

## Variation and Diversity: A Tribute to Freeman Dyson

by John Staddon

Freeman Dyson, who died this February at the age of 96, was an extraordinary man. He was extraordinarily brilliant and extraordinarily lucky. He was lucky with his upper-middle class English family, father a conductor and composer and later knight of the realm, and mother trained as a lawyer, both lovers of literature, Chaucer and poetry. Educated at Winchester College, the most intellectual<sup>1</sup> of the English ‘public’ schools, he went on to Cambridge University at the age of 15 and then to graduate school with Hans Bethe at Cornell in the US...

### Theoretical Physics

...where he had another great stroke of luck. He first read about and then encountered the authors of two apparently incongruent ideas about quantum electrodynamics (QED). The first was intricately mathematical, proposed by theoretical physicist Julian Schwinger; the second was intuitive and graphical, the product of another physicist, Richard Feynman<sup>2</sup>. These two views seemed very different, though both gave the same answers to important physics questions. How could they be both different and right?

Young Dyson spent ten days in late summer of 1948 in San Francisco and Berkeley “taking a holiday from physics”<sup>3</sup>, then returned to a fellowship at the Princeton Institute for Advanced Study. In a boring Greyhound bus, traveling across Nebraska, the 25-year-old student mulled over these two disparate views. He had a “eureka!” moment, seeing at once that they were saying the same thing in very different ways. When he arrived at Princeton, he gave a series of talks on his idea. At first, he was harshly criticized by Robert Oppenheimer, head of the Institute, who thought he was on the wrong track. By the end, though, Oppenheimer was won over, sending the young Dyson a note reading “Nolo contendere.”

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<sup>1</sup> Sample question from a 1973 Winchester *entrance* exam in math (for 12-year-olds). 13 similar questions had to be answered within an hour.

In a certain translation the image of A(-2,2) is B(2,2). The image of D(2,-2) is C. (i) What are the coordinates of C? (ii) What kind of quadrilateral is ABCD? (iii) Name fully a single transformation under which C is the image of A and D is the image of B.

The exam that child Dyson took in 1935 was possibly harder than this.

<sup>2</sup> Beautifully explained in Feynman’s little book *QED: The strange theory of light and matter*. Princeton U. P., 1985.

<sup>3</sup> *Disturbing the Universe*, New York: Harper & Row, 1979.

Dyson soon put together his unification paper: “The radiation theories of Tomonaga<sup>4</sup>, Schwinger and Feynman”, which in 1953 got him the job of a lifetime, an appointment at the Institute. Like his now colleague, Albert Einstein, his duties were simply to participate in the intellectual life of the place and to think. He never finished his PhD.

Tomonaga, Schwinger and Feynman shared the physics Nobel in 1965; Dyson was not included, three being the max. He did not regret his omission, saying “It is much better to be asked why you did not get the prize than why you did.”

Without great natural gifts, all Dyson’s luck would have been unavailing. Like so many talented mathematicians, he began early, making calculations almost in his crib. These got cleverer as he got older. For example, in the 1970s he is reported to have answered as follows a question about finding a number that doubles its value when you move its last digit to the front (e.g., 123 to 312): “Oh, that’s not difficult...but of course the smallest such number is 18 digits long.”

Young Dyson’s first encounter with real math came at the age of fifteen, while he was on Christmas holiday at his family’s seaside retreat. He had ordered an affordable book called *Differential Equations*, by H. T. Piaggio, which had the great benefit of containing some seven hundred test problems. Dyson absorbed the book in three weeks: “Never have I enjoyed a vacation more” he writes. (Fifteen seems to be a critical age: I can remember a similar experience when, during a one-week, wet family holiday in a cheap holiday camp I imbibed organic chemistry from Lancelot Hogben’s splendid, Fabian-inspired, *Science for the Citizen* — much easier than Piaggio, I think, but it was not *my* best vacation!)

Dyson’s great success was in unifying two versions of quantum electrodynamics. But his talent and his love was not for unification but for *diversity*, real diversity — of approach, of ideas and of interests — not that grab-rail for officious identicrats, the boring and alienating faux diversity of skin color, ethnicity and sexual anomaly that now infects the culture.

