THE WINHAM PAPERS

5. The Three Prongs of Science (2021)

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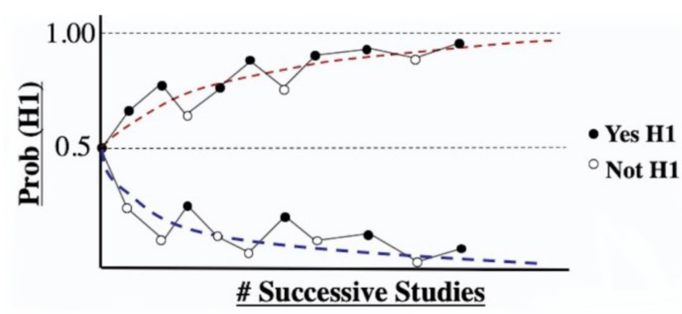
This essay is primarily for fellow scientists, or for young people who are thinking about becoming scientists. Despite a lifetime doing science, I have only belatedly perceived some differences in approach among my many colleagues that sometimes lead to tribalistic antagonisms and misunderstandings of each other's work. Maybe these patterns are already obvious to some, but it has been my recent experience that they are not as widely appreciated as they should be. My hope is that this essay will save the younger people coming up through the ranks some of the hassles that we older folks experienced.

Commonalities in science. Scientists are trying to build up a comprehensive and coherent understanding of the world. By comprehensive, I mean that no phenomenon can escape their attention. By coherent, I mean that a finding in Biology should be consistent with existing findings in physics or chemistry. The optimal methodology is called strong inference. Having selected a phenomenon to be understood, the scientist collates information from existing knowledge in whatever fields are relevant to create a set of alternative hypotheses that might explain that phenomenon. Ideally this list would be exhaustive so that one of them has to be true. This depends of course on whether the prior knowledge from which the hypotheses are being derived is accurate; sometimes the prior knowledge is not accurate and the actual true hypothesis isn't even one of those considered. However, most of the time a list of hypotheses that includes the true answer can be drawn up. Scientists then begin various kinds of studies including experiments to test the predictions that should be verified if a given hypothesis is true. Often there are many such predictions that can be tested, and in some cases multiple hypotheses make the same prediction. It is thus often most useful to focus on those predictions which discriminate between alternative hypotheses. The best hypothesis is the one for whom all of its predictions are met when none of the other hypotheses can meet this criterion.

It often takes many scientists and many studies to understand any particular phenomenon. Techniques and devices are not error-free and the accuracy of any given study is unlikely to be perfect. A result by one scientist that supports a given hypothesis might be challenged when replicated by another scientist and found not to be the case due to some error. The result is that the approach to the "truth" in science is always asymptotic as shown on the right. If a result appears to be close to the truth, but somehow conflicts with some other parts of science, this can cause a major re-examination of all the assumed concepts from which the hypotheses were drawn. Again, results should be coherent both within a discipline and across disciplines. If they are not, one has to re-examine where the problems are and start over.



While understanding individual cases is valuable in itself, what has made modern science so powerful is the subsequent search for general patterns among sets of many cases. Again and again, general patterns have been found in nature. Widely general patterns become known as "principles". Examples include evolution, general relativity, and the ubiquitous DNA code. So once scientists feel they have gotten close to the truth for a particular phenomenon, someone has to determine whether this outcome fits any general patterns that have been observed in other similar phenomena. Does the result provide support for a general principle? Does it challenge some previously accepted generality that needs to be re-examined and reformulated? General patterns and principles have enormous value: they constitute a large fraction of the prior knowledge used to formulate hypotheses for understanding new phenomena, and outside of science, they can provide guidance for governmental, economic, and medical policy making.

