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Strategies of abstraction

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Abstract Abstraction is seen as an active process which both enlightens and obscures. Abstractions are not true or false but relatively enlightening or obscuring according to the problem under study; different abstractions may grasp different aspects of a problem. Abstractions may be useless if they can answer questions only about themselves. A theoretical enterprise explores reality through acluster of abstractions that use different perspectives, temporal and horizontal scales, and assumes different givens.

Keywords Abstraction · Models · Modeling · Complexity · Systems

> *In the analysis of economic forms, moreover,*
> *neither microscopes nor chemical reagents are of use.*
> *The force of abstraction must replace both.*
>
> Karl Marx
> author's preface to *Das Kapital*

Introduction

Complexity is now in fashion. Books, meetings, even whole institutes are devoted to complexity. It is a recognition that the long traditions of reductionist science, so successful in the past, are increasingly inadequate to cope with the systems we are now trying to understand and influence. The great errors and failings of attempts to

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apply science to matters of urgent concern have come from posing problems too narrowly, too linearly, too statically. Infectious disease did not disappear as was predicted 30 or 40 years ago. Pesticides increase pest problems, antibiotics create new pathogens, hospitals are foci of infection. Food aid may increase hunger. The straightening and "taming" of rivers increase floods. Economic development does not necessarily lead to equitable, just societies. It is therefore intensely practical and even permissible to assert some principles of a more dialectical view of things:

- The truth is the whole (Hegel).
- Parts are conditioned and even created by their wholes.
- Things are more richly connected than is obvious.
- No one level of phenomena is more "fundamental" than any other. Each has a relative autonomy and its own dynamics but is also linked to the other levels.
- Things are the way they are because they got that way.
- Things are snapshots of processes. They remain the way they are long enough to be recognized and named because of opposing processes that perturb and restore them.
- The dichotomies into which we split the world—biological/social, physiological/psychological, genetic/environmental, random/deterministic, intelligible/chaotic—are misleading and eventually obfuscating.

We can ask: Why are things the way they are instead of a little bit different? Why are things the way they are instead of very different? The first is the question of self-regulation and homeostasis. The second is the question of evolution, development and history. And then we have to ask, what are the relations between the stabilizing and destabilizing processes? How do the reversible short-term processes of restoration and maintenance that can buffer against long-term forces for a while also give rise to directional changes that alter the stabilizing processes and eventually overwhelm them.

Of course we cannot really look at the "whole," but Hegel's injunction has two kinds of practical value: First, a problem should be poised large enough for a solution to fit. It is usually better to present a problem that is too big and then reduce it than to start with the problem too small. For in that case, we may never be able to expand it enough. If we fail to do so, we are either condemned to ingenious solutions to trivial questions or to explanations that are mostly external: some external influence caused what we observe, but we have no explanation for that external influence. It is merely given, perhaps observed and measured.

It takes some imagination and experience to know how to pose a question big enough, because this goes against all our training. Then, even after we have posed the problem as broadly as we know how, we always have to be aware that there is more out there that might overwhelm our theories and thwart our best intentions.

Once we accept both the need for wholeness and also its impossibility, we have to resort to processes of abstraction that can give rise to useful models. In my 1965 paper I urged that since each model is partly false we need independent models to converge in on the truths we are looking for. But I did not deal with the question of how to chose these models. Now I want to focus more explicitly on the processes of abstraction. In this effort I have been influenced by Bertel Ollman's perceptive work *The Dance of the Dialectic* (2003) which discusses several kinds of abstraction. Different abstractions from the same wholes capture different aspects of the reality but also leave us with different blindnesses. Therefore it is always necessary to recognize that our abstractions are intellectual constructs, that an ‘‘object’’ kicks and screams when it is abstracted from its context and may take its revenge in leading us astray. A particular tree species in a catalog of the trees of the West Indies is not the same tree that we saw on the wind swept beach, purple fruit fragrant with volatile compounds and flavored with salt spray, leaves showing the zigzag trails of lepidopteran larvae. It is merely a Linnean binomial abstracted into ‘‘typicalness.’’

