. I wonder what it feels like to drag that tender skin—with a smooth, soft belly made for sliding over wet leaves—across the asphalt.

I stoop to pick her up, circling my two fingers just behind her front legs. There is surprisingly little resistance. It's like picking up an overripe banana: my fingertips sink into her body, cold and soft and wet. I gently set her down on the shoulder and wipe my hands on my pants. Without a backward glance, she lunges over the embankment, down to the pond.

The females are the first to arrive. Heavy with eggs, they will slide into the shallows and disappear among the decaying leaves on the bottom. They wait, fecund and sluggish in the cold water, for the males, who will make the same journey down from the hillsides a day or two later.

They come out from under logs and across streams all pointed in the same direction: the pool where they were born. Their route is circuitous because they don't have the ability to climb over obstacles. They follow along the edges of any log or rock until it ends and they are free to go forward, on to the pond. The natal pond may be as much as half a mile from their wintering spot, and yet they locate it unerringly. Salamanders have a guidance system easily as complex as the "smart bombs" winding their way to targets in Iraqi neighborhoods tonight. Without the benefit of satellite or microchip, salamanders navigate by a combination of magnetic and chemical signals that herpetologists are just beginning to understand.

Part of their direction-finding ability relies on a precise reading of the lines in the earth's magnetic field. A small organ in the brain processes magnetic data and guides the salamander to its pond. Though many other ponds and vernal pools lie along the route, they will not stop until they arrive at the birthplace, struggling mightily to get there. Once they are close, homing in salamanders seems to be similar to salmon identifying their home river: they smell their way with a nasal gland on their snouts. Following the earth's magnetic signals gets them to the neighborhood and then scent takes over to guide them home. It's like getting off an airplane and then finding your way to your childhood home by following the ineffable odor of Sunday dinner and your mother's perfume.

On last year's mission to the hollow, my daughter begged to follow the salamanders and see where they were going. We trailed behind by flashlight as the amphibians twined between scarlet stems of red osier and clambered over flattened tussocks of sedge. They stopped far short of the main pond, on the edges of a vernal pool, a small depression in the land that goes unnoticed in summer but reliably fills with snowmelt every spring, making a watery mosaic. Salamanders choose these temporary basins to lay eggs because they are too shallow and short-lived for fish, which would gobble up the salamander larvae, to inhabit. The pool's evanescence is the newborn's protection from fish.

We followed the salamanders to the water's edge, where platelets of ice still clung to the shore. They did not hesitate, but strode purposefully into the water and disappeared. My daughter was disappointed, expecting to see them loitering on the beach or doing belly flops into the pool. She searched the water's surface with her flashlight, wanting to see what happened next, but there were only dappled leaves on the bottom of the pool, patches of light and dark. Nothing to see—until we realized that the patches of light and dark were not leaves at all, but the black and yellow spots of dozens of salamanders. Everywhere the light stopped there were salamanders, the bottom of the pool a blanket of animals. And they were moving,

swirling about each other like a room full of dancers. Compared to their ponderous movement on land, they were fleet in the water, swimming as gracefully as seals. One flick of the tail and they were gone from the circle of light.

The glassy surface of the pond was suddenly broken from below, like the upwelling of a surging spring, and the water started to churn as they moved together in a roiling crowd, yellow spots flashing. We stood in amazed witness to their mating ritual, a congress of salamanders. As many as fifty males and females danced and swirled together, a rapturous celebration after a long year of solitary, celibate existence eating bugs under a log. Bubbles rose from the bottom of the pond like champagne.

Unlike most amphibians, *Ambystoma maculata* does not spill its eggs and sperm freely into the water for a frenzy of mass fertilization. The species has evolved a more probable scheme to ensure the meeting of egg and sperm. Males break away from the dancing swarm, take a gulp of air, and swim for the bottom of the pond, where they release a glistening spermatophore—a gelatinous sac of sperm with a stalk to attach it to a twig or a leaf. The females then leave the dance and seek out the quarter-inch sacs, which hover like shiny Mylar balloons bobbing in the water. They draw the spermatophores into an internal cavity where eggs are waiting. Safely inside, the sperm are then released from the sac and fertilize the pearly eggs.

A few days later, each female will lay a mass of one hundred to two hundred eggs in a gelatinous mass. The expectant mother will linger nearby until the eggs hatch, but then she returns, alone, to the woods. The newborn salamanders stay behind in the safety of the pool for several months, metamorphosing until they are capable of life on land. By the time the pool has dried up and forced them out, their gills will be replaced by lungs and they are ready to forage on their own. The juvenile salamanders, or newts, are wanderers who will not return to the pond until they are sexually mature, four to five years later. Salamanders can be long-lived beings. Adults may make the mating migration through a lifetime as long as eighteen years, but only if they can cross the road.

Amphibians are one of the most vulnerable groups on the planet. Subject to habitat loss as wetlands and forests disappear, amphibians are the collateral damage we blindly accept as the cost of development. And because amphibians breathe through their skin, they have little ability to filter out toxins at that moist membrane between animal and atmosphere. Even when their habitats are safe from industry, their atmosphere may not be. Toxins in the air and water, acid rain, heavy metals, and synthetic hormones all end up in the water in which they gestate. Developmental

abnormalities like six-legged frogs and twisted salamanders are now found throughout the industrialized world.

Tonight the salamanders' biggest threat is the cars that go speeding by, their occupants unaware of the spectacle that is taking place beneath their tires. From inside the car, listening to late-night radio, you just don't know. But standing on the roadside, you can hear the pop of the body, hear the moment when a glistening being following magnetic trails toward love is reduced to red pulp on the pavement. We try to work faster, but there are so many, and we are so few.

A green Dodge pickup I recognize races by and we stand back on the shoulder. It was one of my neighbors who has a dairy farm just up the road, but he doesn't even see us. I suspect his thoughts are far away tonight, straining toward Baghdad. His son, Mitch, is stationed in Iraq. Mitch is a nice kid, the kind who, with a friendly wave, would always pull his slow tractor off to the roadside to let cars pass safely. I suppose he's driving a tank now. The fate of salamanders crossing the road in his old hometown might seem completely unconnected to the scene he faces.

Tonight, though, when the fog wraps us all in the same cold blanket, the edges seem to blur. The carnage on this dark country road and the broken bodies on the streets of Baghdad do seem connected. Salamanders, children, young farmers in uniform—they are not the enemy or the problem. We have not declared war on these innocents, and yet they die just as surely as if we had. They are all collateral damage. If it is oil that sends the sons to war, and oil that fuels the engines that roar down this hollow, then we are all complicit, soldiers, civilians, and salamanders connected in death by our appetite for oil.

Cold and tired, we stop and pour out a cup of soup from the thermos. Its steam rises to mingle with the fog. We sip quietly and listen to the night. Suddenly I hear voices, but there are no houses nearby. Up around the curve I catch the strobes of other flashlights. I quickly shut off my light and close up the thermos. We back away into shadow and watch as the lights come nearer, a whole line of them. Who would be out on a night like this? Only someone out looking for trouble, and I don't want to be it.

