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WHOSE SCIENTIFIC METHOD? SCIENTIFIC METHODS FOR A COMPLEX WORLD*

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ABSTRACT

Critics of the precautionary principle assail it for calling for action before science establishes unquestionably that a substance causes harm. They claim theirs is the viewpoint of the "scientific method." But the conflict is not between science and antiscience but rather between different pathways for science and technology; between a commodified science-for-profit and a gentle science for humane goals; between the sciences of the smallest parts and the sciences of dynamic wholes. This article addresses the social construction of scientific production and the pattern of strengths and weaknesses to which it leads. The author offers proposals for a more holistic, integral approach to understanding and addressing environmental issues.

Opponents of the precautionary principle frequently express two criticisms that have to do with science. They argue that the precautionary principle itself is not "scientific" because it calls for action without full proof that the substance or activity in question is really harmful. These critics call, instead, for action based on objective evidence obtained through the "scientific method." And then they explain this failing of the precautionary principle by accusing supporters of the principle of being "antiscience" or "antitechnology."

In this article, I mainly address the first reproach. But I would like to address, briefly, the charge that advocates of the principle are antiscience, conjuring visions of Luddite machine-smashers who hearken back to an imaginary golden age—a nostalgia for the man with the hoe on the part of people who have never tilled the soil. Proponents of the status quo imagine that there is only one kind of progress, their own version of it, and that the only alternative is stagnation. They contrast their modern pesticides to doing nothing about pests, their modern antibiotics to newts' eyes and holly, their plastic cities to living in caves. Yet progress does not proceed along a single line from backward to advanced. Rather, progress is a branching pathway with choices along the way. The conflict is about those choices.

The progress of science is not the smooth penetration of light into dark corners. "Technology" in contemporary polemics usually stands for "high technology," that is, methods based on electronics, biochemistry, and informatics. But technology is merely the ability to do something, whether it is controlling mosquitoes by spraying with synthetic molecules or by putting a tight-fitting cover on the well. The conflict is not between science and antiscience but between different pathways for science and technology; between a commodified science-for-profit and a gentle science for humane goals; between the sciences of the smallest parts and the sciences of dynamic wholes. This article discusses the social construction of scientific production and the pattern of strength and weakness to which this leads. I offer proposals for a more holistic, integral approach to understanding and addressing environmental issues.

WHAT IS THE SCIENTIFIC METHOD?

Working scientists know that there is no such thing as the scientific method. There are many scientific methods, depending on the nature of the problem and the stage of the investigation.

Certain scientific traditions have developed to avoid at least the most obvious kinds of errors:

- We know that if B follows A, it does not necessarily mean that A caused B. Therefore, we carry out controlled experiments. We might treat two groups of patients identically except that one group receives a new drug and the other receives the standard treatment or a placebo. Then we can claim with some confidence that the new drug does or does not cure the disease. (But only with some confidence: if the two groups of patients were both badly undernourished it may be that neither treatment helps or that joining a study of any kind improves the patients' condition. The things that are held constant can also affect the results.)
- Scientists learned early that the expectations of participants can influence the outcomes of experiments, so that it is important for patients not to know whether they are receiving the new drug. Then they learned that the expectations of researchers can also affect the outcome, and the double blind was invented in which the researchers in contact with the patients do not know which ones belong to which group.
- All sorts of factors might affect outcomes, so we have learned to match study populations for age, sex, income, and other characteristics of possible relevance.

- Two groups of similar animals might differ just by chance. Therefore, we make use of replication and statistical analysis, mathematical models that ask "what if" questions, and formal procedures of hypothesis testing.
- Social criteria have also been developed: scientific evidence must be public, repeatable, and subject to criticism. Ideas must be examined independently of their source. Investigators should know and reveal their biases and conflicts of interest.

Formal discussion of "the scientific method" usually focuses on the last stages of an investigation: hypothesis testing. But investigative methods vary considerably. In some sciences, a single critical experiment, after it is repeated in other labs, can be decisive. In others, knowledge is gained through the accumulation of many different kinds of evidence.

Thus the case for global climate change is not only the direct observation of a temperature rise but also the retreat of glaciers, the melting of icecaps, the upward and northward expansion of plant and animal species, the decline of coral reefs, fossil climates revealed in ice cores, tree rings, geological deposits, pollen succession, and so on. All of this is reinforced by a theoretical basis for climate change in the accumulation of greenhouse gases. Each kind of evidence may be questioned for specific technical reasons, but the massive accumulation of evidence and the diversity of the arguments are overwhelming.