Dyson knew that success in science, and invention, depends on what Charles Darwin called *variation*, the range of things that are tried. Success depends intimately on the possibility of *failure*. We all remember the story of Thomas Edison and the light bulb. The same trial and (much) error — and not a little luck — is behind most important scientific discoveries.

Unfortunately, our current system for funding science is rather hostile to diversity. Failure is punished, criticism inhibited<sup>5</sup> and delay can be fatal. Rapid, noncontroversial and often false

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<sup>4</sup> Physicist Shin’Ichirō Tomonaga, independently, in wartime Japan, came up with a scheme essentially the same as Schwinger’s. His 1943 paper only arrived at Princeton in 1948.

<sup>5</sup> The devolution of social science, [Quillette](#), 2018.

results<sup>6</sup> are rewarded. In the current atmosphere it's OK to condemn Charles Darwin for not ceding priority to Alfred Russel Wallace, who sought to publish the idea of natural selection before Darwin but had no great body of observation and experiment to back it up. Darwin had discovered natural selection almost twenty years earlier, but was not ready to publish until he had amassed a compelling body of data. Wallace perfectly understood and respected Darwin's responsible thoroughness. Twentieth-century critics, obsessed with "scoop" science, have not. More on Darwin in a moment.

Dyson's discussions of the very small — particle physics — will strike non-physicists as strange, surprising, even slightly animistic. Unpredictability abounds; in *Infinite in all directions*<sup>7</sup> [IAD] he writes:

Roughly speaking, matter is the way particles behave when a large number of them are lumped together. When we examine matter in the finest detail in the experiments of particle physics, we see it behaving *as an active agent* rather than as an inert substance. Its actions are in the strict sense unpredictable. It makes what appear to be arbitrary choices between alternative possibilities. Between matter as we observe it in the laboratory and mind as we observe it in our own consciousness, there seems to be only a *difference in degree but not in kind*. [Emphases added]

And then on to string theory:

Even for experts in theoretical physics, superstrings are hard to grasp. Theoretical physicists are accustomed to living in a world which is removed from tangible objects by two levels of abstraction. From tangible atoms we move by one level of abstraction to invisible fields and particles. A second level of abstraction takes us from fields and particles to the symmetry-groups by which fields and particles are related. The superstring theory takes us beyond symmetry-groups to two further levels of abstraction. The third level of abstraction is the interpretation of symmetry-groups in terms of states in ten-dimensional space-time. The fourth level is the world of the superstrings by whose dynamical behavior the states are defined. It is no wonder that most of us had a hard time trying to follow [Ed Witten](#) all the way to the fourth level.