We choose our abstractions

Our abstractions always reflect choices. Bertolt Brecht warned that we live in a terrible time when ‘‘to talk about trees is a kind of silence about injustice’’ (2003). He was wrong about the trees-they now figure prominently in the study of justice. But the point is well taken. Much abstraction is evasive of what matters, chosen for reasons of safety or convenience. The preferred objects of neo-classical economics, individuals making choices in ahistoric markets, can lead to elegant theorems about rational choice, but hide exploitation, monopoly, class conflict and the evolution of capitalism. They even abstract away the specific qualities of the four major market types under capitalism: markets for commodities, labor markets, capital markets, and financial markets, each with their own histories and patterns of ownership, power, and conflicts.Without an historical view it is possible to work with the abstraction of a perfect market. That it is unrealistic is not of itself a devastating criticism-we also abstract away friction from perfect gas models. But if markets are never perfect, and if furthermore they deviate from ‘‘perfection’’ in ways that serve their owners, and become less ‘‘perfect’’ as the power of corporations increases, then the abstraction is not only unrealistic but also actively obfuscating.

We are of course free to abstract as we please. The test of the usefulness of an abstraction is whether it captures what we want of reality, is encumbered with a minimum of scars from the process, and leads somewhere. Abstractions that are full of definitions and axioms but give no theorems are not productive abstractions.

Descriptive abstractions are attempts to turn heuristic notions into quantifiable measures. We use indices of biodiversity or resemblance, population density, nutritional status, efficiency. But once we have defined an index it has a life of its own and might not capture what we are looking for. Consider for instance population density. If a population is spread out over districts or farms of different size, an obvious definition of density would be

$$D_1 = \frac{\Sigma p_i}{\Sigma A_i} \tag{1}$$

where p_i is the population in district i and A_i is its area. But if we are interested in the question, how crowded are people? We might ask how many people live at each density. Then a more suitable measure would be

$$D_2 = \frac{\Sigma(\frac{p_i}{A_i} p_i)}{\Sigma p_i} \tag{2}$$

where p_i/A_i is the density in the ith district, the second p_i is the number of people living at that density, and Σp_i normalizes the measure to preserve the dimensionality of people over area.

We have found more than a 100-fold difference between D_1 and D_2 in some cases (Lewontin and Levins 1989). Efficiency is another index that seems more ‘‘natural’’ than it really is. In agricultural production, the biblical measure of efficiency is seeds harvested per seed sown. In land-scarce Europe it is more likely to measured by yield/unit area, in land rich and labor poor United States we boast of yield per labor day, while ecologists are interested in measuring energy harvested compared to energy invested. We could even invent nonsense indices such as the number of endemic beetles in a country divided by the number of deputies in the national assembly. Once created, it acquires the objective existence of other constructs. It can be measured, compared across countries, traced historically and so on. What makes it a nonsense index is that it does not help us answer any questions other than about itself.

Perspective, extent, and level

The abstractions of greatest interest are the variables and parameters of dynamic systems that we are interested in. Ollman distinguished abstractions of perspective, extent, and level. A sample of ecological abstractions is shown in Table 1. We start with the perspective of the effects of temperature on insects. At the biophysical–biochemical level we know that an increase of temperature increases the rate of chemical processes. The muscular activity of insects is close enough to that level so that the Harvard astronomer Harlow Shapley could estimate the temperature from the rate of movement of ants on his observatory floor.

Table 1 Abstractions of perspective, extent, and level in fruit-fly ecology

Perspective	Horizontal scale	Temporal scale	Dynamics	Constants
Temperature tolerance	Individual fly	Minutes to hours	Mortality	Fly biology, temperature
Adaptation to temperature	Individual fly	Days to a week	Growth and development, acclimation	Fly biology, temperature regimes
Behavior in relation to temperature	Population of flies of one species	Minutes	Attraction to food versus heat stress	Habitat pattern of temperature, food resources
Demography	Population of flies of one species	Seasonal	Reproduction versus mortality	Habitat, community of species
Community	Ecosystem of interacting species	Months to years	Competition, predation	Habitat, community of species
Micro-evolutionary	Single species	Years	Natural selection versus migration and drift	Habitat, community of species

In the next row we choose the level of the individual, its ‘‘horizontal’’ extension limited to replicates of the same insect treated as samples from a population, the particular temperature chosen to permit observation, and the time frame is minutes. In a bottle, the only dynamics is mortality caused by desiccation or denaturation of proteins. The only variable is the number alive, so that we may have an equation for that variable

$$\frac{dx}{dt} = -mx \tag{3}$$

where x is the number still alive and m is the death rate. After all my brave talk about complexity and wholeness, I have come up with a single equation with one variable and one parameter. Where is the rest of the world? This is the question we must always ask about any model: where is the rest of the world?