Similarly, the evidence for the environmental causation of our cancer epidemic is based on its historical association with the oil industry and use of pesticides, the geography of cancers related to specific industries or molecules, the history of the rise in cancer in relation to specific carcinogenic exposures (such as the increase in smoking in the twentieth century), differences among generations of immigrants, population studies, and laboratory research.

The various sciences have their own methods and conventions. Some sciences, such as physics and chemistry, are experimental in the narrow sense that allows replication. In these fields, relatively few kinds of objects occur in vast numbers and can be manipulated many times. Astronomy and geology, in contrast, do not allow for direct experiments, but the large number of stars permits controlled comparisons, and geological processes can be duplicated in the laboratory even if geohistory cannot. Anthropology has no precise replication, and the number of distinct peoples in the world is small compared to numbers of molecules or mosquitoes. Further, the anthropological observer is very much a part of the system studied. (Quantum theory and relativity both introduce the observer as part of the system studied. It is now recognized as relevant to all sciences.) Human physiology and psychology often make use of animals, which are studied as proxies for humans. They differ from people, of course, but it is hoped that they are similar enough to permit transfer of conclusions to humans.

FAILURES OF THE SCIENTIFIC METHOD

The development of the scientific method is aimed at avoiding the kinds of errors we have learned to worry about. And indeed, it has been successful in catching ordinary sloppiness, dirty glassware, division by zero, wishful thinking, and the individual biases of scientists or their economic stake in their findings. It has been less successful at recognizing the shared biases of a whole scientific community, the beliefs that are so much a part of the common sense of the community that they are not even recognized as biases. Therefore, it is instructive to note the history of some major collective scientific errors and failures.

The doctrine of the epidemiological transition proposed that infectious diseases would decline in importance over time [1, 2]. Yet since the mid-1980s, the percent contribution of infectious diseases to total mortality has been increasing. This is true even in developed countries and even if AIDS is excluded. Advocates of this doctrine failed to take into account the broad epidemiological pattern of waves of surging and ebbing human diseases. They also failed to examine thoroughly the disease profiles of other species; the ecology of disease, including the lesson that any major change in land use, vegetation, climate, human settlement, economics, or technology may also cause major changes in our relations with vectors and pathogens; the rapid evolution of resistance to antibiotics and pesticides; and the vulnerability of a socially and economically stratified population. They assumed that the toxicological fact that a chemical could kill insects in a bottle implied the ecological fact that widespread use of pesticides would control populations of the vectors that spread disease.

In agricultural science, the theory that mechanization, monoculture, and widespread use of chemicals would allow increased production to eliminate hunger failed to consider how pesticides exacerbate pest problems by disrupting the communities of species and provoking resistance, that monoculture increases vulnerability to invasion by pests and to unexpected climatic events, and that agribusiness disrupts rural life and displaces populations. In all of these cases, enthusiasm for a new, promising tool mitigated against critical examination of the tool's limitations or harmful consequences.

The commodification of science produces a growing sophistication on the small scale and in the laboratory, but an increasing irrationality in the scientific enterprise as a whole. Economic concerns encourage the narrowness that runs through the major debacles of modern applied science. The quest for profits exaggerates the benefits of innovations, belittles the dangers, and claims more knowledge and control than is possible. Furthermore, as science becomes an increasingly commodified knowledge industry, the criteria of quality shift from validation by open and critical peer testing to those applied to any commodity: Does it sell? How profitable is it? Crucial knowledge is withheld in the name of proprietary information. The most egregious example is perhaps the tobacco industry's concealment of smoking's long-known toxic effects.

Any serious scientific method must correct not only individual error but also the prevailing collective biases. I would propose several guidelines.

Preparing for Surprises

Science must recognize Hegel's principle that the truth is the whole. A problem must be posed broadly enough to accommodate a solution. Even then, we must acknowledge that there will be surprises. The best that science can do is study the unknown by pretending provisionally that it is like the known. This is the case often enough to make science possible. But the unknown is also unlike the known, deeply enough to make science necessary. Especially in times of rapid change, there will be surprises. It is therefore useful to ask, how do other species cope with uncertainty? We must be prepared to be surprised, and we must develop science equipped to deal with the unknown, using the following approaches.