Differences in science. Scientists certainly differ in many ways, including whether they work in the field or in a laboratory, focus on fine or large-scale phenomena, rely on complicated devices, advanced statistics, or interactive networks, etc. But here, I want to draw attention to another pattern of differences which I think extends across every field of science. It has to do with the questions that are being asked about natural phenomena. Most phenomena involve some entity that undergoes some process or activity resulting in some consequence. The entity could be a single living cell, a plant, a whole biological species, an ocean, a star, or even empty space. Activities could involve how the entity got to where it is currently, or processes that it may be undertaking now or in the future. Consequences involve the impacts the process has on both the entity and its contexts. This model sets us up to ask any of three different questions about a phenomenon. "**What"** questions focus on the entity itself. "**How"** questions focus on the activities. And "**why"** questions deal with the consequences of the activities. Actually, things are a little more complicated than that, but this is a good place to start. Let us examine each question in turn.

What Questions. All science begins by characterizing a focal entity: what are its traits, when does it occur, and where does it occur? One can think of this kind of study as defining the "natural history" of that entity. But description of a particular case is only the first step in good science. The next step is to see where this particular case fits or doesn't fit into existing general patterns. The general patterns relevant to people asking What questions are classification schemes or "taxonomies". This requires comparing the traits of this new entity to those of other previously studied ones. In what ways is it similar and in what ways is it different? Knowing which traits are shared by a large number of entities and which by only a few allows one to build a hierarchical taxonomy. Examples of such taxonomies include the classification of living organisms, the periodic table of elements in chemistry, the classification of stars in astronomy, and the standard model of subatomic particles in physics.

Note that the building of a hierarchical taxonomy is often recursive: the criteria used to create a taxonomic scheme may no longer work when a new entity is added. It may be necessary to reorder the criteria and restructure the taxonomy to accommodate the new entity. In addition, advances in technology allow previously hidden traits to be evaluated and compared and may drastically change an existing taxonomy. An example is the addition of genetic information to biological classification schemes based only on anatomical traits. Different taxonomists may disagree about how to weight the relative importance of different traits. So, while What questions may seem simple descriptions at first, properly placing an entity in its taxonomic position can be quite complicated. Every scientific field relies on those members who are good at answering the What questions and classifying new entities. This is where nearly every scientific field began historically, and even today it plays a critical role when new entities are discovered or better classification schemes are envisioned.

How Questions. How question scientists seek to characterize specific processes or activities exhibited by a focal entity. If it can be assumed that similar entities are likely to exhibit similar processes, one can look to other already studied entities to build a list of hypotheses for how a current focal entity does what it does. In other words, scientist pursuing How questions often rely on results of prior taxonomic work by What scientists. In biology, the use of model organisms to help understand other species is a good example. How scientists are often considered "reductionists" because they dismantle the process into its component parts. But reduction is only part of explaining the system as one must also identify how those various parts work together to produce the observed results.

The majority of modern scientists are concerned with How questions. This is in part because understanding the mechanism of a phenomenon's processes will often give us some way to control it or at least anticipate its occurrences. And the assembling of many such results into general patterns has enabled scientists to deal with phenomena that have not yet been studied. Our understanding of how viruses take over the replication processes in host cells allows us to develop mRNA vaccines that mimic a new virus just enough to stimulate immunity. Our understanding of how various forces work together to make an object orbit the earth allows us to put stationary or moving satellites right where we want them. Our understanding of plate tectonics helps us anticipate where and when there next may be earthquakes or volcanic activity. Our understanding of how heat is gained or lost at the earth’s surface and in the atmosphere allows us to predict the trajectory of global warming and come up with ways to prevent it.

Both the large number of scientists asking How questions and their practical relevance have encouraged an explosive development of new technologies to test the predictions of alternative hypotheses. It is now possible to insert genetically modified proteins into living nerve cells in the brain that light up with different colors when they are active. Two-photon microscopes can see into living cells without hurting them. Massively powerful computers make extremely powerful predictions possible and crunch large data sets to get results. Atomic physics, astronomy, earth sciences, polymer chemistry, and most other fields now rely on similarly sophisticated technologies. All of this takes a lot of money, but both governments and commercial enterprises have been willing to provide it.