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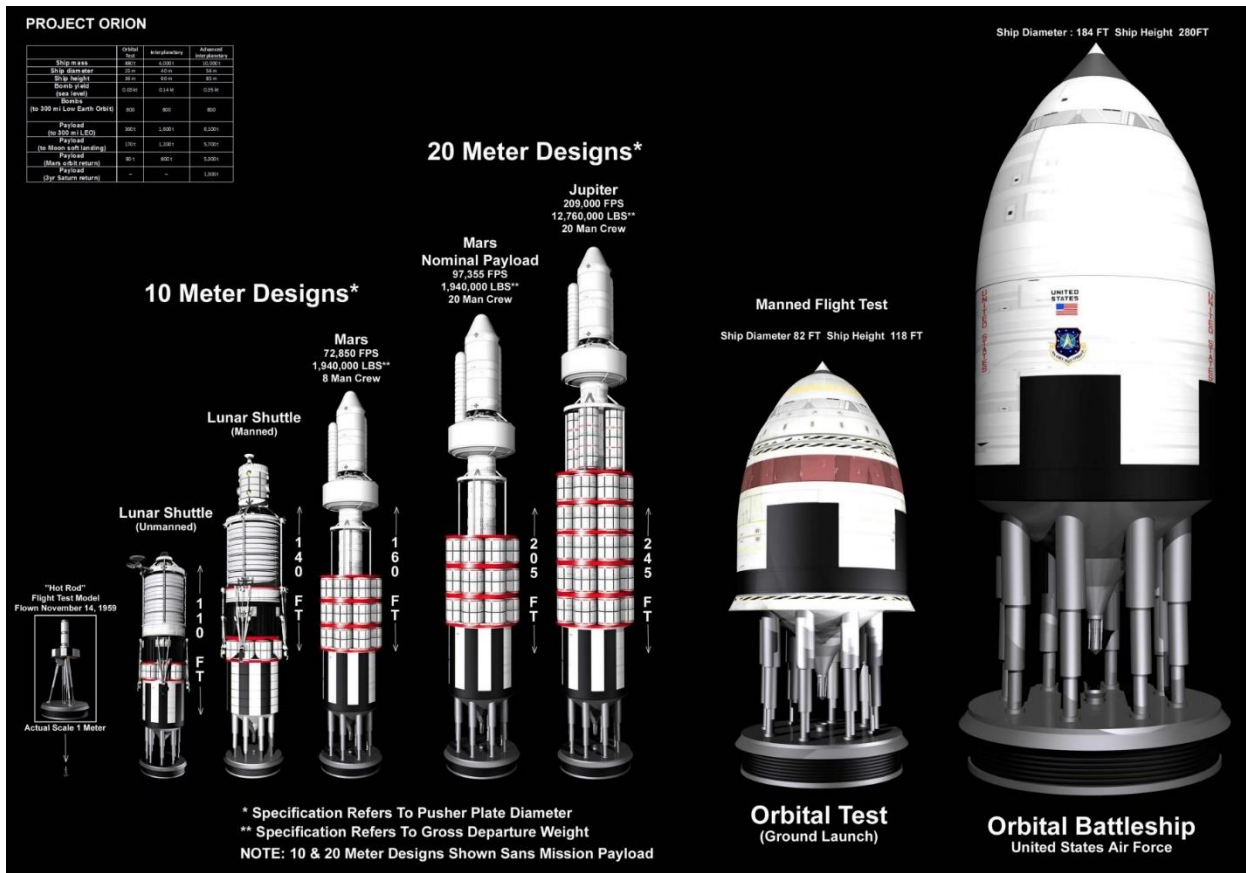
<sup>6</sup> See, for example, Peer Review: the Publication Game and The Natural Selection of Bad Science, [Martin Center](#), 2018; The Irreproducibility Crisis of Modern Science Causes, Consequences, and the Road to Reform. [National Association of Scholars](#), 2018.

<sup>7</sup> Freeman Dyson *Infinite in all directions* Harper & Row, based on the Gifford Lectures, Aberdeen, April-November 1985.

Superstrings, an attempt at the ultimate physical theory, survives because of its abstract elegance; it is apparently [not empirically testable](#).

Practical Physics: Nuclear Energy

Dyson had been a fan of nuclear power since reading the enthusiastic accounts of Arthur Eddington, an English astronomer and science popularizer, in the 1930s. Eddington inspired many science-oriented kids both before and after WW II, me included. Napoleon Bonaparte once said, “To understand the man you have to know what was happening in the world when he was twenty.” Dyson and I inhabited very similar worlds: we both left the UK in our early twenties and spent the rest of our lives in the US. Yet we both still look to the intellectual landmarks of our English youth. Despite the fact that Dyson was born half a generation before me, we share many: Arthur Eddington (*The Nature of the Physical World.*), biologist J. B. S. Haldane (*Daedalus* and professor at my London alma mater), science fiction writer Olaf Stapledon (*Last and First Men*, and originator of the “Dyson sphere”), H. G. Wells (*An Outline of History* and *War of the Worlds*), Aldous Huxley (*Brave New World*), E. T. Bell (*Men of Mathematics*), G. H. Hardy (*Pure mathematics* and the Hardy-Weinberg law) and even X-ray crystallographer J. D. “Sage” Bernal: communist, fan of Stalin, apologist for Trofim Lysenko,



author of the excellent *Science in History* — and father of Martin, my best friend in primary school.