Kids use this road sometimes as a drinking spot, a place to shoot beer cans. I once saw a pair of young men kicking a toad between them like a hacky sack. I shudder to think what brings them here. The lights are closer now, at least a dozen all scattered across the road like a patrol. The beams scan back and forth over the road. As they come closer, the pattern of their lights becomes oddly familiar. It is the

very same pattern we've been making all night. And then I hear their voices through the fog.

"Look, here's another one—a female."

"Hey—I got two over here."

"Add three peepers."

Grinning in the dark, I switch on my light again and step out to meet them as they bend and carry the salamanders to safety. We are so glad to see each other and we pump each other's hands as our voices rise in laughter around a virtual campfire made by flashlights. I pour out soup for everybody and we are all momentarily bound together with the giddiness of relief, both to know that the approaching lights are friend and not foe and to recognize that we are not alone in our efforts.

We all introduce ourselves and get a look at the faces under the dripping hoods. Our fellow travelers are students from a herpetology class at the college. They all have clipboards and Rite in the Rain notebooks to record their observations. I feel embarrassed to have assumed that they were troublemakers. Ignorance makes it too easy to jump to conclusions about what we don't understand.

The class is here to study the effects of roads on amphibians.

They tell us that frogs and toads take only about fifteen seconds to cross the road and mostly escape the cars. The spotted salamanders average eighty-eight seconds. They may have evaded countless predators, survived the summer drought, endured the winter without freezing, but it all comes down to eighty-eight seconds.

The students' efforts on behalf of *Ambystoma* go beyond roadside rescue. The highway department could install salamander crossings, special culverts that allow the animals to avoid the road, but they're expensive and the authorities need to be convinced of their importance. The class mission tonight is to take a census of the amphibians crossing the road to estimate the total numbers of animals who move from the hills to the pond, and the number who die en route. If they can get adequate data to show that road deaths endanger the viability of this population, then they may be able to persuade the state to take action. There's just one problem. In order to obtain accurate estimates of salamander mortality, they have to count both the animals who make it across the road and those who don't.

It turns out that tallying death is easy: they've developed a system for identifying the species of animal by the size of the blotch it leaves on the road, which is then scraped up to avoid counting it again on the next traverse of the road. Sometimes death occurs even without collision. Salamanders are so soft bodied that merely the pressure wave generated by a passing vehicle can be fatal. The missing number is the denominator of the death equation—the number of animals who d o make it safely across. How can they take inventory of the successful crossings on a long stretch of road in total darkness?

At widely spaced intervals along the road, drift fences have been installed. A drift fence is simply a length of snow fence about eight feet long, with a foot-high strip of aluminum roof flashing wired like a wall along its base. The salamanders can't wiggle through. Confronting this obstacle, they edge along the drift fence as if it were a log or a rock. They attempt to follow it to its end, slithering along in the darkness, moving by feel of the fence against skin. Until suddenly the ground vanishes and they fall into a buried plastic bucket from which they cannot escape. The students come along every so often and count the animals in the bucket, record the species on their clipboards, and then gently release them on the other side of the fence, on their way to the pond. At night's end, the number of animals caught by the drift fences provides an estimate of the number who safely crossed the road.

These studies may provide the evidence that will save the salamanders, but there is a short-term cost to that long-term benefit. In order to do the research properly, no human intervention is allowed. When a car is coming, the students have to stand back, grit their teeth, and let it happen. Our well-intentioned salamander rescues have in fact biased the experiment tonight, as we decreased the number who normally would have been hit, causing an underestimate in the serious losses that occur. It poses an ethical dilemma for the students. The dead who could have been saved become the collateral damage of the study—a sacrifice that they hope will pay off in future protection for the species.

This roadkill monitoring is the project of James Gibbs, an internationally renowned conservation biologist. He is a leader in conserving Galapagos tortoises and Tanzanian toads—but his concerns are also here in Labrador Hollow. He and his students set up the drift fences, patrol the road, and stay up all night counting. Gibbs confesses that sometimes, on rainy nights when he knows the salamanders are moving—and dying—he can't sleep. He puts on a raincoat and goes out to carry them across. Aldo Leopold had it right: naturalists live in a world of wounds that only they can see.

As night deepens, there are no more headlights twisting down the hollow. By midnight even the slowest salamander can cross in safety, so we trudge back to the car and head for home, driving at a snail's pace until we're out of the hollow lest our own wheels undo our work. We're painfully careful, but I know we are as guilty as anyone.

Driving home through the fog, we hear more war news on the radio. Columns of tanks and Bradley Fighting Vehicles are advancing over the Iraqi countryside, through a sandstorm as dense as the fog that shrouds us here. I wonder what is crushed beneath them as they pass. Cold and tired, I crank up the heater and the car fills with the smell of wet wool. I think back on our night's work and the good people we met.

What is it that drew us to the hollow tonight? What crazy kind of species is it that leaves a warm home on a rainy night to ferry salamanders across a road? It's tempting to call it altruism, but it's not. There is nothing selfless about it. This night heaps rewards on the givers as well as the recipients. We get to be there, to witness this amazing rite, and, for an evening, to enter into relationship with other beings, as different from ourselves as we can imagine.

It has been said that people of the modern world suffer a great sadness, a "species loneliness"—estrangement from the rest of Creation. We have built this isolation with our fear, with our arrogance, and with our homes brightly lit against the night. For a moment as we walked this road, those barriers dissolved and we began to relieve the loneliness and know each other once again.

Salamanders are so very much the "other," cold, slimy creatures verging on repulsive to the warm-blooded Homo sapiens. Their startling otherness makes it all the more remarkable that we were here tonight in their defense. Amphibians offer few of the warm fuzzy feelings that fuel our protection of charismatic mammals that look back at us with Bambi's grateful eyes. They bring us face to face with our innate xenophobia, sometimes directed at other species and sometimes directed at our own, whether in this hollow or in deserts halfway around the globe. Being with salamanders gives honor to otherness, offers an antidote to the poison of xenophobia. Each time we rescue slippery, spotted beings we attest to their right to be, to live in the sovereign territory of their own lives.

Carrying salamanders to safety also helps us to remember the covenant of reciprocity, the mutual responsibility that we have for each other. As the perpetrators of the war zone on this road, are we not bound to heal the wounds that we inflict?

The news makes me feel powerless. I can't stop bombs from falling and I can't stop cars from speeding down this road. It is beyond my power. But I can pick up salamanders. For one night I want to clear my name. What is it that draws us to this lonely hollow? Maybe it is love, the same thing that draws the salamanders from under their logs. Or maybe we walked this road tonight in search of absolution.

As the temperature drops, single voices—clear and hollow—replace the keening chorus: the ancient speech of frogs. One word becomes clear, as if spoken in English. "Hear! Hear! Hear! The world is more than your thoughtless commute. We, the collateral, are your wealth, your teachers, your security, your family. Your strange hunger for ease should not mean a death sentence for the rest of Creation."

"Hear!" calls a peeper in the headlights.