The parameter m depends on the physiological state of the insect. This is partly determined genetically but in *Drosophila melanogaster* it can change with exposure to different temperatures for 2–3 days. In the lab I could control the temperature they are exposed to, but in nature it will depend on the habitat and the behavior of the flies.

Survival also depends on the size of the fly, since the surface/volume relation makes small insects lose a greater fraction of their water per second than larger individuals. When half the flies have died, the survivors are on the average bigger than those that died. Size is also dependent on temperature since development speeds up with moderately higher temperatures while growth is less accelerated. The result is that at higher temperatures smaller individuals are produced, but they are produced sooner. But size also depends on the genotype.

When flies are subject to frequent temperature stress, genotypes which produce larger flies at those temperatures may be selected for. On a time scale of generations, say months or years, higher temperature improves survival by selection for larger size. This is observed in that flies collected in hotter, drier climates in Puerto Rico are the same size as those from the rain forest, but at the same temperatures in the laboratory they are larger than their rainforest conspecifics. Their size has been increased by the selection effects of temperature and reduced by the direct impact of temperature on their development. Thus temperature increases survival by selecting for size, it reduces survival by accelerating development, it increases survival through physiological adaptation, and reduces survival by desiccating the flies.

Now shift the level to populations of flies in their habitat. I observe the numbers of flies around my traps of fermenting fruit. The time scale is still minutes, the level is now the population of actively foraging flies, the dynamic is the movement of flies attracted to the fruit but repelled once they feel desiccation stress. Thus we may produce a model of the dynamics:

$$\frac{dx}{dt} = A - rx \tag{4}$$

where A depends on the total population of *D. melanogaster* in the foraging range and the abundance of fruit that might compete with my traps, which in turn depends on the vegetation and season but is considered constant for the duration of my study of 1 day. The parameter r depends on the temperature effects discussed at the individual level. The rest of the world enters through A, the total local population.

Population depends on the balance of birth and death rates. In this sense all organisms follow the same law of population. Temperature enters the birth rate by way of generation time. Among mosquitoes, a rise in temperature within a moderate range shortens the generation and therefore results in larger populations of smaller individuals who cannot fly as far or remain active as long, and who have lower fecundity and shorter lives. At some point above their optimum temperature the increase in mortality outweighs the shorter generations and populations decrease.

The same approach can be taken to examine the number of ants foraging in a given area. But it would be a mistake simply to transfer the categories and methods adopted for fruit flies. Ants are social; we can observe the numbers coming and going from each nest. Species competition is directly visible and influences the impact of temperature. At the level of the colony on a time scale of minutes to hours, the numbers of foragers leaving the nest is the result of the push out, the success in finding food (signaled to mobilize more foragers) and the pressures to return. Thus we can start with an equation

$$\frac{\mathrm{d}x}{\mathrm{d}t} = p(T - x) - rx. \tag{5}$$

The push out, p, is related to the need for food in the nest, the number of immature ants to be fed, the good news that successful foragers bring home and signal chemically, and the total number of foragers available in the colony, T. In our time frame, p, T, and r could be treated as constants. The return depends on successful foraging, heat stress, and species interactions. For instance we found that on one Caribbean island the ant Brachymyrmex heeri would come to tuna fish bait and surround it completely. If the bait was in the shade, the lion ant Phediole megacephala mobilized soon after (its nest was further away) and could displace the brachys in about 20 min. But if the site were then in direct sunlight the lion ants were soon stressed and left, and brachy returned.

We could alternate sunlight and shadow experimentally by the appropriate placing of opaque students. If the alternation were rapid, say every 10 min, the competition was fierce and brachy got most of the food. But if sunlight and shadow alternated over hours, the food was divided between them more or less equally. If we move to the time scale of weeks, the numbers of foragers in the nest and the demand for protein from the larvae changed. These changes depended on the success of the foraging, while the hourly flux was taken as given.

