# Nanotechnology and Gaia

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The world's environmental problems are adumbrated. Strong attention has been directed towards nanotechnology, because it has been asserted that it will enable the environment to be repaired to a pristine state. Although the environment has traditionally been divided into the geosphere and the biosphere, comprising, respectively, the inanimate and the animate, the two are inseparably linked. This forms a central tenet of Gaia theory, which is critically examined. The present state of the environment is then examined in more detail. A brief survey of nanotechnology is given, followed by an assessment how it could be used to arrest environmental degradation. The final section examines what technology in general, of which nanotechnology is the latest and perhaps ultimate manifestation, can hope to achieve for humanity.

## 1. Introduction

I have always been intrigued by the little snippet of historical information that the Greek, and later Roman city of Paestum (the modern Pesto, in the province of Salerno in southern Italy) was abandoned at some point during the Middle Ages "due to bad air". I had speculated that it might have been due to some kind of industrial activity, such as brickmaking (which certainly generated bad air in Marston Valley or Vale, south of Bedford in England—albeit the scale of manufacture was very large, and the (fletton) bricks were made from lower Oxford clay, which contains humus), but according to Ramage the bad air originated from nearby marshes and was reputed to be malarial.[1] Presumably when the city was founded and during its many centuries of existence the marshes were properly drained; one speculates that some change in land use led to the drainage system becoming ineffective. If so, it would have been an early example of man influencing his environment. This has lately become very topical. Regarding global warming, Holt and Ramsden remarked "it might be considered … man's greatest achievement that after some 5 million years on Earth he has altered the weather!".[2] Even before global warming and

[1] C.T. Ramage, *The Nooks and Byways of Italy. Wanderings in Search of its Ancient Remains and Modern Superstitions*, pp. 6–7. Liverpool: E. Howell (1868).
[2] G.C. Holt and J.J. Ramsden, Introduction to global warming. In: *Complexity and Security* (eds J.J. Ramsden & P.J. Kervalishvili), pp. 147–184. Amsterdam: IOS Press (2008).

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climate change came into prominence, however, there was a feeling that "the environment", vague and nebulous as it was as a concept, was somehow important to man, man's well-being and man's survival. In the United Kingdom, a government Department of the Environment was created in 1970 (by combining three existing ministries), reflecting that feeling: that the environment was not merely a passive backdrop to man's activities but something that needed to be properly managed. Many of the "Global Issues" put forward by the United Nations deal with the environment: "environment" is explicitly one of the issues, and has been at least since the 1972 (Stockholm) UN Conference on the Human Environment—§6 of the conference Declaration states that "A point has been reached in history where we must shape our actions throughout the world with a more prudent care for their environmental consequences…". Agriculture, climate change, oceans and water are other "Global Issues" strongly connected with the environment. Since that conference, 5 June of every year is World Environment Day (joining World Water Day, the International Day for Biological Diversity, World Day to Combat Desertification and Drought, and so forth).

The early work of Fourier on global warming confined itself to the physical aspects of the phenomenon,[3] as did the later work of Arrhenius. In other words, it was considered to be a problem of the geosphere. At the same time, man's growing population was also bringing him into conflict with wild animal life. The last dodo died on Mauritius around 1680, a victim not only of human hunters but also of the domestic animals introduced by European migrants. As the artist C.F. Tunnicliffe has written,[4] "All this [environmental] variety maintains a corresponding variety of wild life, except in those places where humans are dominant … Soon, unless man becomes suddenly more intelligent, we shall have to face the fact that where he lives and works, animal life will continue to suffer, and where he is in complete control the animals must disappear completely." Over a hundred years ago, "progress" was perceived to result in, essentially, a scorched Earth. In E.M. Forster's *The Machine Stops*, Vashti, seated in her artificial underground cell, remarks: "The surface of the Earth is only dust and mud, no life remains on it…".[5] The conversion of the fertile "great plains" covering parts of Colorado, Kansas, New Mexico, Oklahoma and Texas into a dust bowl covering around 400,000 km$^2$, through a combination of drought and reckless overexploitation, doubtless seemed like a fulfilment of this prophecy. More recently, the Aral Sea has undergone a fate similar in both size and severity, albeit as a consequence of deliberately diverting nearly all the water feeding it for irrigation. Grandiose water engineering schemes have featured prominently in many countries during the last 200 years,[6] but nowadays many rivers, especially in China, are so badly polluted they are no longer suitable as a source of potable water (and "providing access to clean water" is one of the "Grand Challenges for Engineering" (2008) of the National Academy of Engineering of the USA). A further challenge is deforestation. Prior to 1700 it is estimated that about 4,000,000 km$^2$ of temperate forest had been lost through human activity; since the beginning of

[3] J.-J.J. Fourier, Mémoire sur les températures du globe terrestre et des espaces planétaires. *Mém. Acad. R. Sci.* **7** (1827) 569–604.
[4] C.F. Tunnicliffe, *Asian Wild Life*. London: Brooke Bond (*ca* 1960).
[5] E.M. Forster, *The Machine Stops*. Oxford and Cambridge Review (1909).
[6] E.g., D. Blackbourn, *The Conquest of Nature: Water, Landscape, and the Making of Modern Germany*. New York: Norton (2006).

the 20th century, loss of tropical forest has exceeded that of temperate forest—about 8,000,000 km$^2$ of tropical forest have been lost during the last hundred years,[7] and presently in the East Indies alone about 10,000 km$^2$ are lost annually.