"Hear! " calls a young man trapped in a tank far from home. "Hear! " calls a mother whose home is now a burnt-out ruin.

There must be an end to this.

By the time I get home it is late and I cannot sleep, so I walk up the hill to the pond behind my house. Here too the air is ringing with their calls. I want to light a sweetgrass smudge, to wash away the sadness in a cloud of smoke. But the fog is too heavy and the matches just bleed a red streak on the box. As it should be. There should be no washing away tonight; better to wear the grief like a sodden coat.

"Weep! Weep!" calls a toad from the water's edge. And I do. If grief can be a doorway to love, then let us all weep for the world we are breaking apart so we can love it back to wholeness again.

Preface

The essay that follows is the first full published report on a project originally conceived almost fifteen years ago. At that time I was a graduate student in theoretical physics already within sight of the end of my dissertation. A fortunate involvement with an experimental college course treating physical science for the non-scientist provided my first exposure to the history of science. To my complete surprise, that exposure to out-of-date scientific theory and practice radically undermined some of my basic conceptions about the nature of science and the reasons for its special success.

Those conceptions were ones I had previously drawn partly from scientific training itself and partly from a long-standing avocational interest in the philosophy of science. Somehow, whatever their pedagogic utility and their abstract plausibility, those notions did not at all fit the enterprise that historical study displayed. Yet they were and are fundamental to many discussions of science, and their failures of verisimilitude therefore seemed thoroughly worth pursuing. The result was a drastic shift in my career plans, a shift from physics to history of science and then, gradually, from relatively straightforward historical problems back to the more philosophical concerns that had initially led me to history. Except for a few articles, this essay is the first of my published works in which these early concerns are dominant. In some part it is an attempt to explain to myself and to friends how I happened to be drawn from science to its history in the first place.

The final stage in the development of this essay began with an invitation to spend the year 1958–59 at the Center for Advanced Studies in the Behavioral Sciences. Once again I was able to give undivided attention to the problems discussed below. Even more important, spending the year in a community composed predominantly of social scientists confronted me with unanticipated problems about the differences between such communities and those of the natural scientists among whom I had been trained. Particularly, I was struck by the number and extent of the overt disagreements between social scientists about the nature of legitimate scientific problems and methods. Both history and acquaintance made me doubt that practitioners of the natural sciences possess firmer or more permanent answers to such questions than their colleagues in social science. Yet, somehow, the practice of astronomy, physics, chemistry, or biology normally fails to evoke the controversies over fundamentals that today often seem endemic among, say, psychologists or sociologists. Attempting to discover the source of that difference led me to recognize the role in scientific research of what I have since called "paradigms." These I take to be universally recognized scientific achievements that for a time provide model problems and solutions to a community of practitioners. Once that piece of my puzzle fell into place, a draft of this essay emerged rapidly.

Since my most fundamental objective is to urge a change in the perception and evaluation of familiar data, the schematic character of this first presentation need be no drawback. On the contrary, readers whose own research has prepared them for the sort of reorientation here advocated may find the essay form both more suggestive and easier to assimilate. But it has disadvantages as well, and these may justify my illustrating at the very start the sorts of extension in both scope and depth that I hope ultimately to include in a longer version. Far more historical evidence is available than I have had space to exploit below. Furthermore, that evidence comes from the history of biological as well as of physical science. My decision to deal here exclusively with the latter was made partly to increase this essay's coherence and partly on grounds of present competence. In addition, the view of science to be developed here suggests the potential fruitfulness of a number of new sorts of research, both historical and sociological. For example, the manner in which anomalies, or violations of expectation, attract the increasing attention of a scientific community needs detailed study, as does the emergence of the crises that may be induced by repeated failure to make an anomaly conform. Or again, if I am right that each scientific revolution alters the historical perspective of the community that experiences it, then that change of perspective should affect the structure of postrevolutionary textbooks and research publications. One such effect—a shift in the distribution of the technical literature cited in the footnotes to research reports—ought to be studied as a possible index to the occurrence of revolutions.

Finally, and perhaps most important of all, limitations of space have drastically affected my treatment of the philosophical implications of this essay's historically oriented view of science. Clearly, there are such implications, and I have tried both to point out and to document the main ones. But in doing so I have usually refrained from detailed discussion of the various positions taken by contemporary philosophers on the corresponding issues. Where I have indicated skepticism, it has more often been directed to a philosophical attitude than to any one of its fully articulated expressions. As a result, some of those who know and work within one of those articulated positions may feel that I have missed their point. I think they will be wrong, but this essay is not calculated to convince them. To attempt that would have required a far longer and very different sort of book.

VI. Anomaly and the Emergence of Scientific Discoveries

Normal science, the puzzle-solving activity we have just examined, is a highly cumulative enterprise, eminently successful in its aim, the steady extension of the scope and precision of scientific knowledge. In all these respects it fits with great precision the most usual image of scientific work. Yet one standard product of the scientific enterprise is missing. Normal science does not aim at novelties of fact or theory and, when successful, finds none. New and unsuspected phenomena are, however, repeatedly uncovered by scientific research, and radical new theories have again and again been invented by scientists. History even suggests that the scientific enterprise has developed a uniquely powerful technique for producing surprises of this sort. If this characteristic of science is to be reconciled with what has already been said, then research under a paradigm must be a particularly effective way of inducing paradigm change. That is what fundamental novelties of fact and theory do. Produced inadvertently by a game played under one set of rules, their assimilation requires the elaboration of another set. After they have become parts of science, the enterprise, at least of those specialists in whose particular field the novelties lie, is never quite the same again.

We must now ask how changes of this sort can come about, considering first discoveries, or novelties of fact, and then inventions, or novelties of theory. That distinction between discovery and invention or between fact and theory will, however, immediately prove to be exceedingly artificial. Its artificiality is an important clue to several of this essay's main theses. Examining selected discoveries in the rest of this section, we shall quickly find that they are not isolated events but extended episodes with a regularly recurrent structure. Discovery commences with the awareness of anomaly, i.e., with the recognition that nature has somehow violated the paradigm-induced

expectations that govern normal science. It then continues with a more or less extended exploration of the area of anomaly. And it closes only when the paradigm theory has been adjusted so that the anomalous has become the expected. Assimilating a new sort of fact demands a more than additive adjustment of theory, and until that adjustment is completed—until the scientist has learned to see nature in a different way—the new fact is not quite a scientific fact at all.