Feeding success depends on the total available food in the foraging area, the distance from the nests of all foraging species, the kinds of interactions among them, and the species-specific responses to the weather. The foraging area itself depends on the density of nests, and on the scale of months we have a dynamic of production of queens and their loss to predation before they are able to dig a nest. The variable is the number of nests. The colony formation rate depends on the accumulation of nutrients in the form of reproductives, which in turn depends on the foraging success at the shorter term level. Thus we can have a hierarchy of models in successively larger time scales in which the constants of one level become the variables of interest on another. The species interactions also affect evolution: on an island where the fire ant *Solenopsis geminata*, and its smaller, less aggressive relative *S. globularia* coexist, the fire ant expels its cousin from the cooler sites into the exposed beaches and bare rocks. Therefore they are exposed to a different environment from what their own preferences would produce. Populations of *S. globularia* are exposed to more selection for heat tolerance and are in fact more tolerant than populations of the same species on islands without the fire ant.

Comparing the cases of flies and ants, we see that the theoretical approach, nested sets of abstractions, is applicable to both. But the kinds of observations and the specific questions we can ask are different. Our work depends both on generalization and respect for specificity.

But it is now artificial to continue making temperature the point of view. If nobody had ever thought about temperature before in ecology, I might be straining to prove its relevance. I could write a series of papers on ‘‘the role of temperature in fly development,’’ ‘‘the role of temperature in fly foraging,’’ ‘‘the role of temperature in fly communities’’ and so on. If my concern were to illustrate the abstraction we call ‘‘abstraction,’’ I could continue tracing the role of temperature across levels and extensions. It makes more sense to change our point of view and ask what determines fly communities, the abundance and diversity of *Drosophila*. We will not exclude any role for temperature that might become relevant but it is no longer our perspective. The total population depends on the long-term food supply, competition from other species, and predators. This leads us to the point of view of species interaction dynamics.

The elementary pair-wise interactions between species have been studied extensively. But whatever the model the core relation is the feedback loop, negative for predator/prey relations and positive for competition and mutualism. It can be a direct two-species loop or much longer and indirect. The negative feedback loop is shown in Fig. 1. It has some immediate consequences. For instance it explains why the use of pesticides is often counterproductive. Suppose that a pesticide kills both predator and prey. Its effect in the community is found by tracing the direct negative impact of the pesticide and the indirect effect through species interactions. The predator is harmed both directly, as the toxic impact of the pesticide, and indirectly, by killing its food. The prey is also harmed directly, but the pathway by way of the predator is positive (negative impact on predator times negative link from predator to prey): it is poisoned but so is its enemy. Thus while the predator is always harmed the prey may increase or decrease.

The predator/prey loop tells us about the statistical correlation between the two species. If the rest of the world enters by way of the prey, an increase in the prey is transmitted to the predator as an increased food supply and the correlation between them is positive. But if the environment enters directly through the predator, any impact is transmitted in the opposite direction to the prey, generating a negative correlation. When we abstract a single species pair, the most important thing about

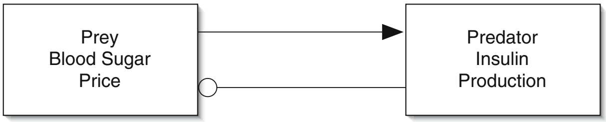

Fig. 1 A simple negative feedback loop. Positive links are shown by a sharp arrow head, negative links by circles. Predator/prey, insulin/blood sugar and price/production have the same dynamic structure

the rest of the world is whether it impacts the loop from the prey end or the predator end.

Suppose instead that we had ignored the effect of the prey population on its predator. Then we would model with unidirectional causation. The predator is the independent variable and the prey the dependent variable. If we measure the predator population diligently we might propose a regression model

$$\text{Prey} = a + b(x \text{ predators}). \tag{6}$$

We could estimate a and b with great precision and get a good fit and conclude that predators "account for" 60% of the variance. Such a procedure is not wrong. It is a legitimate procedure in the sense that it answers the question it asks. We might even arrange to hold temperature and other "confounders" constant so that the "error" variance is as small as possible. But the parameter b may be quite different in different field situations, even of opposite sign. And if environmental variation acts directly on both species the regression may be zero.