What about classifying How questions? Once the processes for a number of entities have been characterized, is it possible to use similarities or differences to generate a taxonomy of processes? It is, but there are different ways to do this depending upon one's goals. Most entities are capable of multiple processes. If the main focus is on a given type of process, then classifying entities according to similarities or differences in how they accomplish this process will clarify which components in the process are most conserved and which most variable. Note that the classification of the entities by a single process may be quite different from that based on other traits of the entity. Alternatively, one might include processes with other entity traits during classification. Most often as noted above, scientists use the taxonomy based on traits other than processes to classify the entities, and then examine the degree to which a given process varies across this taxonomy. We take up this approach further in the next section.

Why Questions. Why questions are best framed as comparative ones: why does a focal phenomenon have the properties it does instead of one of the likely alternatives? It is useful to divide this question into Why/What and Why/How categories. In the first case, one wants to know why a particular entity exhibits particular traits (other than processes instead of one of the alternatives. In the second case, one wants to know why a particular entity exhibits a particular process instead of an alternative. In both cases, there are several possible answers:

- **History**: Entities rarely are created from nothing. They usually have a history and antecedents. Two different entities might exhibit similar traits and perform similar activities simply because they came from a common source. Thus most species of birds are born with wings and can fly because these adaptations evolved in a common ancestor. On the other hand, rocks that undergo a similar metamorphic process may end up with quite different properties depending on whether they started as sedimentary, igneous, or other types of metamorphic rock. Many subatomic particles can only have certain properties if the particles from which they are derived had those properties.
- **Context**: In many cases, the context in which an entity exists can play an important role in which traits exhibit and what processes it undertakes. For example, we can ask why the planets in our solar system closest to the sun are rocky and small, whereas those farther away are giant balls of gases. The answer is the proximity to the sun. When the planets were forming out of the solar nebula, only the heavier elements with a higher melting point could become solid and coalesce. Only further from the sun could gaseous components solidify and coalesce, and since these were present in larger amounts then the heavier elements, they formed larger planets. In evolutionary biology, many Why questions are answered by considering the economics. One wants to know which alternative is likely to appear produces the highest fitness. Birds living in very patchy environments are more likely to have polygynous mating systems, whereas others in less patchy environments are more likely to be monogamous. The difference has to do with how easily males can defend large patches of resources and therefore attract multiple females. The biochemical systems that run our bodies form complicated networks. There is often a trade-off in such networks between the system being highly efficient on one hand, or robust to breakdowns and perturbations on the other. Where the trade-off has been set by evolution depends on how critical that system is to the organism's fitness, and can often vary depending upon the organism's environment. The relative positions of the earth's tectonic plates and their supported continents have played critical roles in shaping the current climate of the earth, and therefore which organisms could survive on it. Pangea was a fairly hostile place to live!
- **Random Events:** A third reason Why phenomena have the properties and processes they exhibit may be a prior random event. Search events can be random in when they occur, where they occur, or both at the same time. Mammals have replaced dinosaurs on the earth, (except for the birds), because of a random collision of a large meteor and the earth, perhaps aggravated by the concurrent irruptions of a chain of volcanoes in India. Again turning to biology, mutations are largely random in living thing's genetic material. These provide the diversity on which evolutionary selection can then operate. Species that had a common

ancestor, and have retained similar ecologies, may end up looking quite different if geographically separated due to the random accumulation of mutations.

- **Structure:** Given that an entity has a particular structure, which could be due to its history, context, or even random events, it may only be able to perform certain processes. For example, stable atoms require equal numbers of nuclear protons and orbital electrons. As more protons and neutrons are added to a nucleus, additional electrons must be added. Given the repulsive properties of electrons with each other, only a certain number of electrons can be packed into a given orbital shell around the nucleus. The reason that the different elements in chemistry that differ in the number of protons and neutrons in the nucleus can be ordered into a "periodic table" in which elements in the same column have similar chemical properties is because all of those elements in that column have the same degree of filing of their outer most electron shell. Whales swim because they have all the anatomical structures necessary and cannot move on land. Why their ancestors moved into the water from the land is another question.
- **Some combination of the above:** The properties and processes of most phenomena are likely due to a mixture of the three factors listed above. In sum, the history and antecedent characteristics of an entity are more important than context or random process. In other cases, context appears able to trump history. And a major random event such as a collision between earth and another body can totally disrupt both history and context.