To see how closely factual and theoretical novelty are intertwined in scientific discovery examine a particularly famous example, the discovery of oxygen. At least three different men have a legitimate claim to it, and several other chemists must, in the early 1770's, have had enriched air in a laboratory vessel without knowing it.[1] The progress of normal science, in this case of pneumatic chemistry, prepared the way to a breakthrough quite thoroughly. The earliest of the claimants to prepare a relatively pure sample of the gas was the Swedish apothecary, C. W. Scheele. We may, however, ignore his work since it was not published until oxygen's discovery had repeatedly been announced elsewhere and thus had no effect upon the historical pattern that most concerns us here.[2] The second in time to establish a claim was the British scientist and divine, Joseph Priestley, who collected the gas released by heated red oxide of mercury as one item in a prolonged normal investigation of the "airs" evolved by a large number of solid substances. In 1774 he identified the gas thus produced as nitrous oxide and in 1775, led by further tests, as common air with less than its usual quantity of phlogiston. The third claimant, Lavoisier, started the work that led him to oxygen after Priestley's experiments of 1774 and possibly as the result of a hint from Priestley. Early in

[1] For the still classic discussion of oxygen's discovery, see A. N. Meldrum, *The Eighteenth-Century Revolution in Science—the First Phase* (Calcutta, 1930), chap. v. An indispensable recent review, including an account of the priority controversy, is Maurice Daumas, *Lavoisier, théoricien et expérimentateur* (Paris, 1955), chaps. ii–iii. For a fuller account and bibliography, see also T. S. Kuhn, "The Historical Structure of Scientific Discovery," *Science*, CXXXVI (June 1, 1962), 760–64.

[2] See, however, Uno Bocklund, "A Lost Letter from Scheele to Lavoisier," *Lychnos*, 1957–58, pp. 39–62, for a different evaluation of Scheele's role.

1775 Lavoisier reported that the gas obtained by heating the red oxide of mercury was "air itself entire without alteration [except that] . . . it comes out more pure, more respirable."[3] By 1777, probably with the assistance of a second hint from Priestley, Lavoisier had concluded that the gas was a distinct species, one of the two main constituents of the atmosphere, a conclusion that Priestley was never able to accept.

This pattern of discovery raises a question that can be asked about every novel phenomenon that has ever entered the consciousness of scientists. Was it Priestley or Lavoisier, if either, who first discovered oxygen? In any case, when was oxygen discovered? In that form the question could be asked even if only one claimant had existed. As a ruling about priority and date, an answer does not at all concern us. Nevertheless, an attempt to produce one will illuminate the nature of discovery, because there is no answer of the kind that is sought. Discovery is not the sort of process about which the question is appropriately asked. The fact that it is asked—the priority for oxygen has repeatedly been contested since the 1780's—is a symptom of something askew in the image of science that gives discovery so fundamental a role. Look once more at our example. Priestley's claim to the discovery of oxygen is based upon his priority in isolating a gas that was later recognized as a distinct species. But Priestley's sample was not pure, and, if holding impure oxygen in one's hands is to discover it, that had been done by everyone who ever bottled atmospheric air. Besides, if Priestley was the discoverer, when was the discovery made? In 1774 he thought he had obtained nitrous oxide, a species he already knew; in 1775 he saw the gas as dephlogisticated air, which is still not oxygen or even, for phlogistic chemists, a quite unexpected sort of gas. Lavoisier's claim may be stronger, but it presents the same problems. If we refuse the palm to Priestley, we cannot award it to Lavoisier for the work of 1775 which led

[3] J. B. Conant, *The Overthrow of the Phlogiston Theory: The Chemical Revolution of 1775–1789* ("Harvard Case Histories in Experimental Science," Case 2; Cambridge, Mass., 1950), p. 23. This very useful pamphlet reprints many of the relevant documents.

him to identify the gas as the "air itself entire." Presumably we wait for the work of 1776 and 1777 which led Lavoisier to see not merely the gas but what the gas was. Yet even this award could be questioned, for in 1777 and to the end of his life Lavoisier insisted that oxygen was an atomic "principle of acidity" and that oxygen gas was formed only when that "principle" united with caloric, the matter of heat.[4] Shall we therefore say that oxygen had not yet been discovered in 1777? Some may be tempted to do so. But the principle of acidity was not banished from chemistry until after 1810, and caloric lingered until the 1860's. Oxygen had become a standard chemical substance before either of those dates.

Clearly we need a new vocabulary and concepts for analyzing events like the discovery of oxygen. Though undoubtedly correct, the sentence, "Oxygen was discovered," misleads by suggesting that discovering something is a single simple act assimilable to our usual (and also questionable) concept of seeing. That is why we so readily assume that discovering, like seeing or touching, should be unequivocally attributable to an individual and to a moment in time. But the latter attribution is always impossible, and the former often is as well. Ignoring Scheele, we can safely say that oxygen had not been discovered before 1774, and we would probably also say that it had been discovered by 1777 or shortly thereafter. But within those limits or others like them, any attempt to date the discovery must inevitably be arbitrary because discovering a new sort of phenomenon is necessarily a complex event, one which involves recognizing both *that* something is and *what* it is. Note, for example, that if oxygen were dephlogisticated air for us, we should insist without hesitation that Priestley had discovered it, though we would still not know quite when. But if both observation and conceptualization, fact and assimilation to theory, are inseparably linked in discovery, then discovery is a process and must take time. Only when all the relevant conceptual categories are prepared in advance, in which case the phenomenon would not

[4] H. Metzger, *La philosophie de la matière chez Lavoisier* (Paris, 1935); and Daumas, *op. cit.*, chap. vii.

be of a new sort, can discovering *that* and discovering *what* occur effortlessly, together, and in an instant.

Grant now that discovery involves an extended, though not necessarily long, process of conceptual assimilation. Can we also say that it involves a change in paradigm? To that question, no general answer can yet be given, but in this case at least, the answer must be yes. What Lavoisier announced in his papers from 1777 on was not so much the discovery of oxygen as the oxygen theory of combustion. That theory was the keystone for a reformulation of chemistry so vast that it is usually called the chemical revolution. Indeed, if the discovery of oxygen had not been an intimate part of the emergence of a new paradigm for chemistry, the question of priority from which we began would never have seemed so important. In this case as in others, the value placed upon a new phenomenon and thus upon its discoverer varies with our estimate of the extent to which the phenomenon violated paradigm-induced anticipations. Notice, however, since it will be important later, that the discovery of oxygen was not by itself the cause of the change in chemical theory. Long before he played any part in the discovery of the new gas, Lavoisier was convinced both that something was wrong with the phlogiston theory and that burning bodies absorbed some part of the atmosphere. That much he had recorded in a sealed note deposited with the Secretary of the French Academy in 1772.[5] What the work on oxygen did was to give much additional form and structure to Lavoisier's earlier sense that something was amiss. It told him a thing he was already prepared to discover—the nature of the substance that combustion removes from the atmosphere. That advance awareness of difficulties must be a significant part of what enabled Lavoisier to see in experiments like Priestley's a gas that Priestley had been unable to see there himself. Conversely, the fact that a major paradigm revision was needed to see what Lavoisier saw must be the principal reason why Priestley was, to the end of his long life, unable to see it.

[5] The most authoritative account of the origin of Lavoisier's discontent is Henry Guerlac, *Lavoisier—the Crucial Year: The Background and Origin of His First Experiments on Combustion in 1772* (Ithaca, N.Y., 1961).