It is particularly the phenomenon of mass deforestation in the tropics and how it might influence global warming that has forced consideration of the interaction between the geosphere—rocks, water and atmosphere—and the biosphere, the realm of plants and animals as well as microbes. Mass deforestation, typically enacted by burning down the trees, contributes directly to global warming by releasing heat from the combustion, and indirectly by putting large amounts of carbon dioxide into the atmosphere.[2] Furthermore, the burnt-down forest is no longer able to absorb gaseous carbon dioxide ($CO_2$), hence promoting higher atmospheric concentrations, and is no longer able to release aerosols into the atmosphere, which act to increase the albedo of the planet, either directly or by nucleating water vapour into clouds. This interaction is captured by Lovelock's "Gaia" theory, which will be described in more detail in the next section.

Faced by all the challenges that have just been mentioned, and many more, including widespread pollution through excessive use of pesticides and fertilizers in agriculture, it must surely have been with great excitement that the world heard what has become an almost iconic phrase: "In this 'nano society', energy will be clean and abundant, *the environment will have been repaired to a pristine state*, and any kind of material artefact can be made for almost no cost" (emphasis added).[8] A major goal of this essay is to examine practical ways how that might be done.

## 2. Gaia

The Gaia hypothesis, formulated by J.E. Lovelock, appears to have emerged from the realization that the atmosphere of the Earth has a very different composition from what it would have by considering it to be in equilibrium with the rest of the geosphere (conversely, measurement of atmospheric composition in effect constitutes a life detection experiment).[9, 10] Having arrived at this crucial insight, it may have seemed natural to consider the geosphere and biosphere as inseparable parts of the unified system. Doubtless this view was influenced by the emergence of general systems theory at around the same time.[11] In a subsequent paper, however, Lovelock went further, proposing that "the physical and chemical conditions of most of the planetary surface have never varied from those most favourable for life",[12] a proposition that

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7 *State of the World's Forests*. Rome: FAO (2012).

8 S. Ward, R. Jones and A. Geldart, *The Social and Economic Challenges of Nanotechnology*. Swindon: ESRC (2003).

9 J.E. Lovelock and C.E. Giffin, Planetary atmospheres: compositional and other changes associated with the presence of life. *Adv. Astronaut. Sci.* **25** (1969) 179–193.

10 J.E. Lovelock, Thermodynamics and the recognition of alien biospheres. *Proc. R. Soc. B* **189** (1975) 167–181.

11 L. von Bertalanffy, The history and status of general systems theory. *Acad. Management J.* **15** (1972) 407–426.

12 J.E. Lovelock and L. Margulis, Atmospheric homeostasis by and for the biosphere: the Gaia hypothesis. *Tellus* **26** (1974) 2–10.

was later to be called "geophysiology".[13] Lovelock created the "Daisyworld" model to provide a plausible illustration of how such homeostasis could be achieved in practice.[13–16] Daisyworld was likely influenced by another seminal observation, that planktonic algae in seawater produce dimethyl sulfide, which oxidizes in the atmosphere to form a sulfate aerosol, which both directly increases the Earth's albedo, and also is able to nucleate cloud formation.[17]

Gaia is, therefore, a cybernetic model of the Earth. It seems to be entirely consistent with the concept of directive correlation,[18] although that is not referred to in Lovelock's papers. Rather than emphasizing that fruitful connexion, more effort seems to have gone into developing the idea of a "living planet".[19] Considerable emphasis has been put on feedback as an essential component of the geosphere–biosphere system. This may not, however, be particularly useful: as Ashby has pointed out, the feedback concept is really only useful when there are just two parts in the system.[20] A major empirical reason for rejecting the "living planet" (or "strong Gaia") concept was the recognition that instability, often leading to catastrophe, has been and is an integral part of the Earth's history, vitiating the notion of homeostasis.[19] Geologists also had difficulty with the idea of the biosphere or, more properly, "bioshell" (an ultrathin layer at the surface of the solid part of the geosphere) controlling the fate of the vastly greater latter entity.[19] "Weak Gaia", the position of retrenchment, merely acknowledges the integrality of the bio- and geo-components of the planetary system, a position for which there is now overwhelming empirical evidence.

This debate has been more sterile than it might been because of the failure to see the Earth as a whole as an example of directive correlation in action (Figure 1). The principal disturbance is the very slowly increasing luminosity of the Sun. Almost certainly there is an upper limit to the solar flux at which life can be maintained, which defines the degree of directive correlation. Within the acceptable bounds of $D$ we see an enormous variety of correlating mechanisms, ranging from more intense plant growth as irradiance increases, to the nucleation of albedo-

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[13] J.E. Lovelock, Geophysiology, the science of Gaia. *Rev. Geophys.* **17** (1989) 215–222.