Can you ever answer a Why question? Just because one can imagine a plausible explanation for something does not mean that this is the correct answer. Nobody was around when the planets congealed out of the solar nebula or when the meteor strike killed off the dinosaurs. What kind of experiment could one possibly perform? And how does one sort out the relative importance of each of the three factors listed above?

As noted earlier, the answers to Why questions are best found by comparing known or likely alternative forms of the phenomenon under study. Given that a set of alternatives can be identified, there are a number of tools that can be used to sort out the most likely among them. Because there is more confusion about how to deal with Why questions than the other two, it is worth taking a few minutes to spell these out.

- **Traces of history:** Although events affecting prior states of a phenomenon may have occurred long before humans developed science, many of these events leave traces that can be detected and used to discriminate between alternative reasons for why and entity has the properties and processes that it currently does. Biological fossils can show which properties of a current organism were also present in its ancestors, and the surrounding strata of the fossil can usually indicate something about the context in which the organism lived. Early developmental stages in modern organisms can exhibit traits of the ancestors which are then lost in the adult. Gill slits in the human fetus are a case in point. Traces of elements that are more common in meteors than on earth in the geological strata concurrent with the extinction of the dinosaurs provided key evidence for why this large group of animals disappeared. The presence of cosmic microwave radiation in space today provides evidence for the big bang theory of the universe.
- **Correlation with context:** Correlations between the presence or absence of specific traits and the ambient context of a group of entities can also be a useful tool. The number of entities being compared needs to be larger than the number of contexts to achieve any

statistical significance. Since two entities might exhibit the same properties or processes because they were derived from a common ancestor or source, some method to separate out the effects of history and context is required. The "Comparative Method" of evolutionary biology provides tools that allow for the quantitative estimation of the relative effects of history and context on particular traits. Even with quantitative methods, correlation is not necessarily associated with causation, and this method is best used in conjunction with one or more of the others.

- **Models and Simulations:** Often one can model or simulate the alternative ways that an entity might have acquired the properties it has, or alternative processes that the entity could've used in the same context. Once one has a general model, one can vary the values of critical parameters in the model to see which ones have the greatest effect on the outcome, and which values of those parameters are most likely to produce the observed results. One can then exclude those alternatives that can only be achieved with parameter values that are unlikely to exist. For those models that are possible with realistic parameter values, the simulation can make predictions that can then be tested. In addition to proximity to the sun, the generation of small rocky planets close to the sun and large gaseous ones further away might have been generated by the different rotational velocities of successively more distant bands around the sun or the differences in area traversed and thus densities of condensing materials. We know enough about physics in space, the melting points of different elements and compounds, and other parameters to model the system and discriminate between the alternative hypotheses. The powerful computer systems available today make creating and exploring such simulations feasible in ways that were never possible before. The main constraint on models is that they are always simplifications of reality. Some components or factors are invariably left out. The decisions on what to leave out depend on prior knowledge and the judgment of the modeler. Models can be wrong in that they leave out the wrong things, or they make assumptions that are incorrect. As with other parts of science, alternative models need to be tested and compared to find the ones that best explains what we observed in nature.
- **Economics:** Economic approaches focus on the consequences of alternative entity properties or processes. If some optimization principle can be applied to the consequences of alternatives, this can often provide insight into why a particular alternative is the one that is found. In evolutionarily biology, the optimization criterion is the maximization of fitness. The fitness of any realizable alternative depends on its costs and benefits, and these depend on the context. In physics and chemistry, the optimization criterion might be minimal energy state or stability. In some cases, one knows enough about the alternative entities that one can generate an economic model, input contextual parameters, and identify which alternative best meets the optimization criterion. Where several alternatives actually exist in the same context, one can measure the consequences and see if this predicts which is the most common. Economic analyses are widely used in all the sciences.
- **Experimental Manipulation:** By experiment, I mean direct manipulation of something as opposed to just measuring a parameter. If studying an entity who's traits or processes are more affected by context than history, manipulation of contextual variables in a systematic way may induce changes in the entity that confirm or disapprove hypotheses about why it is the way it is. If using an economic model, changing contextual variables may affect the consequences of an entity's properties or processes, and these changes in the consequences can be compared to predictions from alternative hypotheses. If one can alter the traits of

the entity or its processes, resultant changes in the consequences can also be informative. Where a process such as the formation of planets around a star is not directly manipulatable, a good simulation can allow one to manipulate properties, processes, and contacts in the model to compare alternative scenarios. While experimentation is usually associated with research on How questions, it is increasingly possible through technology and other forms of manipulation do you use it to test alternatives for Why questions.