Wells and Eddington nurtured Dyson's futurism, a wish to turn science fiction into science fact. He speculated wildly throughout his life on inter-planetary travel, genetically modified trees that could live on comets and various other bioengineered extravagances. He rarely had an opportunity to translate this speculation into action. An opportunity was provided in 1957 by Project Orion ([picture](#)). The aim was to send a vast nuclear-powered spaceship to the outer planets<sup>8</sup>. The project began with engineer Ted Taylor, who "looked like an ordinary American Westerner" but "inside, there was tremendous detachment, imagination and stubbornness". Taylor believed, correctly, that chemical rockets are too weak and expensive to power interplanetary travel. Nuclear power is required. He also thought that the necessary spaceship, powered by a series of nuclear explosions, could be designed by a small group of appropriately talented and motivated people. He assembled such a group which included, besides Dyson (who supported the project enthusiastically, partly because it would be a way to use up ever-growing stockpiles of nuclear bombs), mathematical physicist Stanislaw Ulam and a couple of dozen engineers. Over a seven-year period, funded (increasingly uncertainly) by the Defense Department, they proved the concept by building a small test rocket powered by chemical explosions.

There is little doubt that Orion was doable. It was killed, says Dyson<sup>9</sup>, by political factors, not the least of which was the understandable taboo attached to earthbound nuclear explosions. The 1963 partial test-ban treaty was the final nail in Orion's coffin.

An unfortunate result of the aversion to nuclear power has been the loss of interest in exploring types of reactors. In *Disturbing the universe* Dyson concluded:

The fundamental problem of the nuclear industry is not reactor safety, not waste disposal, not the dangers of nuclear proliferation, real though all these problems are. The fundamental problem of the industry is that nobody any longer has any fun building reactors. Sometime between 1960 and 1970 the fun went out of the business. The adventurers, the experimenters, the inventors, were driven out, and the accountants and managers took control.

Dyson was involved in the design and production of one of the few safe and profitable reactors, the TRIGA, designed to produce not power but medically useful isotopes. I was surprised, as a

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<sup>8</sup> [To Mars by A-bomb.](#), BBC documentary.

<sup>9</sup> F. Dyson Death of a project (1965) *Science*, 149, 141-144.

non-physicist, to see how many different types of reactor there are and how few of the possibilities have been explored. There are some signs of a revival: so-called [micro-reactors](#) are getting a bit of a boost at the Department of Energy.

## War

Late in the second world war Dyson was working as a civilian scientist at an RAF Bomber Command airbase. What he learned there formed his attitude to war and bureaucracy. Heavily laden Lancaster bombers went out every night to carpet bomb German cities. The bombing killed and destroyed, but because it was poorly targeted had little or no effect on the German war effort. The military value of “area bombing” was a myth.

Twenty planes took off each night from the Wyton airbase, typically one — seven men — would fail to return. Another myth was that experienced crews were less likely to be lost than newer ones. A simple calculation of conditional probability showed that was not correct, but new crews were still told their chances are better with experience. Finally, Dyson and other tech people pointed out that the overloaded Lancaster might do better if the heavy and ineffective gun turrets were removed. (The guns were ineffective because they could not hit targets below the plane — and the Germans had installed upward-firing guns on their fighters.) The planes would be lighter and faster, would have a better chance of evading detection, and two fewer men would be at risk. The brass refused even to try an experiment with modified planes. Unfortunately, the cost of failure is often much more real to bureaucracies than the benefits of success.

Dyson blames the head of Bomber Command for these blindly destructive policies but, interestingly, even thirty years after the war ended, does not call out Sir Arthur “Bomber” Harris by name. In another account from the same time, Dyson quotes a murderous-sounding official he refers to only as “Z”. Dyson was always tactful and even flattering, which is perhaps why he could take positions that many thought outrageous while rarely provoking active hostility.

## Biology: The Inadequacy of Natural Selection

Dyson was unusual in being able to discuss emotional topics without getting upset. When he encountered what seemed to be an unreasonable, affect-laden reaction, rather than backing off, he was more inclined to push back. This led him into some biological controversies.

One involved questioning Darwin and natural selection. Dyson was impressed by the work of geneticist Motoo Kimura<sup>10</sup> which shows that “smaller populations evolve faster”. Kimura was a

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<sup>10</sup> [Six characters in search of an author](#). *The Edge*, 2/19/19.



fan of “genetic drift” the effect of random mutations on a gene pool: the smaller the pool, the further it can drift from its starting point. Dyson thought that drift may be behind a range of biological variation, from peacocks’ tails to bizarre courtship rituals to human intelligence itself, that seems to go far beyond the requirements of natural selection. “There is a mismatch between the real world, with its amazing richness of diverse species, many of them obviously burdened with superfluous flowers and feathers, and the theoretical world of Darwinian evolution in which only the fittest should survive.” These ideas led him to question the sovereignty of natural selection.