[14] Daisyworld is a planet with two kinds of daisies, dark-coloured and light-coloured, that compete with one another. The temperature starts at below 5 °C but gradually increases (due to gradually increasing solar flux); at 5 °C the seeds germinate. Up to the growth optimum of 22.5 °C, the dark-coloured daisies are in the lead because by absorbing more light they will be slightly warmer than their light-coloured congeners. Eventually the light-coloured daisies take over since growth declines beyond 22.5° C. At 40 °C the daisies die. This simple model shows temperature homeostasis of the planet until the fatal threshold is reached, unlike a "dead" planet without daisies, whose temperature gradually increases *pari passu* with solar flux. It is a trivial extension to add daisies of intermediate colour, which give an even better temperature homeostasis.[13]

[15] A.J. Watson and J.E. Lovelock, Biological homeostasis of the global environment: the parable of Daisyworld. *Tellus* **35**B (1983) 284–289.

[16] T.M. Lenton and J.E. Lovelock, Daisyworld revisited: quantifying biological effects on planetary self-regulation. *Tellus* **53**B (2001) 288–305.

[17] R.J. Charlson, J.E. Lovelock, M.O. Andreae and S.G. Warren, Oceanic phytoplankton, atmospheric sulphur, cloud albedo and climate. *Nature* (Lond.) **326** (1987) 655–661.

[18] G. Sommerhoff, *Analytical Biology*. Oxford: Clarendon (1950).

[19] M. Ogle, Gaia theory: model and metaphor for the 21st century. In: *Gaia in Turmoil: Climate Change, by Depletion, and Earth Ethics in an Age of Crisis*.(eds E. Crist & H.B. Rinker), ch. 16. Cambridge, Mass.: MIT Press (2010).

[20] W.R. Ashby, *An Introduction to Cybernetics*. London: Methuen (1964).

increasing clouds by the solar wind that typically accompanies the light delivered by the Sun. The Gaia notion can encompass all of this without invoking teleology. As Nietzsche has pointed out,[21] what are so often taken to be opposites in an argument are, actually, qualitatively the same and merely differ in some quantitative aspect.

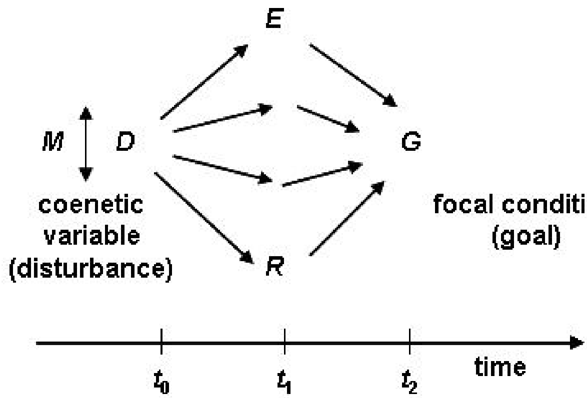


Figure 1. Directive correlation.[18] The coenetic variable $D$ is some kind of disturbance to the system. This affects both the environment $E$ and the regulator $R$, and $G$ is the focal condition (goal), which occurs later in time. $M$ is the degree of directive correlation, which is the range of variation of $D$ over which directive correlation can be maintained. The range of directive correlation is the number of correlated and coenetic variables involved.

Some really intriguing aspects of the matter do not yet appear to have been discussed. The first is that even a single bacterium creates a focal condition for life to be maintained. There is, of course, some noise in the system; much as in the classic process of nucleation of small solid particles within a condensing vapour, many nuclei appear and again evaporate before they can grow large enough to be stable; similarly in the primordial "warm little pond", protobacteria may have formed and then unformed many times before life stably existed.

The second is the role of mankind. Many writings concerned with Gaia place man in a superordinate position, able to intervene at will. They also make a distinction between "artificial" and "natural" processes. Thus, for example, burning fossil fuel in motor vehicles is an "artificial" activity, even though it has been engineered by man, who is indubitably an integral part of the natural world. This segregation of anthropogenic processes from everything else going on on the planet has been brought about by the realization that many of man's actions do not seem to be directed towards maintaining life but rather towards its annihilation. As von Foerster has written:[22] "If one looks around, the world appears like an anthill where its inhabitants have lost all sense of direction. They run aimlessly about, chop each other to pieces, foul their nest, attack their young, spend tremendous energies in building artifices that are either abandoned when completed, or when maintained, cause more disruption than was visible before, and so on." The mistake, so very human, is perhaps to have assumed that Gaia is above

[21] F. Nietzsche, *Menschliches, Allzumenschliches*, §1. [*Werke in zwei Bänden*, Band I. Munich: Carl Hanser Verlag (1964).] (first published in 1878).

[22] H. von Foerster, Perception of the future and the future of perception. *Instructional Sci.* **1** (1972) 31–43.

all concerned with maintaining *human* life (within the bounds fixed by the degree of directive correlation). It is hard to see why the focal condition of Gaia should make any distinction between different life forms. Despite the enormous growth in human population, we remain vastly outnumbered by bacteria, and presumably they, along with some of the other ancient and remarkably robust lineages such as those of cockroaches and snails, will outlive us.[23] What we are doing to our planet does indeed often appear to be incomprehensible, but perhaps no more so than the manifestly life-shortening lifestyles voluntarily adopted by so many of us.