Two other and far briefer examples will reinforce much that has just been said and simultaneously carry us from an elucidation of the nature of discoveries toward an understanding of the circumstances under which they emerge in science. In an effort to represent the main ways in which discoveries can come about, these examples are chosen to be different both from each other and from the discovery of oxygen. The first, X-rays, is a classic case of discovery through accident, a type that occurs more frequently than the impersonal standards of scientific reporting allow us easily to realize. Its story opens on the day that the physicist Roentgen interrupted a normal investigation of cathode rays because he had noticed that a barium platinocyanide screen at some distance from his shielded apparatus glowed when the discharge was in process. Further investigations—they required seven hectic weeks during which Roentgen rarely left the laboratory—indicated that the cause of the glow came in straight lines from the cathode ray tube, that the radiation cast shadows, could not be deflected by a magnet, and much else besides. Before announcing his discovery, Roentgen had convinced himself that his effect was not due to cathode rays but to an agent with at least some similarity to light.[6]

Even so brief an epitome reveals striking resemblances to the discovery of oxygen: before experimenting with red oxide of mercury, Lavoisier had performed experiments that did not produce the results anticipated under the phlogiston paradigm; Roentgen's discovery commenced with the recognition that his screen glowed when it should not. In both cases the perception of anomaly—of a phenomenon, that is, for which his paradigm had not readied the investigator—played an essential role in preparing the way for perception of novelty. But, again in both cases, the perception that something had gone wrong was only the prelude to discovery. Neither oxygen nor X-rays emerged without a further process of experimentation and assimilation. At what point in Roentgen's investigation, for example, ought we say that X-rays had actually been discovered? Not, in any

[6] L. W. Taylor, *Physics, the Pioneer Science* (Boston, 1941), pp. 790–94; and T. W. Chalmers, *Historic Researches* (London, 1949), pp. 218–19.

case, at the first instant, when all that had been noted was a glowing screen. At least one other investigator had seen that glow and, to his subsequent chagrin, discovered nothing at all.[7] Nor, it is almost as clear, can the moment of discovery be pushed forward to a point during the last week of investigation, by which time Roentgen was exploring the properties of the new radiation he had *already* discovered. We can only say that X-rays emerged in Würzburg between November 8 and December 28, 1895.

In a third area, however, the existence of significant parallels between the discoveries of oxygen and of X-rays is far less apparent. Unlike the discovery of oxygen, that of X-rays was not, at least for a decade after the event, implicated in any obvious upheaval in scientific theory. In what sense, then, can the assimilation of that discovery be said to have necessitated paradigm change? The case for denying such a change is very strong. To be sure, the paradigms subscribed to by Roentgen and his contemporaries could not have been used to predict X-rays. (Maxwell's electromagnetic theory had not yet been accepted everywhere, and the particulate theory of cathode rays was only one of several current speculations.) But neither did those paradigms, at least in any obvious sense, prohibit the existence of X-rays as the phlogiston theory had prohibited Lavoisier's interpretation of Priestley's gas. On the contrary, in 1895 accepted scientific theory and practice admitted a number of forms of radiation—visible, infrared, and ultraviolet. Why could not X-rays have been accepted as just one more form of a well-known class of natural phenomena? Why were they not, for example, received in the same way as the discovery of an additional chemical element? New elements to fill empty places in the periodic table were still being sought and found in Roentgen's day. Their pursuit was a standard project for normal science, and success was an occasion only for congratulations, not for surprise.

[7] E. T. Whittaker, *A History of the Theories of Aether and Electricity*, I (2d ed.; London, 1951), 358, n. 1. Sir George Thomson has informed me of a second near miss. Alerted by unaccountably fogged photographic plates, Sir William Crookes was also on the track of the discovery.

X-rays, however, were greeted not only with surprise but with shock. Lord Kelvin at first pronounced them an elaborate hoax.[8] Others, though they could not doubt the evidence, were clearly staggered by it. Though X-rays were not prohibited by established theory, they violated deeply entrenched expectations. Those expectations, I suggest, were implicit in the design and interpretation of established laboratory procedures. By the 1890's cathode ray equipment was widely deployed in numerous European laboratories. If Roentgen's apparatus had produced X-rays, then a number of other experimentalists must for some time have been producing those rays without knowing it. Perhaps those rays, which might well have other unacknowledged sources too, were implicated in behavior previously explained without reference to them. At the very least, several sorts of long familiar apparatus would in the future have to be shielded with lead. Previously completed work on normal projects would now have to be done again because earlier scientists had failed to recognize and control a relevant variable. X-rays, to be sure, opened up a new field and thus added to the potential domain of normal science. But they also, and this is now the more important point, changed fields that had already existed. In the process they denied previously paradigmatic types of instrumentation their right to that title.

In short, consciously or not, the decision to employ a particular piece of apparatus and to use it in a particular way carries an assumption that only certain sorts of circumstances will arise. There are instrumental as well as theoretical expectations, and they have often played a decisive role in scientific development. One such expectation is, for example, part of the story of oxygen's belated discovery. Using a standard test for "the goodness of air," both Priestley and Lavoisier mixed two volumes of their gas with one volume of nitric oxide, shook the mixture over water, and measured the volume of the gaseous residue. The previous experience from which this standard procedure had evolved assured them that with atmospheric air the residue

[8] Silvanus P. Thompson, *The Life of Sir William Thomson Baron Kelvin of Largs* (London, 1910), II, 1125.

would be one volume and that for any other gas (or for polluted air) it would be greater. In the oxygen experiments both found a residue close to one volume and identified the gas accordingly. Only much later and in part through an accident did Priestley renounce the standard procedure and try mixing nitric oxide with his gas in other proportions. He then found that with quadruple the volume of nitric oxide there was almost no residue at all. His commitment to the original test procedure—a procedure sanctioned by much previous experience—had been simultaneously a commitment to the non-existence of gases that could behave as oxygen did.[9]

Illustrations of this sort could be multiplied by reference, for example, to the belated identification of uranium fission. One reason why that nuclear reaction proved especially difficult to recognize was that men who knew what to expect when bombarding uranium chose chemical tests aimed mainly at elements from the upper end of the periodic table.[10] Ought we conclude from the frequency with which such instrumental commitments prove misleading that science should abandon standard tests and standard instruments? That would result in an inconceivable method of research. Paradigm procedures and applications are as necessary to science as paradigm laws and theories, and they have the same effects. Inevitably they restrict the phenomenological field accessible for scientific investigation at any

[9] Conant, *op. cit.*, pp. 18–20.