The regression approach is not wrong. But we criticize it because what it leaves out is crucial to answering the question, "what determines the abundance of prey?" and therefore it offers a superficial answer, in part because it does not account for the "independent" variable and because of this it will give inconsistent results from place to place or time to time, yet all of them statistically valid. The abstraction we used to study species' abundance ignores everything else about a population. But individuals differ in their nutritional status, age, sex, genotype and so on. We can restrict the horizontal scale to a species pair but consider effects within each species. If the environmental change enters the system as more food for the prey, fecundity increases. The predator also increases so that birth and death rates for the prey are increased whether or not there is an increase in numbers (that depends on the presence or absence of self-damping of the predator). The positive correlation between predator and prey means that when the prey are abundant they are also young and well fed, and that when they are rare they are also older and scrawnier. The predator is well fed when abundant and poorly fed and older when rare, the opposite of Malthusian expectations. But if the system is driven from the predator end, the correlation is negative and the predators are poorly fed when they are most abundant and well fed when rare. Once we understand the simple negative feedback loop, it can be applied to situations that are physically different with the same dynamics. Thus the insulin/glucose loop or the relation between prices and production in a capitalist economy have the same dynamic properties.

We can expand the abstraction "horizontally" to include more species and consider also the self-damping loops. Now the impact of some environmental change depends on the whole network of feedbacks. It can be expressed formally as the derivative of the equilibrium level with respect to any parameter change. (A parameter change, which might come from nutritional state of the organism or from genetic substitution, is "external" to the model even if inside the bug).

When we look at the whole ecosystem (only relatively "whole" of course), we create a new abstraction. We work with a network in which the vertices are species population sizes and their links are the direct interactions. This network can be described in terms of pathways between variables, feedback loops, the stability and resistance of the whole and of the subsystems. It can then be used to find the direction of change of the variables when external events impinge on one of the species and the effects percolate through the whole. It allows us to understand why sometimes the obvious effect of a pathway is reversed so that adding nitrogen to a pond reduces nitrogen levels, pesticides increase pests, some species remain the same despite environmental change, what properties of the system lead to oscillations or abrupt transitions.

We can now change the point of view to that of evolution. Then the horizontal scale is one species, the temporal scale is long, the"population" consists of a set of genotypes influencing temperature tolerance, and the environment is represented by selection coefficients.

Each of these abstractions is both legitimate and incomplete, while the set of all of them together is a closer approximation to the reality. For all of them, it is necessary to recognize their status as abstractions, intellectual constructs.

Pluralism

This view of theory as depending on a diversity of perspectives is quite different from the fashionable "post-modernist" advocacy of pluralism. The divergent abstractions of perspectives have to be loosely consistent with each other and validated within their limitations. We demand only loose consistency. In the history of genetics, the linear array of genes on the chromosome seemed to contradict the cytological observations of bumpy, branching "lamp brush" chromosomes. This was a tolerable contradiction,[1] eventually resolved by recognizing that the "lamp brush" referred to gyres in the chromosome that could be in flux during development. Unlike formal logic, where a contradiction makes all propositions provable and demolishes the whole edifice, in science a certain level of contradiction is almost always present and is a motor for more research. Its influence is usually limited to a domain of nearby propositions. What makes these contradictions benign is the belief that they will eventually be resolved. Post-modernist pluralism is different in kind. It grants equal validity to all viewpoints and sees their discord as a virtue.

If we examine the development of our knowledge, we recognize somethings we can be pretty sure of. These ideas have a long-term stability and have frequent verification with numerous cross-links to other information that is reliable. But even their status as certainties is not absolute. We can look at the history of science from the viewpoint that theories have a half-life. To stress this point, I ask students to imagine under what circumstances the second law of thermodynamics might be overthrown.

Then there are claims that are terribly wrong from the start and do not contribute at all to advancing our understanding. Creationism, holocaust denial, doctrines of racial or gender inferiority and similar "perspectives" are of this type. They are perspectives that obscure the realities and are introduced into the scientific agenda from non-scientific, even anti-scientific, concerns. We can confront them with the *postulate of partisanship*: all theories are wrong which promote, justify or tolerate injustice.

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[1] Marxists see contradiction as process in time, as opposed to the standard view in analytic philosophy which sees contradiction as a static, set-theoretic relation. The relationship between these concepts is discussed in the last chapter of *The Dialetical Biologist.*

This postulate of partisanship does not refute these claims. It does not tell us how they may be wrong: errors of conceptualization, of observation, of validation, of interpretation or application. But it is a powerful working rule that can guide our research.