Detection of a Problem and Response

In order to be effective, the response must be rapid enough to prevent vast damage and to operate before things have changed again. Foraging ants return to the nest when the day gets too hot. Plants wilt when water loss becomes excessive. Insulin is released when blood sugar levels rise. Prey species flee their predators. In all of these cases, the response comes after the changed condition has been detected. In order for this to be successful, detection must be accurate and rapid enough in relation to the duration of the threat. Otherwise, organisms would always be responding to the previous situation.

In preparing for new disease problems, the public health system is concerned with efficient surveillance and reporting programs. It is important that these programs operate rapidly enough to stay ahead of the spread of disease. Similarly, long delays in recognizing problems with toxic chemicals lead to a dynamic state in which new pollutants are introduced into the environment as fast as or faster than old ones are detected and removed.

Prediction

Many insects with short generations, such as aphids, prepare for winter by becoming dormant. However, the signal that starts dormancy is not winter itself, that is, low temperature or lack of food. Such signals would not be reliable, since cold spells could occur in midsummer. Rather, the insects respond to the shortening days of autumn as a predictor of winter. But the silkworm responds differently. It has only two generations per year. The first emerges in early spring when the short days indicate that it is the first generation and can have time for a second one, whereas the long summer days inform it that there will not be time for another generation. It is the information content of the environmental signal that matters. There is no necessary relation between the signal and the condition it predicts [3]. For human well-being, we need short-term prediction of the usual sort, for example: if a few cases of West Nile virus appear, there may be more. We also need longer-range predictions: if there are more mosquitoes, expect mosquito-borne disease. More rain will mean more mosquitoes and maybe more disease. If we build dams, dig irrigation ditches, and kill mosquito predators, we may have more mosquitoes and mosquito-borne disease. If we allow a depletion of biodiversity, exotic invaders are more likely to be successful.

There is also need for long-range, evolutionary prediction based on comparative epidemiology. We should identify those groups of insects that are potential disease vectors or major agricultural pests, that have the flexibility to extend their host ranges or modes of transmission or to adapt to new habitats. Most vectored human diseases are transmitted by flies, including mosquitoes, or by ticks. Among the plant viruses, the majority are transmitted by homopterans (aphids, scale insects, mealybugs). Like mosquitoes, they are sucking insects that remove liquid from their hosts and return liquid to offset the vacuum their sucking creates. We should know which mammals are good reservoirs of viruses that could also infect people, which groups share more diseases with humans, and which kinds of diseases are likely to be shared. For instance, the human gut and the gut of a cow are quite different, but our lungs are similar, so we might be alert to the spillover of respiratory diseases.

Broad Tolerance

Plant breeders distinguish between "vertical resistance" and "horizontal resistance." Vertical resistance, provided by a single gene, gives complete protection but only to one pathogen type. It lasts only until the pathogens overcome that resistance. Horizontal resistance usually depends on many genes. It protects against a broad range of enemies, and it persists because pathogens or insects have to do many things, more than they are capable of doing, to overcome it. In general, biodiversity provides horizontal resistance. It reduces the vulnerability of communities and is an important element of ecosystem health.

We need to design horizontally resistant systems that will defend against most diseases and poisons, even if we do not know what these might be or when they might appear. The vulnerability of our eco-social systems thus becomes a major target for research. It is especially important to take into account Schamlhausen's Law [4]: systems in extreme or unusual conditions or at the boundary of their tolerance are more sensitive to all environmental factors.

Poor and oppressed populations are more vulnerable to slight changes. This shows up in increased variability of health status. For instance, for any age group, blood pressure is more variable among African Americans than among Whites, and life expectancy varies more across cities. In evaluating the potential effects of environmental or socioeconomic changes, we must look at the most vulnerable groups.

Prevention

Organisms can change their environments in ways that make potential threats less likely to arise. For instance, trees create the forest environment, which modulates the flow of water and slows down strong winds. Ants nesting in the soil create environments where temperature extremes are less frequent.

The precautionary principle encourages prevention as far upstream as we can reach. Instead of looking only at how to regulate an industrial toxin, we adopt a strategy that starts by asking, "Is this product necessary?" Then, if it is, in fact, necessary, we consider the best way to make and use it, with the least damage to the source of materials, the workers who produce it, the consumers, and the general environment.