[10] K. K. Darrow, "Nuclear Fission," *Bell System Technical Journal*, XIX (1940), 267–89. Krypton, one of the two main fission products, seems not to have been identified by chemical means until after the reaction was well understood. Barium, the other product, was almost identified chemically at a late stage of the investigation because, as it happened, that element had to be added to the radioactive solution to precipitate the heavy element for which nuclear chemists were looking. Failure to separate that added barium from the radioactive product finally led, after the reaction had been repeatedly investigated for almost five years, to the following report: "As chemists we should be led by this research . . . to change all the names in the preceding [reaction] schema and thus write Ba, La, Ce instead of Ra, Ac, Th. But as 'nuclear chemists,' with close affiliations to physics, we cannot bring ourselves to this leap which would contradict all previous experience of nuclear physics. It may be that a series of strange accidents renders our results deceptive" (Otto Hahn and Fritz Strassman, "Uber den Nachweis und das Verhalten der bei der Bestrahlung des Urans mittels Neutronen entstehended Erdalkalimetalle," *Die Naturwissenschaften*, XXVII [1939], 15).

given time. Recognizing that much, we may simultaneously see an essential sense in which a discovery like X-rays necessitates paradigm change—and therefore change in both procedures and expectations—for a special segment of the scientific community. As a result, we may also understand how the discovery of X-rays could seem to open a strange new world to many scientists and could thus participate so effectively in the crisis that led to twentieth-century physics.

Our final example of scientific discovery, that of the Leyden jar, belongs to a class that may be described as theory-induced. Initially, the term may seem paradoxical. Much that has been said so far suggests that discoveries predicted by theory in advance are parts of normal science and result in no *new sort* of fact. I have, for example, previously referred to the discoveries of new chemical elements during the second half of the nineteenth century as proceeding from normal science in that way. But not all theories are paradigm theories. Both during preparadigm periods and during the crises that lead to large-scale changes of paradigm, scientists usually develop many speculative and unarticulated theories that can themselves point the way to discovery. Often, however, that discovery is not quite the one anticipated by the speculative and tentative hypothesis. Only as experiment and tentative theory are together articulated to a match does the discovery emerge and the theory become a paradigm.

The discovery of the Leyden jar displays all these features as well as the others we have observed before. When it began, there was no single paradigm for electrical research. Instead, a number of theories, all derived from relatively accessible phenomena, were in competition. None of them succeeded in ordering the whole variety of electrical phenomena very well. That failure is the source of several of the anomalies that provide background for the discovery of the Leyden jar. One of the competing schools of electricians took electricity to be a fluid, and that conception led a number of men to attempt bottling the fluid by holding a water-filled glass vial in their hands and touching the water to a conductor suspended from an active

electrostatic generator. On removing the jar from the machine and touching the water (or a conductor connected to it) with his free hand, each of these investigators experienced a severe shock. Those first experiments did not, however, provide electricians with the Leyden jar. That device emerged more slowly, and it is again impossible to say just when its discovery was completed. The initial attempts to store electrical fluid worked only because investigators held the vial in their hands while standing upon the ground. Electricians had still to learn that the jar required an outer as well as an inner conducting coating and that the fluid is not really stored in the jar at all. Somewhere in the course of the investigations that showed them this, and which introduced them to several other anomalous effects, the device that we call the Leyden jar emerged. Furthermore, the experiments that led to its emergence, many of them performed by Franklin, were also the ones that necessitated the drastic revision of the fluid theory and thus provided the first full paradigm for electricity.[11]

To a greater or lesser extent (corresponding to the continuum from the shocking to the anticipated result), the characteristics common to the three examples above are characteristic of all discoveries from which new sorts of phenomena emerge. Those characteristics include: the previous awareness of anomaly, the gradual and simultaneous emergence of both observational and conceptual recognition, and the consequent change of paradigm categories and procedures often accompanied by resistance. There is even evidence that these same characteristics are built into the nature of the perceptual process itself. In a psychological experiment that deserves to be far better known outside the trade, Bruner and Postman asked experimental subjects to identify on short and controlled exposure a series of playing cards. Many of the cards were normal, but some were made anomalous, e.g., a red six of spades and a black four of hearts. Each experimental run was constituted by the display of a single card to a single subject in a series of gradually increased exposures. After each exposure the subject was asked what he had seen, and the run was terminated by two successive correct identifications.[12]

[11] For various stages in the Leyden jar's evolution, see I. B. Cohen, *Franklin and Newton: An Inquiry into Speculative Newtonian Experimental Science and Franklin's Work in Electricity as an Example Thereof* (Philadelphia, 1956), pp. 385–86, 400–406, 452–67, 506–7. The last stage is described by Whittaker, *op. cit.*, pp. 50–52.

Even on the shortest exposures many subjects identified most of the cards, and after a small increase all the subjects identified them all. For the normal cards these identifications were usually correct, but the anomalous cards were almost always identified, without apparent hesitation or puzzlement, as normal. The black four of hearts might, for example, be identified as the four of either spades or hearts. Without any awareness of trouble, it was immediately fitted to one of the conceptual categories prepared by prior experience. One would not even like to say that the subjects had seen something different from what they identified. With a further increase of exposure to the anomalous cards, subjects did begin to hesitate and to display awareness of anomaly. Exposed, for example, to the red six of spades, some would say: That's the six of spades, but there's something wrong with it—the black has a red border. Further increase of exposure resulted in still more hesitation and confusion until finally, and sometimes quite suddenly, most subjects would produce the correct identification without hesitation. Moreover, after doing this with two or three of the anomalous cards, they would have little further difficulty with the others. A few subjects, however, were never able to make the requisite adjustment of their categories. Even at forty times the average exposure required to recognize normal cards for what they were, more than 10 per cent of the anomalous cards were not correctly identified. And the subjects who then failed often experienced acute personal distress. One of them exclaimed: "I can't make the suit out, whatever it is. It didn't even look like a card that time. I don't know what color it is now or whether it's a spade or a heart. I'm

[12] J. S. Bruner and Leo Postman, "On the Perception of Incongruity: A Paradigm," *Journal of Personality*, XVIII (1949), 206–23.

not even sure now what a spade looks like. My God!"[13] In the next section we shall occasionally see scientists behaving this way too.

Either as a metaphor or because it reflects the nature of the mind, that psychological experiment provides a wonderfully simple and cogent schema for the process of scientific discovery. In science, as in the playing card experiment, novelty emerges only with difficulty, manifested by resistance, against a background provided by expectation. Initially, only the anticipated and usual are experienced even under circumstances where anomaly is later to be observed. Further acquaintance, however, does result in awareness of something wrong or does relate the effect to something that has gone wrong before. That awareness of anomaly opens a period in which conceptual categories are adjusted until the initially anomalous has become the anticipated. At this point the discovery has been completed. I have already urged that that process or one very much like it is involved in the emergence of all fundamental scientific novelties. Let me now point out that, recognizing the process, we can at last begin to see why normal science, a pursuit not directed to novelties and tending at first to suppress them, should nevertheless be so effective in causing them to arise.