Tribalism vs Complementarity: it has been my experience that most scientists tend to favor one of these questions in their own research over others. Some people seem to be particularly good at providing meticulous descriptions and sorting entities into clearly defined taxonomies. Others seem drawn to the challenges of designing discriminating experiments and recruiting new technologies to sort out just how something works. Scientist who are attracted to Why questions are often those who are also most interested in big picture science. Charles Darwin and Albert Einstein would be classic examples.

It is not surprising that there might be competition and rivalry within the group of scientists pursuing the same kind of question. Taxonomists are often very strict about the rules that can be used to classify entities and there is often strong disagreement about which sets of traits are most reliable in producing a classification scheme. How question scientists have frequently competed to be the first ones to finally solve a particular process. The race to understand how genes and DNA work is a case in point. Why questions can also lead to polarized views and debates such as that over Lamarckian versus Darwinian evolution.

There will probably always be competition within disciplines, not only over competitive views, but also over limited funds for research. Most of this is healthy and advances the science. There is, however, another form of conflict which is not so healthy, and that is antagonistic tribalism by scientists pursuing one kind of question against those pursuing one of the other kinds of questions. During the rise of molecular biology in the 1950s and 1960s, numerous authors at the time promoted the reductionist approach of molecular biology as intellectually superior to the descriptive methods of natural history. This was despite the fact that molecular biologists pursuing How questions invariably started with and relied on prior descriptive and taxonomic results from work by What question scientists. A similar conflict occurred in the 1980s when evolutionarily biologist began asking Why questions about animal and human social structure. The critics claimed that the Why scientists were only coming up with "just so" stories, ignoring the many techniques that Why scientist developed to discriminate between alternative hypotheses. These arguments might seem like just rhetoric, but in fact they often caused major shifts in funding allocations and staff hiring. The tendency for each scientist to favor one type of question for their own research and the zero-sum game that characterizes scientific funding have both contributed to continuing tribal animosities across many fields of science.

It should be obvious by now that the three types of questions in science should be complementary and not competitors. As we noted earlier, Why scientists might seek the reasons an entity has the traits it does instead of alternatives (Why/What) or why it exhibits a particular process instead of an alternative (Why/How). But the interactions can actually go further than this. Knowing why a particular consequence is favored by evolution or energetics or other reasons may help explain why the entity does it the way it does. Knowing how an entity performs a process instead of an alternative may help explain why it does it. Longer chains of question interactions are possible. A bird of paradise may have a long tail because its diet (context) precludes it from defending a big enough territory to attract a co-resident female, so it must display competitively with other males to attract females for copulation (a particular process). Over time, this selects for longer tails in males (an entity trait). This sequence is: Why→How→What. An element undertakes particular chemical reactions (process) determined by its electron configuration (trait) which is determined by the number of protons and the rules of electron shell packing (context). This can be envisioned as a Why→What→How chain.

The point is that we are better scientists if we not only acknowledge but pay attention to the work done by our colleagues asking different kinds of questions. In addition, it doesn't hurt to consider whether asking one of the other questions of our own study system might not shed some new perspectives or approaches that we would not think of otherwise. For young scientists just starting out, it can be very useful to apprentice oneself to a senior scientist pursuing a What question, then one pursuing a How question, and then one pursuing a Why question. Not only does this help young scientists decide which approach fits them best, it also gives them the tools and the experience needed to incorporate information and approaches of those pursuing the other two questions. In short, it does not help anybody to be tribalistic in science. We do best if we work together, respect each other's work, and share perspectives to stimulate new ideas.