Prevention includes doing the right kind of research so that practical and reasonable alternatives are available. The organization of research, the setting of priorities, and the allocation of resources should be a matter of public debate. We must not continue to follow the spontaneous and haphazard course of investigations that lead to marketable commodities but ignore the complex relationships that might thwart the beneficial effects of invention, bring unexpected "side effects," and divert scientific attention from less intrusive, gentler technical possibilities.

Mixed Strategy

The best strategy combines all of these approaches. It prepares us to cope with the possibility that, even after we have used our best judgment and proposed the best solution we can find, we may still be wrong. It cautions us not to be caught up in technological fashions but to reserve the capacity to prepare for something different.

Rejecting Reductionism

The demand for a science of wholeness is a reaction against the very powerful but limited reductionism that sees the truth residing in the smallest pieces of reality. A science of wholeness does not reject reduction—taking something apart to see what it is made of—as a research tactic, but it does reject reductionism—the illusion that once that has been done, the rest is an exercise for the reader.

The conflict between reductionism and a complex science of wholes has emerged from the domain of abstract philosophical contention to become a practical political issue. It expresses the division between those who see the world as separate objects to be domesticated and processed for market and those who see the world as themselves and the places they live; between those who are reluctant to take responsibility for their actions beyond the most narrow, immediate effects of their products and those who see themselves responsible for their actions as they percolate through the world to the furthest detectable consequence.

Recognizing Connections

Things are more connected than we realize, even across disciplinary boundaries. Human biology is a socialized biology that varies according to our positions in the world. Real physiological differences exist among social classes in such things as the cortisol (stress hormone) cycle, immune system, and balance of excitatory and calming neural activity [5]. The common dichotomies of social/biological, genetic/environmental, physiological/psychological, lifestyle/ social circumstance are false and misleading. The task of science in studying the complex ecosocial phenomena of concern is not to assign relative weights to various factors but to understand how the wholes fit together. These wholes include physical, biological, and social processes.

Recognizing Bias and Partisanship

We are part of the system. The agendas and methods of science have their history, their strengths, and their biases. Science has a dual nature as part of the generic progress of human understanding and the product of a knowledge industry that helps its owners maintain their prosperity, power, and self-justification. Therefore, we need to look at our own biases as well as those of the fields we work in and not accept as given the rules that represent conventional wisdom.

It is important to acknowledge that science is often a battleground in which interests are defended in the guise of seeking truth. While striving for objectivity is necessary in science, neutrality is not. Just as industrial science serves industry, critical, dissenting scientists should acknowledge a frank and joyful partisanship: we do science in order to understand the rich complexity of the world; to have a deeper appreciation of the beauty and excitement of a marvelous, intricate, and spontaneous biosphere and to cherish and protect it; and to benefit humanity, but especially the people most excluded from the benefits of our society.

Partisanship also implies a departure from the Earth Day injunction not to point fingers. The history of tobacco, asbestos, PCBs, pesticides, auto tires, and many other industries shows that corporations lie to protect profits. They mobilize staffs of public relations experts, lawyers, and politicians to prevent interference with the quest for profit. While it is sometimes possible to demonstrate to an industry that improved environmental protection is also profitable, this is not always so, and profit is still the goal of business.

So we are in a conflictive relationship with private, corporate industry. While ecology demands the limiting of growth to what is needed, corporations require growth. While ecology seeks to minimize inputs of energy and materials, industry seeks new products for turning resources into commodities. While ecology recognizes the unique qualitative properties of different species, habitats, resources, and people, a commodified economy measures them all on the single scale of economic value and treats them as interchangeable. While corporations must seek to limit their responsibility to the narrowest possible effects of their actions, an ecological approach traces the consequences of industrial activity through the complex networks of the biosphere.

The corporate economy sees people as labor power or consumers, and spends millions to make us insecure enough to need its products, discover new uses for the raw materials corporations own, and invent new needs regardless of impact on health and well-being. Therefore, any suggestion of potential harm is regarded as "bad for the economy." But the ecological perspective sees resource use justified only insofar as it improves human life. Thus, we do have to point fingers and hone our science for battle.

Democratization

Democratizing science would help to mobilize the collective intelligence of our species for the solution of shared problems. The discovery that every place is different, every forest and beach unique, every species special, means that there will never be enough scientists to analyze and study every phenomenon. We need everybody's imagination, experience, and knowledge. Each time a previously excluded group—people of color, women, working people—has been able to enter science, new insights have emerged that previous positions of privilege obscured.