In the development of any science, the first received paradigm is usually felt to account quite successfully for most of the observations and experiments easily accessible to that science's practitioners. Further development, therefore, ordinarily calls for the construction of elaborate equipment, the development of an esoteric vocabulary and skills, and a refinement of concepts that increasingly lessens their resemblance to their usual common-sense prototypes. That professionalization leads, on the one hand, to an immense restriction of the scientist's vision and to a considerable resistance to paradigm change. The science has become increasingly rigid. On the other hand, within those areas to which the paradigm directs the attention of the

[13] *Ibid.*, p. 218. My colleague Postman tells me that, though knowing all about the apparatus and display in advance, he nevertheless found looking at the incongruous cards acutely uncomfortable.

group, normal science leads to a detail of information and to a precision of the observation-theory match that could be achieved in no other way. Furthermore, that detail and precision-of-match have a value that transcends their not always very high intrinsic interest. Without the special apparatus that is constructed mainly for anticipated functions, the results that lead ultimately to novelty could not occur. And even when the apparatus exists, novelty ordinarily emerges only for the man who, knowing *with precision* what he should expect, is able to recognize that something has gone wrong. Anomaly appears only against the background provided by the paradigm. The more precise and far-reaching that paradigm is, the more sensitive an indicator it provides of anomaly and hence of an occasion for paradigm change. In the normal mode of discovery, even resistance to change has a use that will be explored more fully in the next section. By ensuring that the paradigm will not be too easily surrendered, resistance guarantees that scientists will not be lightly distracted and that the anomalies that lead to paradigm change will penetrate existing knowledge to the core. The very fact that a significant scientific novelty so often emerges simultaneously from several laboratories is an index both to the strongly traditional nature of normal science and to the completeness with which that traditional pursuit prepares the way for its own change.

Sketch for *We Were Always Scientists* (2019) by Shanequa Gay

IN THE BEGINNING
A Bedtime Story

ONCE UPON A TIME, THERE WAS A UNIVERSE. WE ARE NOT sure about how it started or whether there is a reason. We don't know, for example, if spacetime is ordered or disordered at the smallest scales, which are dominated by the weirdness of quantum mechanics. We are pretty sure that during the first sliver of a trillionth of a second it expanded very rapidly so that for the most part it looked the same in every direction and looked the same from every position. It was sameness everywhere. Except that particles started to blip out of nothing due

to random fluctuations caused by quantum effects, maybe in spacetime, we are still not super sure about that. Then again, we are not super sure about this, either: for some reason those particles formed more matter than antimatter. That process, which formed a particle type called baryons, is called baryogenesis. From there those baryons started to form structures, and from those structures stars formed. Then the stars got old and some of them died in super epic, rather fabulous fashion. They exploded into supernovae, making heavy elements like carbon and oxygen in the process. Those elements went on to be the basis for all life on Earth. Earth is a planet, one of the structures that formed around stars from the leftovers of supernovae. Eventually, a smaller type of structure that we call life formed on Earth. Some of the life-forms that evolved were relatively hairless apes that use a variety of methods of communication. There are about 7 billion of these apes, with various levels of eumelanin and pheomelanin in their skin and hair, giving them a range of colors. The apes also have a lot of different hair textures. Some of the ones with less eumelanin have for a long time now been cruel to the ones with more, some of whom we know as "Black people." We know why this is although we don't fully understand the why, but it might be due to laziness or because they are jealous of our boogie. But despite this, Black lives come from the same baryogenesis, the same supernovae, and the same structure formation. No matter what the lowest-eumelanin people say, Black Lives Are Star Stuff and Black Lives Matter—all of them.

DESPITE THE FACTS OF THIS STORY, THERE'S STILL A LOT THAT we don't know about the universe. In science, we tend not to think in these terms—imagining the subject (us) and object (universe) to be distinct. This way of thinking is something we inherit from European thought, specifically the ideas of René Descartes. When we study the Andromeda Galaxy, we record its details as Cartesian thinkers, seeing it as something apart from ourselves and our home in the Milky Way. But at the same time, we are in a very technical sense bound up with Andromeda. It has its own story: it is the Milky Way's nearest major neighbor, and its existence does not trace back to a common origin with the Milky Way. Yet, in the future, these two galaxies will merge because they are bound together in a gravitational potential, which we can think of as a well in which they are both slowly spiraling downward, destined to eventually meet. Don't worry—this collision isn't set to be fully underway for another 4 billion years, and it won't be the kind of violent chaos that we imagine when we think about the word "collision." This isn't two cars smashing into each other, quickly and violently. Rather, it is stars and gas and (maybe?) dark matter particles reorganizing themselves into a new formation, guided by their gravitational relationships with one another.

This story is maybe our story. I say maybe because around the time that this collision occurs, our sun will be dying and our solar system will be destroyed in its death throes. Before its life ends completely, the sun will expand the amount of space it takes up, changing what constitutes the habitable zone of this solar system before eventually destroying the earth entirely. By then, we may have self-immolated anyway, but perhaps we will have just relocated to another solar system in a galaxy far, far away, using technology that is completely unimaginable and even unbelievable to me now. Or perhaps we will be in a solar system closer by, still in the Milky Way, in which case we will be carried along with the collision. The observations that our progeny will use to watch this phenomenon slowly unfold over the

course of millions of years will require careful calculations about their location relative to all of the action.

As it is, we already do this. We are always studying our location in the universe, even when we tell ourselves that we are simply looking outward, beyond ourselves. In our attempts to learn more about the structure of galaxies, we spend an enormous amount of time looking at our own and wondering if it is normal. We are still unsure whether the Milky Way is an average spiral galaxy or whether there is something special about it. Even though we are not the center of the universe, because indeed the universe has no center, we are the reason that we bother with the universe at all. Our location in all of it matters.

Some of us wonder about where we belong more than others. I am a descendant of Indigenous Africans whose connection to the land was forcibly severed through kidnapping and the colonization of their bodies. West Africa is enormous and full of so many different peoples. I do not know and will likely never know for sure which Indigenous communities my ancestors came from, so the question of location remains fraught for me. I am also by and for East LA (east of downtown Los Angeles), and forged from Black American, Black Caribbean, Eastern European Jewish, and Jewish American histories. Today I split my time between where I live on the Seacoast region of New Hampshire and where my spouse lives in Cambridge, Massachusetts. Los Angeles, Cambridge, and New Hampshire are colonial names for the homelands of the Tongva, Pennacook, Wabanaki Confederacy, Pentucket, Abenaki, and Massachuseuk Nations. These locations and the people rooted in them matter in this universe too.

I am also a scientist who as a child terrorized her single mother by persistently questioning everything. I am a born empiricist, someone who by nature (ask my mother!) takes seriously that information should be collected and then provided as a mechanism for explaining why the world is organized in the ways that it is. This commitment to rationalizing order often seemed to center on my household chores, but I also wanted to know why mathematics so accurately described the universe and how deep that relationship goes. That question, along with the need to have some kind of career because I knew that bills had to be paid somehow, is why I decided at age 10 to become a theoretical physicist. It is also a question that remains the subtext of my work as a theoretical physicist nearly 30 years later.

But I also wanted to know why my third-grade teacher had left all the Black children with two Black parents off the playbill for our class's forthcoming modernist production of *Strega Nona* (produced and directed by actress Conchata Ferrell z"l), where I was to play one of Macbeth's three witches. Mrs. M threw me out of class for asking the question, but at the time I didn't think of it as a challenge to her authority. I simply wanted to know if she was a racist. I was curious. I had watched my mom's grassroots organizing combating racism and sexism, I had experienced racism by her side trying to get motel rooms on road trips, and I just wanted to know if I had discovered an instance of it on my own.