Dyson was not the first to question the omnipotence of natural selection. Alfred Russel Wallace never believed it an adequate explanation for human intelligence. But at this point Dyson’s account gets a bit muddy. It is not at all obvious how random variation and the directional movement it can impart to the gene pool of a small population can lead to the kind of variety that troubled Dyson. It may be that “The random jumps of genes in a small population produce evolutionary change much faster than the gentle push of natural selection” — but why the diversity?

There is an answer, implied by Darwin but not fully developed by him because, like many after him — including Richard Dawkins, who Dyson celebrates as the inventor of “memes” — he assumed that variation is “small and random”. I think that Darwin only half believed it; he was well aware of spontaneous large variations in plants, called “sports” and surely also knew of the occasional birth of “monsters” that differ from their parents in major ways. But he hewed to the “small and random” line because of a fear of “catastrophism”, which had been defeated by an opposing principle: *uniformitarianism*, successfully advocated by one of Darwin’s mentors, Charles Lyell<sup>11</sup>. Lyell argued that nature is best understood not by referring to imagined past catastrophes, but in terms of processes observable now. Artificial selection of small variants was well known to have successfully modified breeds of animals and plants. Best stick with that as an explanation for the origin of species.

In fact, variation is *not* random: “Natural selection is the editor, rather than the composer of the genetic message.”<sup>12</sup> Understanding the composer, the processes of variation and ontogeny (development), is one of the great unsolved problems of biology<sup>13</sup>.

Dyson was right about one other thing, though, that evolution proceeds most rapidly in small, isolated populations. This is as true of cultural as biological evolution. In DU, Dyson writes: “It

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<sup>11</sup> Lyell C. (1830–1833) *Principles of Geology* (Murray, London, UK) 3 vols.

<sup>12</sup> J. L. King and T. H. Jukes (1969) Non-Darwinian evolution. *Science*, 3881, 788-798.

<sup>13</sup> See, for example, [Was Darwin wrong?](#) Or have critics – and some fans – missed the point? *Intellectual Takeout*, April 2018.

is likely that in the future our survival and our further development will depend in an equally crucial way on the maintenance of cultural and biological diversity.” Yet the dangers of nuclear war led Einstein and many others to see world government as the only path to peace: “The case for World Government as [Alexander] Hamilton and Einstein presented it is logically compelling. Fortunately or unfortunately, World Government has a fatal defect. Nobody wants it. [IAD]” We see some other defects of globalization now, with the current C19 pandemic. So perhaps nationalism isn’t so bad, as Yoram Hazony<sup>14</sup> has recently argued. Dyson suggests that nationalism might be restrained by an old notion, the balance of power, but then admits that that problem has never been solved either. He hints at a religious solution as way to achieve a non-nuclear world but seems in the end to think that science and technology (“star wars” or a successor) can solve the problem.

### Teleology in Science

Since David Hume, most scientists understand that “ought” must be kept separate from “is”. The facts of science are just that, facts. Dyson quotes the molecular biologist Jacques Monod “Any mingling of knowledge with values is unlawful, forbidden.” If a fact seems to urge us to action it is because it has been multiplied by a [value](#). People are starving in some parts of the war-torn world. So what — unless we value human life and act accordingly.

Dyson disagrees with Hume and Monod, but I am not sure why. One of Dyson’s great talents was the ability to look at emotional issues like climate change and nuclear weapons, then disagree politely with activists and change his position when the evidence changed. Our morality may take notice of a fact and urge us to action. But surely, we should try to assess the truth of the fact first, before worrying about its ethical implications.

Dyson writes in IAD: “My third problem is the problem of forbidden teleology, the conflict between human notions of purpose and the operational rules of science... Purpose is not acceptable as an explanation of scientific phenomena.” But teleology is OK for what Dyson calls *meta-science*, by which he seems to mean a kind extra-material, even religious, realm of knowledge which allows him, for example, to take Dawkins’ “selfish gene” metaphor literally — genes *want* to reproduce. He is a fan of the *anthropic principle*, which says “that laws of nature are explained if it can be established that they must be as they are in order to allow the existence of theoretical physicists to speculate about them.” [IAD] In other words, this rather solipsistic idea is that the universe was arranged (by whom, we might wonder?) just so that human beings can exist in it.