Democratization has three elements: a democracy of recruitment into science; the popularization of science in a way that respects people's capacity as well as acknowledges their past limited access; and encouragement of nonprofessional participation in setting agendas, gathering and examining information, and analyzing results. Many examples illustrate the value of popular participation in science. Here are several:

- In environmental struggles such as those at Love Canal in New York State or Woburn, Massachusetts, neighbors recognized a problem long before epidemiologists began to think about it [6]. The environmental justice movement has identified patterns of discrimination and inequality. Groups such as the River Network monitor local pollution (http://www.rivernetwork.org).
- Ornithology has a long history of amateur participation. In just one Ornithological Laboratory survey of backyard birds, more than 16,000 people submitted more than 53,000 checklists reporting 4.5 million birds belonging to 442 species [7]. Despite uneven sampling and possible misidentifications, this mass effort gave a good sense of the status and changes in U.S. bird populations.
- In Cuba, epidemiologists organized teams to survey more than five million potential mosquito breeding sites around Havana, both to evaluate the

effectiveness of control programs and to judge current problems. In 72 days, a recent outbreak of Aedes aegypti was stopped by the combined efforts of some 11,000 people who identified and eliminated breeding sites [8].

Address Biases in Experimentation and Hypothesis Testing

Currently accepted methods of experimentation and hypothesis testing create certain biases that are so standard that they are seldom examined but rather are taken for granted.

Limited Hypotheses

A hypothesis is tested and shown to be likely only in comparison to certain other hypotheses. Therefore, the choice of which hypotheses to compare is crucial. When the chemical industry claims that new genetically engineered varieties are needed to save the world from hunger, they compare the expected yields of their products to doing nothing to improve yields. Or the industry may compare applying pesticides to letting the bugs run rampant. Such choices ignore such alternatives as diversifying plantings, encouraging predators and parasites of the pests, and strengthening the physiological resistance of crops through nutritional management of soil. Similarly, pharmaceuticals are tested against placebos or standard treatments but not usually against holistic approaches. The design of hypothesis testing requires a bold imagination to create real alternatives worth testing.

Healthy Populations

Statistical design is usually improved by reducing sources of extraneous variation. Thus, laboratory animals are of a uniform genetic makeup, in good health, and are raised under constant conditions. Human populations are selected with careful exclusion of people who may have extraneous conditions. They are matched for such things as age, sex, smoking habits, number of children, body weight, dietary habits, or anything else the investigators think might confound the results, provided the data are available. Often convenience, such as likelihood of being able to monitor people for a long time, determines the class or occupation of the participants. In occupational work, researchers want to examine people who have been at the same job for a long time. Thus, we miss the effects of a pollutant against a background of many pollutants, unstable employment, and varying economic conditions.

In order to avoid this type of error, studies must be conducted with the most vulnerable populations, often minority and poor communities. The variance of data exhibited in such studies is not simply noise interfering with detection of "main effects," but also an object of interest in its own right, an indicator of stressful conditions leading to greater vulnerability. For instance, my colleagues and I found that when we grouped human settlements by size (central metropolitan area, smaller metropolitan area, smaller cities, and rural) across the populations within each category, the variance of mortality was greater for African Americans than for Whites. African Americans are more vulnerable to economic differences and to differences in the structure of racism that has had much less effect on Whites [9].

Multiple Risks

In a population subject to multiple risks, statistical tests are less sensitive. For instance, suppose that in an exposed population a toxin causes 20 deaths per hundred and, in a control population, only 10. The relative risk is 2. But if, in addition to deaths caused by the toxin under study, there are 100 deaths due to other causes, the total deaths are 120 and 110. The relative risk has fallen to 1.1. Dioxin has not become less toxic for the exposed population; rather, the environment has become worse. Each environmental toxin helps to mask the effects of the others.

Sample Size

Statistical tests all depend on sample size. Studies often do not show sufficient numbers of positive results to achieve statistical significance. A lack of statistical proof is often misinterpreted as evidence that there is no problem. Instead, the appropriate description of negative findings is that with this particular sample a suspected effect has not been detected. A more robust, interdisciplinary approach might detect a problem that a single statistical test might miss.