## 3. Environmental degradation

In the 1970s a great furore was created by the publication of *Limits to Growth*.[26] This book described the results of a rather elementary (although it seemed advanced at the time, because the sheer volume of calculations necessitated very large computing power) attempt to model the world and predict its fate. The model was based on Jay Forrester's system dynamics (cf. general systems theory[11]),[27] confidence in which had been boosted by an early success—the demonstration that constructing low-cost housing in depressed urban areas exacerbated poverty (because it took up space that could otherwise be used for businesses creating jobs, and drew in people who needed jobs).[28] This was particularly successful because the result of the simulation is counterintuitive yet apparently correct. The basic tenet of *Limits to Growth* is much more intuitive—if population, and consumption, continue to grow exponentially, famine and pestilence will cause disaster—repeating the message of Malthus 200 years earlier, although his predictions turned out to be unfounded: technology also grew exponentially, or even superexponentially in some cases, and enabled disaster to be staved off.

Meadows et al. focused on simulating five economic subsystems: pollution, food production, industrial production, pollution and consumption of nonrenewable natural resources. The "standard run" scenario (also known as "business as usual") of their model collapsed around the middle of 21st century. There have been numerous criticisms of system dynamics and, *a fortiori*, of *Limits to Growth*. Some were rather technical: for example, inadequate details were given in the book *Limits to Growth* to permit the validity of the assumptions to be assessed.[29, 30] Others were of a rather bombastic and miscellaneous kind,

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[23] Furthermore, the bacteria living in the gut (for example) appear to have the ability of influencing the behaviour of their host.[24, 25]

[24] J.F. Cryan and T.G. Dinan, Mind-altering microorganisms: the impact of the gut microbiota on brain and behaviour. *Nature Rev. Neurosci.* **13** (2012) 701–712

[25] A.J. Montiel-Castro, R.M. González-Cervantes, G. Bravo-Ruiseco and G. Pacheco-López, The microbiota–gut–brain axis: neurobehavioural correlates, health and sociality. *Frontiers Integrative Neurosci.* **7** (2013) article 70 (online only).

[26] D.H. Meadows, D.L. Meadows, J. Randers and W.W. Behrens, *The Limits to Growth*. Washington, DC: Potomac Associates (1972).

[27] J.W. Forrester, *World Dynamics*. Waltham, Mass: Pegasus Communications (1971).

[28] H.T. Moody, Urban Dynamics: a review of Forrester's model of urban area. *Economic Geography* **46** (1970) 620–626.

[29] T.W. Oerlemans, M.M.J. Tellings and H de Vries. World dynamics: social feedback may give hope for the future. *Nature* (Lond.) **238** (1972) 251–255.

[30] Homilies for the Club of Rome (editorial). *Nature* (Lond.) **238** (1972) 237–238.

hinting at outrage that anyone should be suggesting growth should be limited;[31] it was felt that technical progress would ever and again intervene to ensure that growth could continue.[31] On the other hand, a very general analysis of technical progress shows that its benefits have been entirely, or almost entirely, swallowed up by population growth.[32]

A substantive criticism was the lack of empirical content.[29] Perhaps surprisingly, now that a few decades have elapsed it has been possible to test the predictions of the model against the actual evolution of the planet, and the results have been quite encouraging—that is, bearing out many of the predictions of *Limits to Growth*.[33] Another substantive criticism was the lack of "social feedback", by which is meant the ability of man to consciously intervene to reverse unfavourable trends.[29] The ultimately successful campaign to limit the ozone layer provides some evidence in favour of the working of social feedback, albeit it later turned out that the scientific premisses driving the campaign may not have been very solidly justified.[34]

Some of the specific criticisms concerned what might be considered to be second-order details: for example, societies becoming rich as a result of economic growth are more likely to spend money to prevent pollution. This seems to have something in common with the argument that there is no need to bother with fish conservation, because the scarcer the fish, the more valuable they are, hence fishermen can earn their living with progressively less work. A related argument is that economic growth enables expensive ways of producing energy, such as wind turbines, to be realized, even though more energy might be used in creating the wind turbine and its supporting infrastructure than is generated from it by the wind during its entire life.

A further category of criticism was subdued at the time, because there had been little formal engagement with complexity. It concerns the naïvety of the systems dynamics approach applied to the real world, which is complex. As Peter Allen has pointed out, reality and practice are messy and disorganized.[35] The first simplifying assumption made with the goal of leading to "scientific" understanding of the real situation is to assume a boundary. This is often unexceptionable. If one is considering world dynamics a natural boundary is one that completely encloses the planet. Hence, one excludes very rare (albeit catastrophic) events such as the collision of large, asteroid-sized bodies with the Earth, along with the possibilities of mining other planets and asteroids in the solar system for rare minerals. It is a moot point whether the Sun is also thereby excluded. Variation in the solar flux may play a crucial role in steering climate change, hence the planet-enclosing boundary that excludes the Sun eliminates a major variable input into the system. The second assumption is one of classification. Elements

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[31] W. Beckerman, Economists, scientists and environmental catastrophe. *Oxford Economic Papers* **24** (1972) 327–344.