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<sup>14</sup> Yoram Hazony *The virtue of nationalism*, Basic Books, 2018.



Dyson's willingness to embrace teleology gets him into weedy epistemological waters. I quoted him earlier on fundamental particles: "we see it [matter] behaving *as an active agent* rather than as an inert substance." Compare this with biologist H. S. Jennings' account of a single-celled creature: "[I]f Amoeba were a large animal, so as to come within the everyday experience of human beings, its behavior would at once call forth the attribution to it of states of pleasure and pain, of hunger, desire and the like, on precisely the same basis as we attribute these things to the dog."<sup>15</sup> Unpredictability is everywhere. Human beings have always personalized nature. To say that "Between matter as we observe it in the laboratory and mind as we observe it in our own consciousness, there seems to be only a difference in degree but not in kind" is a comforting even irrefutable position. The danger is that it can block inquiry. If we think that matter makes "arbitrary choices" we are in effect pre-judging the issue, inhibiting discoveries that might render these choices less arbitrary, more predictable.

Teleology is seductive because it promises to unify. Many years ago I put together a collection of papers by psychologists, biologists and economists<sup>16</sup>. They were unified by teleology, by a type of explanation that looked to the outcome of a process as its explanation. Optimizing, explaining a result as the "best" outcome according to some criterion such as Darwinian fitness, as in behavioral ecology. or simply profit, as in much of economics, often works. But when conditions change, it often breaks down. The reason is that optimal behavior is the result of a process that is subject to constraints. The system may optimize under one set of conditions but fail to optimize under others.

For example, economists often assume that people make judgements by equating marginal utilities. If price increases, economics says that demand should fall — because the utility, value, shows diminishing returns. But often (Giffen goods, for example), the result is the opposite. In fact we rarely understand the actual process by which choices are made. Behavioral economics has made much of human "failures to optimize" but as yet the listing of irrationalities does not amount to a real theory<sup>17</sup>. The weakness of optimality theory as a general account is even more easily demonstrated in experiments and observations with animal subjects. Looking at a biological problem, like mating strategies or wing design, to see what is optimized can be very helpful as a tool. But the hope that biology, psychology and economics could be unified by optimality theory has turned out to be false.

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<sup>15</sup> Jennings, H. S. *Behavior of the lower organisms*. Bloomington: Indiana University Press. (1906, p. 336)

<sup>16</sup> Staddon, J. E. R. (Ed.) (1980). *Limits to action: The allocation of individual behavior*. New York: Academic Press.

<sup>17</sup> Staddon, John (2016) Theoretical Behaviorism, Economic Theory, and Choice. In *Economizing mind, 1870-2016: When economics and psychology met...or didn't*. Marina Bianchi & Neil De Marchi (Eds.) Duke University Press, 2016. Pp. 316-331.

The difference between outcome-based — *functional* — theories and causal theories is less obvious in physics. Here is an example. Imagine you are throwing a ball into a lake for your dog to retrieve. You throw at an angle. What will the dog do? Will he dive straight into the water, or will he run along the shore for a bit and then dive into the water? If he goes straight into the water he must swim, slowly, directly towards the ball. If he runs, quickly, a bit more along the shore, he will need to swim a shorter distance. In practice, dogs make a pretty good balance, diving into the water at a point that more or less minimizes the total time to reach the ball.

Light does a better job. Light is bent when it passed from air to water. The reason is that light travels more slowly in water. Dutch astronomer Willebrord Snell showed in 1621 that the angle of refraction is a simple function of the refractive indices of air and water: the ratio of the sines angles of incidence and refraction is equal to the ratio of refractive indices. This law is an empirical matter, but it can be derived from an optimality assumption: that the light ray follows the path of least time. The brilliant Irish mathematician William Rowan Hamilton (1805-1865) discovered the *variational principle* which allowed him and others to derive many physical laws as optima of one sort or another. For example, the catenary shape of a chain suspended at both ends is the shape that minimizes the chain's potential energy. In other words, in physics it often doesn't matter: you can derive laws from Maxwell's equations or from the principle of variation; the result is the same. Perhaps it is the indifference of physicists to causal vs. functional theories that allowed Dyson to be so accepting of teleology in science.