At the advancing front of our sciences there are unresolved questions where diversity and controversy are part of the process of finding out, and the experiences of different disciplines with their own perspectives enrich the process. This is the domain of constructive pluralism. Beyond this frontier there are questions about which we have no means of resolution and speculation has full freedom. And finally there are the questions it has not yet occurred to us to ask. But if the diversity persists about the same questions for long periods of time, this is not evidence of the health of our science but of its stagnation or of the scientific dispute being a surrogate for clashing interests.

The processes by which we arrive at our consensus in science is very different when there are conflicting interests at stake. What follows is a first attempt to formalize this process of adversary science.

In this abstraction the point of view is that of the observer of science watching the changing views of a problem. The first term in the equation is the survival of evidence from one period to the next. The parameter a_1 is the erosion rate. The second term is the creation of new evidence. It is produced more rapidly when the other side is more threatening (larger $y/(x + y)$) but more slowly if the total mass of evidence is large (e–$(x + y)$. Finally c_1 is the rate of production of evidence from other fields, independent of the dispute. The second equation is similar. In this model, for one parameter set we obtained the process shown in Fig. 2. In this case, the relative evidence $x/(x + y)$ shows a complex pattern overtime. There is nothing sacred about these equations. Anyone following the development of these ideas could ask, ‘‘but

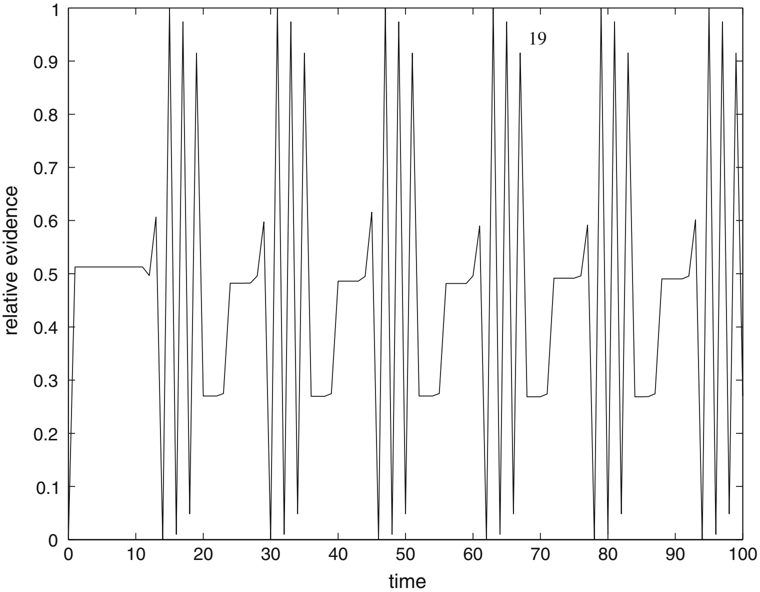

Fig. 2 A model of consensus formation displaying complex patterns

haven't you failed to take into account *x*?'' Or, ''That isn't necessarily so. In our field ...'' or ''But what is evidence for an ecologist may not carry much weight for a pharmacologist''. It is easy to propose other models in which the impact of evidence inhibits further research sympathetic to that evidence, discourages further research aimed at refuting it, or may reflect other relations. At this stage of the inquiry the important thing is to recognize the dispute as an object of study and ''evidence'' for and against a proposition as dynamic variables. This makes it possible to ask when a dispute will lead to resolution, when it can stalemate with a fixed level of conviction, when it will fluctuate over time, with some conclusion seeming to be obvious at one time and absurd at another.

We have abstracted away the substance of the dispute and worked from the viewpoint of sociology of science. Therefore argument about the specific model is completely beside the point because it is meeting the model on a different level of abstraction. The validation of this work is not prediction about any particular dispute but rather the verification that studying the dynamics of dispute in this way leads to worth while insights into controversy.

How does it apply to us?

Human ecology is the most complex ecosystem of all. It is a convergence of biological and social processes in which our biology has become socialized, but for that is no less biological.