[32] J.J. Ramsden and Gy. Kiss-Haypál, On a possible limit to economic progress. *Nanotechnol. Perceptions* **9** (2013) 71–81.

[33] G. Turner, *Is global collapse imminent?* (MSSI Research Paper no 4). The University of Melbourne: Melbourne Sustainable Society Institute (2014).

[34] E.g., D. R. Keiller, S.A.-H. Mackerness and M.G. Holmes, The action of a range of supplementary ultraviolet (UV) wavelengths on photosynthesis in *Brassica napus* L. in the natural environment: effects on PS II, $CO_2$ assimilation and level of chloroplast proteins. *Photosynthesis Res.* **75** (2003) 139–150 and references therein.

[35] P.M. Allen and M. Strathern. Complexity, stability and crises. In: *Complexity and Security* (eds J.J. Ramsden and P.J. Kervalishvili), pp. 71–92. Amsterdam: IOS Press (2008).

within the boundary are classified into types. Above all, this is a matter of convenience: previously established behaviour and responses of similar types can be used to predict behaviour in the system under present consideration, and this is indeed often done. The generally very limited success of such predictions nevertheless provides an empirical warning against making this assumption. One reason for failure could be that the classification is too coarse-grained. For example, consider the type (concept) “tomato”. Many culinary recipes and agricultural statistics merely refer to “tomatoes”. Nevertheless, even an average supermarket is likely to stock several varieties, differing significantly in flavour, price etc., and there are many more varieties, probably far superior to those traded in large quantities, that might nowadays only be found in rather remote, more or less self-sufficient areas of the world. The main shortcoming is that for this, and many other concepts, a proper ontology (concept system) has not been worked out. Hence, it may not even be clear, let alone consensually agreed, what are the essential features. Another reason for failure is that the parts of the system may change over time. Some of the parts initially present may disappear, some completely new ones may emerge, and even those that recognizably remain may undergo some change. The third assumption is that of average types: every agent of the same type in the system has a unique and fixed set of parameters. Such a system, lacking microdiversity, has no capacity to evolve. Modelling making the assumptions introduced so far is like taking a snapshot of the scene, and it is self-contradictory to use such models to make predictions about a distant future. At this point one can make a choice regarding further simplification: one can assume that sufficient time has elapsed such that the system has reached a stationary state (equilibrium). Alternatively, one can assume that the system continues to change dynamically and can be mechanically represented by the dynamics of the mean or first moment of the probability distribution of relevant variables, assuming them to be uncoupled from higher moments. This is deterministic system dynamics, and the attractors of the system represent the long-term outcome. Whichever choice is made, the model is now highly constrained and far from reality. It will be noticed that this is a much broader category of criticism, which essentially encompasses the others.

Despite the criticisms, as mentioned, comparison of the predictions of *Limits to Growth* with the actual events of the last 40 years has shown rather good agreement between reality and the “standard run” scenario of the model (“business as usual”).[33] The impression gained by the general public, either from direct first-hand experience through travelling or from the newspapers and other media, would tend to concur. Many kinds of environmental degradation, ranging from deforestation to the ubiquity of pesticide residues, are subsumed in the single parameter of mean earth temperature, with the assumption that this is rising due to rising levels of carbon dioxide in the atmosphere, and that, in turn, these levels are anthropogenic in origin, arising through the deliberate burning of forests, of fossil fuels, and the manufacture of cement, iron and steel. Although the climate change bandwagon has lost a great deal of its former prestige, through too many widely publicized breaches of the norms of scholarly scientific work, it was active for long enough to have entered the public mind, and many policies of the State formulated with the desire of limiting the anthropogenic production of carbon dioxide, such as the carbon emissions trading system of the European Union, are now firmly in place.

On the whole, therefore, it can scarcely be asserted that things have gone better than anticipated. On the contrary, some dire warnings have been issued, such as Lovelock’s *Revenge* *of Gaia*,[36] the main message of which is the need to reduce carbon dioxide emissions in order to limit global warming. Even in such a relentlessly technologically optimistic book such as Kaku's *Visions* it is conceded that while "our headlong journey into science and technology will one day lead us to evolve into a true Type I civilization", "in the background always lurks a possibility of a nuclear war, the outbreak of a deadly pandemic, or a *collapse of the environment*" (emphasis added).[37] The question to be addressed in the next two sections is whether nanotechnology can neutralize these threats at the global scale required.

A number of reports have sought to document the state of the environment more systematically and quantitatively. A very recent one is the report of the Rockefeller Foundation–Lancet Commission on what they call "planetary health".[38] Although Gaia is not mentioned at all in this 56-page report, it seems to have been inspired by it. Graphical representations of global trends in population, consumption, health and the environment show that many environmental indicators are increasing *pari passu* with population (i.e., exponentially): the use of energy, water and fertilizer, for example (from which it might be inferred that the pollution associated with energy generation, water contamination and fertilizer residues are all increasing). It was already pointed out that global gross domestic product (GDP) tracks population,[2] and carbon emissions follow a similar trend. The main interpretation assigned to the phrase "planetary health" is, however, the health of the human population on the planet. The seemingly inexorable increase of mean life expectancy suggests that global health is constantly improving despite all the environmental setbacks. This actually creates something of a paradox. Furthermore, many of the afflictions whose prevalence is indubitably increasing—such as obesity, diabetes and allergies—seem to have nothing to do with climate change.