Confidence Levels

Estimates of the outcome take the form of a most likely effect, a comparison of difference (where zero means no difference, no effect), or a risk ratio (where a value of 1 means equal risk with and without the suspected toxin). This is presented with a confidence interval. If the confidence interval includes zero (for differences) or 1 (for risk ratios), we conclude that the suspected effect is not demonstrated. The press and industry then interprets this as proving there is no effect. But suppose that the risk analysis comes out 1.3 ± 0.7 (with 1.3 being the relative risk and 0.7 the confidence level). That means the result is compatible with a risk level of 1 (no effect) or as much as a doubling of risk. It is even compatible with the conclusion that the substance is beneficial. However, in such cases of high uncertainty, a possible doubling of risk may be sufficient grounds for action.

Separate Variables

All statistical tests examine the relationship between some possible cause and an outcome of concern. They presume some model that relates the suspected cause to its effect. The model usually identifies a dependent variable or outcome, such as cancer, and independent variables that might influence it, such as pesticide use. The statistical analysis attempts to show whether or not there is an effect and how great it is. Then the model assumes that the prevalence of cancer is equal to the impact of a unit of variable 1 multiplied by the degree of exposure to that variable, plus the impact of a unit of variable 2 multiplied by exposure to this variable, and so on. If there is no impact, that variable contributes nothing to the prevalence of the cancer.

Adversary Statistics

Adversary statistics is the use of statistics by opposing parties, each selecting new sets of data until they are satisfied with the results. They are fundamentally different from studies in which a design procedure is set in advance, followed, and conclusions drawn. If a contending party does not like the results, a new study is done, and the process is continued until the results satisfy the sponsors. These are then reported as newer research that refutes "generally held beliefs."

Long after Gregor Mendel's classic experiments with pink and white peas that established the foundation of Mendelian genetics, it was observed that the data were suspiciously close to the 3:1 ratio that confirmed Mendel's hypothesis. Further research suggested that Mendel was so sure of his result that he continued counting peas until they came as close to 3:1 as he could reasonably expect, and then stopped. This did not constitute cheating, since Mendel was not guided by statistical theory, but it was erroneous.

This revelation opened up interest in optional stopping and the field of "sequential analysis." The criteria for accepting hypotheses when we are free to carry out as many studies as we want are different from fixed-sample statistics in which it is decided before the study how much data to examine. This process is more complex than the now familiar optional stopping of sequential analysis, in which there is only one decision maker and no conflict of goals. There is at present no general statistical theory to address adversary statistics in which contending parties carry out additional studies until they like the outcomes.

These considerations refer to duplications of previous research. A whole new domain opens up when continued research uncovers new harmful effects of chemicals, and the terms of the dispute evolve along with the information. As one question is settled, new ones arise.

Besides recognizing and addressing these standard biases, I would propose two further improvements in scientific method. First, incorporate nonprofessional data. A democratized science with nonprofessional data collection has special statistical properties. On the one hand, technical errors are likely to increase the standard error, expressed as the confidence interval within which the "true" number that we are trying to estimate will lie. On the other hand, the increased number of replications reduces the error. Thus, if the error is increased ten-fold and the sample size k-fold, the new confidence interval will be multiplied by 10/vk. And if k is greater than 10, the estimation is improved. We gain more than we lose by mobilizing community data collection. Moreover, if we want to determine trends, the heterogeneity of the data (times, local site conditions, and so forth) increases the variability of the data and reduces resolving power, but also increases the numbers of possible observations. Further, the heterogeneity itself is a virtue if the conditions under which samples are collected are recorded.

Second, use historical analysis as a useful supplement to traditional testing. The history of most molecules under scrutiny is that, over time, the number of deleterious effects attributable to them has increased as we have looked more closely, tested for more effects, and understood more of the subtleties of interaction. Further, molecules in the same families often differ in the magnitude of their effects but tend to be qualitatively similar. For example, molecules in which the carbon atoms form a branching structure instead of a straight chain (phthalates, for example, or hydrocarbons combined with chlorine such as dioxins) do not occur naturally in animals. We have not evolved enzyme systems for dealing with them, but they are chemically active and can enter our metabolism. Therefore, they should be suspect even without any direct evidence. Guilt by association is legitimate for molecules.

DISCUSSION

The argument of this article grows out of an ecological approach that sees understanding dynamic complexity as the central scientific problem of our time. It looks at science itself as an object of study, a historically developed way of producing knowledge that creates a rich mix of insights and confusions. This argument is frankly partisan, rejecting the notion that feeling is the enemy of reason or that a commitment to human well-being is an enemy of objectivity. The suggestions outlined above would get us closer to a good, combative, perceptive scientific method that is more reflective of the complex, dynamic world in which we live and more supportive of precautionary decisions.

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