Our species is obviously not in equilibrium with its environment. We are a young species, a scant 5,000 generations out from the savannas where we took shape, some 500 generations into agriculture and a mere 20 generations or so afflicted by capitalism. (*Drosophila* can have 20 generations in a year. What have they accomplished in2005?) By our own actions, factors that could previously be treated as external, independent variables, are now also affected by human action. The pathways of causation have been closed to become loops with reciprocal effects and an altered dynamics. Furthermore its non-equilibrium status is not an inconvenience that we could abstract away in order to seek an invariant ''human nature,'' but the central problem. The rates of change and the extent of interconnectedness are accelerating. Consciousness or volition is an emergent fact of our evolution and an ecological force. This reality is often invoked to deny the possibility of scientific study of human affairs. Our attention is called variously to ''human nature,'' ''the human condition,'' or ''the human factor'' or the importance of irrationality in human affairs to suggest that we cannot understand enough about our world to make any helpful decisions about society.

The student of human affairs is also a part of that system, with perspectives that are formed in the networks of which she or he is apart. This leads to the biases that are most difficult to detect because they are shared in the scholarly community and serve to determine respectability of ideas and define the common sense. A base of support outside that community, often rooted in grassroots activism, is a powerful antidote to the consensus bias. Each type of society has its own ecology, its own relations with the rest of nature. This includes patterns of land use, resource extraction and rehabilitation, population dynamics, social inequalities, relations with microorganisms and with the chemosphere and climate.

Back to earth

Abstracting is only one part of the process of seeking understanding. The inverse process is the return to world from which the abstractions were made. I am not concerned here with the familiar statistical hypothesis testing or Popperian falsification that results in a hypothesis being accepted or rejected. We may get good statistical fit without knowing the system any better if too much has been left out, or we may get good answers to the wrong questions. Rather the inquiry is whether the processes of abstraction as a whole and the observations they lead to have increased our understanding of the world and offered some guide to action for deepening our understanding or making the world a better place. For this purpose, several kinds of questions may be directed at our conclusions.

The Bayesian question

Do the results make sense? We always have some prior knowledge and expectations that come from our previous knowledge or "intuition." Intuition is an integral of diverse knowledge, experience, impressions, and preferences that may often give insights whose source we cannot explain, and sometimes lead us terribly astray.

But priors should not be ignored. If our conclusions are inconsistent with our prior expectation we should investigate why. We might then follow two pathways: we might assume our priors to be correct and look for reasons why the theory led us to a result that contradicts that expectation. This is the more common approach when the priors represent a whole history of a science and the research encompasses only a small area. For instance the failure of a natural selection model to account for observed characteristics in a group of populations does not refute natural selection as an evolutionary explanation but we might question whether other evolutionary forces account for our particular observations.

The second pathway examines our expectations themselves to ask why a wrong conclusion seemed so plausible. This is the more radical response since it can challenge fundamental assumptions of a field. If done with care it can show us new directions. But if every table in our notebook leads us to proclaim a new paradigm there would be total stasis.

If our conclusions are consistent with our priors, we bring out the champagne. But then, being aware of the inevitability of surprise in science, we can still ask, why are they consistent? Is there something in the research project, oriented by our priors, that forced confirmation of our expectations?

What if we're wrong?

This is especially important if the research leads to policy decisions that can affect people's lives. The inevitability of surprise makes it necessary to consider how to deal with the intrinsic uncertainty of the world. One approach we have taken is to ask, how do other species, with a billion years of evolutionary experience behind them, deal with uncertainty? We have found four major modes for coping with surprise, not mutually exclusive: detection and rapid response; prediction; broad tolerance of whatever might happen; and prevention. In practice, a mixed strategy enhances the survival of species. In science it leads to a research strategy that combines prioritizing from our best judgment of a situation with a secondary line of work, perhaps much less promising, but with a potential for important consequences.

The Polya question

Were the different perspectives that were in agreement really different enough or were they slightly different repetitions of the same evidence and argument? In Polya's monumental work on Mathematics and Plausible Reasoning (1990) he discusses testing the hypothesis that in a plane geometric figure the number of vertices minus the number of lines plus the number of enclosed areas equals 1. We might test branching figures, triangles, rectangles, pentagons, hexagons and so on, and they would all support the conclusion. But each additional polygon adds less and less support to the assumption. We need to do something different such as looking at a disconnected figure like two triangles. Then the conclusion is obviously false. Or we can expand the problem to include solid figures, or figures on a sphere or torus. Eventually it leads to the notion of Euler's number and the robust conclusion that vertices minus lines plus areas minus volumes plus ... equals Euler's number for that space.