## 4. What is nanotechnology?

Nanotechnology is atomically precise engineering; the manipulation of matter with nanoscale (i.e., of the order of 1 nm) precision.[39] It is taken to comprise materials, devices and systems; both the objects themselves and the means of fabricating them.[40] An important auxiliary subfield, needed for manufacture and applications, is nanometrology, encompassing practical techniques of measurement in the nanoscale.[41]

Nanomaterials comprise both discrete objects, such as particles and rods, with at least one dimension within the nanoscale (in practice lengths up to 100 nm are considered to be within the nanoscale), and materials with engineered internal structure within the nanoscale; this includes many composite materials. It is a moot point whether a *random* dispersion of nano-objects in a matrix constitutes a nanomaterial. If it does, then we must concede that mediaeval stained glass

[36] J. Lovelock, *The Revenge of Gaia. Why the Earth Is Fighting Back—and How We Can Still Save Humanity*. London: Allen Lane (2006).
[37] M. Kaku, *Visions*, p. 19. Oxford: University Press (1998).
[38] *Safeguarding Human Health in the Anthropocene Epoch*. The Rockefeller Foundation–Lancet Commission on Planetary Health (published online 16 July 2014).
[39] J.J. Ramsden, *Nanotechnology: An Introduction*. Amsterdam: Elsevier (2011).
[40] J.J. Ramsden, Towards a concept system for nanotechnology. *Nanotechnol. Perceptions* **5** (2009) 187–189.
[41] G.N. Peggs, Measurement in the nanoworld. *Nanotechnol. Perceptions* **1** (2005) 18–23.

is a nanomaterial; colloidal (nanoparticulate) gold engenders the characteristic red colour. A further point of ambiguity concerns the many powdered materials manufactured in such a way that they have a broad size distribution, the tail of which extends well below 100 nm. Examples are carbon black and even culinary flour.

A device is said to be "nano" when it has at least one characteristic dimension within the nanoscale. By this reckoning, the current generation of very large-scale integrated circuits are nano devices, because some of the individual transistors etc. are only a few tens of nanometres in size.

A further category—bulk materials machined with a precision of a few nanometres—does not fit easily into either materials or devices. They are typically passive objects, not processing information and hence not machines or devices, and their external dimensions may be very large. The mirrors for the current generation of large terrestrial telescopes are a good example. They have to be individually machined to a precision of a few nanometres (including the roughness of the reflecting surface).[42] This is, in fact, the original meaning of nanotechnology (when the term was first introduced by Norio Taniguchi).

The term "nanosystem" is not much in use at present. The personal nanofactory—a device able to manufacture a vast range of artefacts using acetylene as a feedstock—would be an example. Such molecular manufacturing devices do not yet exist, however.

In order to achieve atomically precise engineering, the goal is to create a eutactic environment, in which each atom is placed with a positional accuracy of the order of 1 nm or less. As has been pointed out by Brian Gray, the energy cost of achieving that is rather high.[43] Schemes for such "assemblers" have been worked out by Eric Drexler and others and their operation has been demonstrated using computer simulation, but no actual devices have been fabricated. The inspiration for this approach came from Richard Feynman, who imagined machines making parts for smaller machines which, when assembled, would in turn make the parts for yet smaller machines and so on down to the atomic level. The assemblers for positioning atoms and building objects atom-by-atom would themselves be not very much bigger than atoms, hence this fabrication technology is known as "bottom-to-bottom". The difficulties, however, appear to be formidable, not least because of the fundamental constraints adumbrated by Gray. Such experimental work as has been carried out has made use of a nanometrology tool, the scanning probe microscope (SPM). Atoms can indeed be picked up, moved and deposited by the tip of the probe. But the SPM itself is very much larger than the nanoscale, hence as a fabrication technology this approach ranks as "top–down". It is sometimes called "mechanosynthesis" and is the closest that we can presently get to working in a eutactic environment. Even though it appears to overcome some of the limitations of chemistry, which works in a Brownian, random environment, the ultimate formation of chemical bonds between atoms juxtaposed mechanically will still depend on potential energy minima, just as chemistry does.

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[42] P. McKeown, J. Corbett, P. Shore and P. Morantz. Ultraprecision machine tools—design principles and developments. *Nanotechnol. Perceptions* **4** (2008) 5–14.

[43] B.F. Gray, Reversibility and biological machines. *Nature* (Lond.) **253** (1975) 436–437; *ibid*. **257** (1975) 72.