When I was 10, I thought that I could keep my curiosity about the mathematics of the universe and the existence and function of racism separate. But it was not to be. A hard lesson I learned

as I emerged from my mother's home into rarified academic settings (first stop: Harvard College) was that learning about the mathematics of the universe could never be an escape from the earthly phenomena of racism and sexism (and now that humanity is moving deeper into our solar system, racism and sexism are no longer earthbound). As I progressed through college, graduate school, and teaching, I learned quickly and painfully that physics and math classrooms are not only scenes of cosmology—the study of the origins and inner workings of the physical universe—but also scenes of society, complete with all of the problems that follow society wherever it goes. There is no escape.

In physics, matter comes in different phases. For example, water and ice are different phases of the same chemical—liquid and solid. A phase transition occurs when matter changes from one phase to another. We see such a phase transition occurring when water evaporates: the liquid becomes gas. When it freezes, the transition is from liquid to solid. Phase transitions also occur in environments that feel far less mundane to us, for example, when a massive star goes supernova and converts from plasma to a neutron star that is some combination of superfluids and solids quite unlike those we find on Earth. Similarly, I had to undergo incredible intellectual phase transitions to conceive of what it meant to go from being a Black girl who loved but did not understand particle physics to a queer agender Black woman who loves—and is one of the chosen few to understand how much we don't understand—particle physics. My new understanding that society would follow me into the world of physics was also something of a phase transition for me.

This book will reflect these different phases in order to provide a holistic picture of the ways of knowing that we call particle physics and cosmology. I used to think physics was just physics, separate from people. I thought we could talk about particles without talking about people. I was wrong. At different points I came to understand physics as something that involved people, and that particular understanding has gone through different phases of its own. Studying the physical world requires confronting the social world. I know personally that social barriers impact the practice of science, its results, and the people who comprise the community we call "science." In this book, I will reflect to readers both my love for science and the difficulties people like me face in holding on to that love. For this reason, what follows is broken into four phases: *Just Physics, Physics and the Chosen Few, The Trouble With Physicists,* and *All Our Galactic Relations*.

This book is also part of a long tradition of scientists taking a moment to share with the wider world how they see science. Historically, scientists have aimed to give readers a sense of what communications researcher Alan G. Gross calls "the scientific sublime"—a feeling of awe at the universe and our place within it. This was a hallmark of Carl Sagan's science communication style, and I think it is why his documentary and book Cosmos captured the world's imagination and sustained me through difficult moments during college. Almost always, the scientists who have had the opportunity to share their views on science have been white men. Necessarily, as a Black agender woman, I see science differently than my science communication ancestors have because contrary to the usual lore, who you are matters in science. When you're looking at the world from the margins, a persistent feeling of "the sublime" can feel out of reach as you

struggle against mundane and pervasive forces of oppression. It may, therefore, be tempting to cast this book as radically outside the popular science genre because I go beyond the sublime to acknowledge the big role that social phenomena play in science. Some will point to my own life as the central narrative of this text, but while you will learn some things about me along the way (and other scientists too), I am not the point. Much more interesting is the question of how we get free.

What does freedom look like? When I put this question to artist Shanequa Gay, she told me, "Freedom looks like choice making without having to consider so many others when I make those choices." I hear in Shanequa's response a deep cry for space to self-actualize, to not always be stuck in survival mode. A sketch of Shanequa's painting, *We Were Always Scientists*, appears at the beginning of this book; I commissioned that painting partly because I was trying to figure out my own answer to this question. I asked Shanequa to envision unnamed Black women scientists under slavery. I wanted to challenge the idea that "scientific thought" has been the exclusive purview of Euro-Americans and those of us who have been trained in their knowledge systems. I also wanted something to remind myself that I belonged in my physics department office, and to remind myself that even in the worst conditions, Black women have looked up at the night sky and wondered.

Those women whose names I do not know, who may or may not be part of my bloodline, are as much my intellectual ancestors as Isaac Newton is. In fact, it is through the lessons those women passed on that I have learned to manage living with the Isaac Newtons of the world: those who are good at physics, but who are not good to people. These ancestors also serve as a reminder that the universe is more than our attempts to manipulate it. I don't have to end up like Newton, who served as warden of The Royal Mint in the late 1600s and was said to enjoy his ability to burn at the stake, hang, and torture coin counterfeiters. I don't have to end up like J. Robert Oppenheimer, the brilliant and tragic theoretical physicist who oversaw the creation of the first nuclear weapons and spent the rest of his life trying to undo the damage. I believe we can keep what feels wondrous about the search for a mathematical description of the universe while disconnecting this work from its historical place in the hands of violently colonial nation-states. With this book, I hope to map out for myself and for others an understanding that creating room for Black children to freely love particle physics and cosmology means radically changing society and the role of physicists within it. In the end, I have two big dreams for Black children and others, besides clean water, good food, access to health care, and a world without mass incarceration:

1. To know and experience Blackness as beauty and power

2. To know and experience curiosity about the night sky, to know it belonged to their ancestors

That, too, is freedom.

בָּרוּךְ אַתָּה יי אֱלֹקֵינוּ מֶלֶךְ הָעוֹלָם אֲשֶׁר בִּדְבָרוֹ מַעֲרִיב עֲרָבִים. בְּחָכְמָה

פּוֹתֵחַ שְׁעָרִים, וּבִתְבוּנָה מְשַׁנֶּה עִתִּים וּמַחֲלִיף אֶת הַזְּמַנִּים, וּמְסַדֵּר אֶת

הַכּוֹכָבִים בְּמִשְׁמְרוֹתֵיהֶם בָּרָקִיעַ כִּרְצוֹנוֹ. בּוֹרֵא יוֹם וָלָיְלָה, גּוֹלֵל אוֹר מִפְּנֵי

חֹשֶׁךְ וְחֹשֶׁךְ מִפְּנֵי אוֹר. וּמַעֲבִיר יוֹם וּמֵבִיא לָיְלָה, וּמַבְדִּיל בֵּין יוֹם וּבֵין לָיְלָה.

יי צְבָאוֹת שְׁמוֹ: אֵל חַי וְקַיָּם תָּמִיד יִמְלוֹךְ עָלֵינוּ לְעוֹלָם וָעֶד. בָּרוּךְ אַתָּה יי,

הַמַּעֲרִיב עֲרָבִים

Blessed are You, Universe, who brings in the evening with a word, in wisdom opening the gates and with understanding changing the times and seasons, ordering the stars along their paths in the sky. Creator of day and night, rolling back light from the dark and dark from the light, You make the day slowly fade and bring in the night, dividing between day and night, how great is Your Name. Living Universe, may we always feel your Presence in our lives. Blessed are You, Adonai, who brings in the evening.

Citation: Prescod-Weinstein, Chanda. The Disordered Cosmos: A Journey Into Dark Matter, Spacetime, and Dreams Deferred. Chapter 1. United States, PublicAffairs, 2021.