But the dog fetching the ball is much more complicated than the bending of a light beam. The dog must learn that he swims more slowly than he can run; he must really want to get that ball, have a real purpose. And when he does 'optimize' it surely is not by mathematically comparing times. A dog will often solve an apparently complex task, like catching a frisbee, by learning a simple rule<sup>18</sup>. Until we understand the rule and how he learns it, we will not be able accurately to predict what he will do when circumstances change. Light is simpler: minimization works for all, glass as well as water, plastic as well as air. Treating causal and functional theories as equally good works in physics, but not in biology or psychology.

## Climate

Freeman Dyson was sensitive to any appearance of unreason. When polite criticism provokes anger, he was suspicious. This seems to be what led him to be critical of anthropogenic global warming (AGW), the passionate belief that human activity, industry, especially, is responsible for a disastrously warming climate: "My objections to the global warming propaganda are not so

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<sup>18</sup> Andrew G. Haldane and Vasileios Madouros. Bank of England. [The dog and the frisbee](#). Speech at Jackson Hole, August 31 2012

much over the technical facts, about which I do not know much, but it's rather against the way those people behave and the kind of intolerance to criticism that a lot of them have."<sup>19</sup>

He had three reservations. First, a scientific model must be testable. Weather models are tested every day, but climate models, which predict the future tens or even hundreds of years into the future, are simply not testable until that time has elapsed. In other words, they are not testable at all. "Syukuro Manabe, right here in Princeton, was the first person who did climate models with enhanced carbon dioxide and they were excellent models. And he used to say very firmly that these models are very good tools for understanding climate, but they are not good tools for predicting climate. I think that's absolutely right." The multiplicity of models (not to mention the meaningless averaging across models when the distribution of error is unknown) makes it unwise to rely on them<sup>20</sup>.

Second, the models take little or no account of biology, the growth and evolution of flora and fauna. "They [the five reservoirs of carbon, ocean, topsoil, fossil fuels, and land vegetation] all interact with each other strongly. So you can't understand any of them unless you understand all of them."

And finally: who says that warming will be disastrous, or even bad? It will be disruptive, but the effects can be mitigated. And overall, increased plant growth might actually be a good thing. Dyson also believed, and this is perhaps more questionable, that the areas being disrupted by climate, such as the Arctic and Greenland, are mostly in the northern hemisphere and can only be improved by warming.

I conclude that the claim that carbon dioxide will cause warming is uncertain; that the claim that warming will be disastrous is questionable; and that much more research should be devoted to the positive as well as negative effects both of warming and of increased carbon dioxide levels. If that should happen, Freeman Dyson will deserve much of the credit.

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Freeman Dyson led a life that most scientists can only dream of, secure in his job, and no onerous duties to distract his wide-ranging curiosity. Above all, able to work without depending on the kindness of grant-proposal reviewers, who, inevitably, are likely to be either competitors or allies, in either case favoring conformity over diversity.

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<sup>19</sup> [https://e360.yale.edu/features/freeman\\_dyson\\_takes\\_on\\_the\\_climate\\_establishment](https://e360.yale.edu/features/freeman_dyson_takes_on_the_climate_establishment)

<sup>20</sup> See also, Staddon, J. The case for carbon dioxide. *Academic Questions*, in press.

Security, of position and of mental state, were his two great gifts. He was a critic, to be sure. But his criticism was always designed to increase the range of thought, rather than reduce it to orthodoxy. His beef with the AGW people was a reaction to their attempts to suppress dissent and look only at one side of the climate-change ledger. He was not pushing a dogma of his own. His criticism of natural selection directs our attention to the patent imbalance between the incredible richness and diversity of life on the one hand and the simplism of random variation and selection as a complete explanation. His criticism of the military bureaucracy in wartime Britain was intended to increase the versatility of the air force, not reduce it. He drew attention to the rigidity of bureaucracies, especially when under stress, a truth that needs to be universally acknowledged.

Before Darwinian *selection* must come adequately rich *variation*. That is Dyson's main message.