Top–down, the kind of nanotechnology envisaged by Taniguchi, is indeed the only really successful approach to nanofabrication to date. In order to achieve nanoscale precision, the milling machines have to be massive in order to be rigid.[42] Also highly successful—demonstrated most vividly by Moore's law—is semiconductor processing technology. Alongside the nanification of individual feature sizes has been the achievement of vastification of parallel fabrication, with astonishing reliability, using larger and larger silicon wafers.

The capital outlay for top–down fabrication is, however, immense; hence, there is continuing interest in developing "bottom-to-bottom" methods. A powerful inspiration has come from the discoveries of molecular biology—the way muscle, bacterial flagellar motors, the enzyme ATPase and the various enzymes involved in nucleic acid synthesis operate. These motors are themselves molecules, albeit large ones, typically comprising of the order of several thousand atoms. These living proofs of principle of bottom-to-bottom fabrication have spawned another subfield of nanotechnology, bionanotechnology, in which biological devices, or mimics thereof, are harnessed by engineers. It is clear that many of these devices do not operate with atoms, but with "nanoblocks", such as a monomeric nucleic acid or a monomeric amino acid, each of which comprises several dozen atoms. Exploiting nanoblocks looks like an attractive way to circumvent some of the difficulties in true atomic-scale fabrication.

A potentially very inexpensive approach to assembling nanomaterials and nanodevices is "bottom–up" or self-assembly. This, too, is bio-inspired, notably by the spontaneous assembly of bacteriophage viruses and some of their components.[44] It is conceptually very different from processes like crystallization, which superficially resembles it. Crystallization does indeed produce an ordered array from a chaotic soup of atoms or molecules, but the size is indeterminate. Only by strong external manipulation (such as bringing about the conditions for crystallization, either by chemical reaction or by condensation, either extremely rapidly or extremely slowly) can the size be controlled to some extent. Bottom–up fabrication is programmable self-assembly. Typically, after a block has added itself to the growing aggregate, it will change its conformation and, hence, its affinities for other species present in order to prevent the growth of aggregates of unlimited size, as in crystallization. Programmable self-assembly has been achieved artificially at the macroscopic scale (using robots),[45] and at the nanoscale by nature (bacteriophage and the folding of linear polynucleic acids and polypeptides into unique, stable, three-dimensional structures).

The large-scale commercial manufacture of nanomaterials is dominated by nanoparticles that are incorporated into a variety of products, including ultraviolet-absorbing but transparent sunscreen (titanium dioxide and zinc oxide), antibacterial textiles and plasters (silver), diesel fuel combustion catalyst (cerium oxide), high-performance lubricants (copper), inks for printed electronics (silver and gold) and a wide variety of materials incorporated into polymers to confer enhanced mechanical strength, fire resistance, wear resistance etc. or diminished gas permeability, coefficient of friction etc. More complex substances are being examined for gas separation and storage purposes, as electrode materials for batteries, etc. Carbon nanotubes and graphene are used to make conductive composites. The metal and metal oxide nanoparticles are

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[44] E. Kellenberger, Assembly in biological systems. In: *Polymerization in Biological Systems*, CIBA Foundation Symposium 7 (new series). Amsterdam: Elsevier (1972).

[45] E. Clavins, Programmable self-assembly. *IEEE Control Systems Magazine* (August 2007) 43–56.

made either by a top–down process (comminution, i.e. grinding and milling) or by a bottom–up process (nucleation and growth). The environments inherent in these manufacturing processes only approximate to eutactic.

As well as these examples, there is a great deal of research activity attempting to use nano-objects for medicinal purposes (as contrast enhancers or drug delivery agents, for example) or to create novel electronic or sensing devices.

One further aspect of nanotechnology does not concern actual materials or devices: it is best described as the "nano viewpoint", according to which structures and processes are examined and analysed in the nanoscale.

## 5. How can nanotechnology arrest environmental degradation?

From the above, it is almost self-evident how nanotechnology benefits the environment. The greatest impact may arise through lightweighting, leading to reduced energy requirements. Polymer beverage containers can be made thinner without loss of gas impermeability by incorporating nanoplatelets into the polymer. Many automotive components can be made from a nanocomposite (a polymer incorporating nano-objects) instead of steel, without compromising strength but yielding a considerable reduction in weight. Miniaturized devices with the same information-processing capability as their larger predecessors are not only smaller but lighter too. All this lightweighting means that not only are transport vehicles themselves lighter and, hence, use less fuel but all the way back up the supply chain less or lighter materials are needed, saving on transport and manipulation costs. Since about one third of global fossil fuel consumption goes on transportation, even modest reductions in weight could result in significantly less fuel being used, and hence less carbon dioxide being emitted into the atmosphere.

Enhanced lubricants also contribute to reducing the energy consumed to produce a given amount of work, and fuel combustion catalysts enhance the energy produced from a given quantity of fuel. Miniature electronic devices dissipate less heat because they require fewer electrons to carry out internal operations.