In the dispute about climate change, a rising temperature in several cities is suggestive. Adding more cities to the list gives a diminishing return. But independent lines of evidence—ocean temperatures, cores from glaciers, decline of coral reefs, spread of species into places that had been too cold for them, accumulation of greenhouse gasses—each may have some separate idiosyncratic explanation or source of error but jointly converge on an unavoidable conclusion. We have to seek lines of evidence as independent as we can in order to support a large scale conclusion.

The search for anomaly

We can apply this approach to cancer epidemiology: while there are specific mutagenic agents that induce particular cancer types there is also a more generic vulnerability that allows the mutations to spread. This is related to the environment and to the way of life. Therefore we expected death rates from different types of cancer to show correlated distributions. In the United States the age-adjusted correlation among all types of cancer over states is 0.20 and in South Korean cities (not age adjusted) it is 0.33. But for non-Hodgkins lymphoma the corresponding figures are 0.12 and 0.08. The rates for men and women for each cancer type are highly correlated, but less so for a few types such as lung cancer where smoking exposures may be different for men and women, and leukemia, where we do not have an explanataion as yet. That is, non-Hodgkins lymphoma more different from the other cancers than they are from each other.

Further, we find that adjacent states or provinces are very similar in their rates for most cancers but not for non-Hodgkins lymphoma. Nebraska has a high rate and Kansas low, Wisconsin high and Minnesota low, Seoul high and the surrounding Gyeonggi province low. The non-Hodgkins anomaly directs our attention to looking for specific conditions that separate adjacent, largely similar areas. But unlike formal logic, where a false proposition brings down the whole edifice, anomaly does not destroy the approach of looking for correlation patterns among cancer rates as support for the idea of environmental causation of cancer. Anomaly enriches the study and serves as a guide toward finding the idiosyncratic factors.

The ethical question

When they encountered an unfamiliar animal in a picture book, my children would ask, ‘‘What does it do to children?’’ Although philosophers go through great contortions to separate questions of reality from questions of ethics, the historic process unites them. Theories support practices that serve some and harm others. Ethicists may debate, over dinner, the rational reasons for feeding the hungry, but for people in poverty food is not a philosophical problem. Any theory of society has to undergo the test, what does it do to children?

What is left out?

A theory may answer its own questions more or less adequately, but our intellectual landscape is filled with herds of 800 pound elephants. For instance, until recently historical studies usually left out women and working men, and in the United States also most Afro-Americans. Then social changes are attributed to noble individuals or legal decisions that ratified processes at work in the larger society but did not create them. The inclusion of the excluded is not only a question of justice. It is crucial for understanding US history as a struggle to win those rights which were proclaimed as universal principles, intended for the few, but taken seriously by the excluded. For instance the allocation of women’s labor between production and reproduction has been a major factor in the economy, demography, and intellectual life of the country.

Conclusion

All of these aspects converge to demand our engagement with dynamic complexity not only in dealing with each problem but also as an object of study. The two kinds of tools we have available are mathematics and philosophy.

Mathematics is used mostly in modeling in order to predict the outcomes of systems of equations. But it also has another use: educating the intuition so that the obscure becomes obvious. When we abstract from the reality of interest to create mathematical objects, we do this because some questions which would seem intractable now can be grasped immediately. We can look at the fluctuating abundance of insects and conclude ‘‘since these bugs vary by several orders of magnitude during the year and yet remain within bounds from year to year, there must be some density dependence operating (a negative feedback),’’ or see that in a particular patient insulin seems to increase blood sugar and we have to ask, ‘‘where is there a positive feedback loop at work?’’ This kind of qualitative mathematics is essential so that we are not overwhelmed by the sheer numbers of equations and variables of predictive models. The teaching of mathematics to scientists must include the mathematics that aims at understanding rather than solving equations or projecting numbers.

The philosophical tools provided by dialectics abstract the general properties of dynamic complex systems. They therefore permit us to see how different approaches fit together or conflict, and help us ask the critical questions about our systems: Where is the rest of the world? How did things get this way? What can we do about it?

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