The above are all indirect and incremental benefits of nanotechnology arising through the use of nanomaterials. Similarly indirect and incremental benefits may arise through the use of nanodevices. The nanification and vastification of very large-scale integrated circuits has enabled the enormous proliferation of inexpensive information processors (computing devices), such that many human activities can be optimized rather effectively, again saving energy consumption and the consumption of superfluous materials, the saving of which saves the energy used in their manufacture and transportation. For example, many farmers nowadays routinely use computationally intensive geographical information systems in order to optimize ploughing, sowing, fertilization etc.; and motors can be much more finely matched to the demands put on them through a combination of environmental sensors (which may also be nano-enabled) feeding into an information processor, which in turn controls the motor.

A more direct benefit of nanotechnology is catalysts fabricated with greater control, providing the ability of greater control of a chemical reactions they catalyse. At present, however, such catalysts, made by an approximation to atomically precise engineering, tend to be too expensive for widespread deployment.

Not so long ago it was hoped that applying certain nano-objects to the soil would indeed be able to repair the environment to a pristine state, in a very direct application of nanotechnology. Specifically, it was already known that iron can remediate organochlorine pollutants in soils, and it was deduced that if nanoscale iron particles are applied, the remediation activity would be much greater, primarily because of the enormously increased iron surface area, at which the remediation—the destruction of the organochlorine molecules—takes place. There have, however, been two problems preventing the development of this technology. Firstly, nano-iron is highly reactive and rapidly oxidizes, transforming it into a far less effective remediation catalyst. Secondly, the nano-iron appears to have adverse effects on the microbiota of the soil, and in many countries there is now a moratorium on adding nanomaterials to the soil.

If productive nanosystems (personal nanofactories) are ever developed,[46] the impact would likely be large enough to have a truly significant impact on the environment. Firstly, almost every human artefact would be made from carbon. This should significantly lower the atmospheric concentration of $CO_2$. Secondly, ultrathin and ultrastrong diamondoid panels could be used for constructing buildings, replacing more traditional materials like brick and concrete produced energy-intensively. Thirdly, because production will be local, a great deal of the transportation associated with distributing manufactured goods will become redundant.

Attractive as this scenario may seem, it is still doubtful when, and even whether, productive nanosystems will be realized. There are, however, other possible nanodevices that can make some contribution to solving global problems. One intriguing example, which does not appear to have yet attracted any significant attention, is the artificial kidney. As is hopefully well known, the kidney is able to extract dissolved components from the blood *against* a concentration gradient.[47] A similar result is seen in the numerous marine microorganisms that extract elements such as calcium and silicon from seawater in order to build their (exo)skeletons. These processes take place a room temperature in an energy-efficient fashion. No man-made process can compete at present. As is well known, the extraction of metals in particular mainly takes place via pyrometallurgy—after crushing and grinding, ores are roasted at high temperatures to create an oxide, which is then reduced with carbon. Such processes doubly contribute to carbon dioxide emissions: both the burning of fuel to create the high temperatures required and the oxidation of the carbon with concomitant reduction of the ore. If metals could be extracted from seawater in the manner of the diatom or the kidney, the industrial landscape would be transformed. This would indeed contribute to restoring the environment to a pristine state. Nanotechnology is involved because in order to mimic the operation of the kidney or the diatom—in the latter case not all details are yet known—intricate structuring of the reaction medium appears to be needed, for which atomically precise engineering (nanotechnology), or an approximation thereto, seems appropriate.

The great strength, at least according to theoretical predictions, of diamondoid panels has already been mentioned, enabling their use in large-scale construction. Carbon nanotubes (and graphene) represent a reification, about which there is already considerable experimentally based knowledge. Although a complete industrial system for creating large-scale objects from carbon

[46] R.A. Freitas Jr, Economic impact of the personal nanofactory. *Nanotechnol. Perceptions* **2** (2006) 111–126.
[47] S.R. Thomas, Modelling and simulation of the kidney. *J. Biol. Phys. Chem.* 5 (2005) 70–83.

nanotubes is as yet lacking, there is already hope that this technological direction might enable the space elevator—a tower reaching up to a high Earth orbit from which spacecraft could be launched at very low cost—to be constructed. In itself the space elevator would have very little impact on the terrestrial environment, but by making the mining of minerals from the Moon and objects farther afield economically viable, it would take the pressure off the Earth's environment.

The phrase "repairing the environment to a pristine state" conjures up a vision of small robots swarming over the land (and swimming in the sea) in great numbers, swallowing up litter and pollution wherever it is encountered, in effect doing on a larger scale what has been conceived as an approach to medicine (i.e., the "nanobot", a machine somewhere between the size of a bacterium and a red blood cell able to circulate in the bloodstream and carry out repairs to the human body[48]). The material they collected would be deposited in a central depôt and used for manufacturing or other purposes. Whereas the nanobot has to be in the nanoscale (if one takes 100 nm as the upper limit of the nanoscale, even a small bacterium is, overall, larger than this but in order to be functional it has to contain much machinery that is significantly smaller), the "envirobot" would have to be large enough to negotiate its way through the landscape and have a reservoir large enough to collect useful quantities of pollution. The connexion of the envirobot with nanotechnology is simply that the trend of the organization of manufacturing in the direction of productive nanosystems, even though we are still a very long way away from them, will generally make the cost of advanced materials and devices lower and lower, such that something like the envirobot becomes a realistic proposition.

The reality of this trend cannot be disputed. In semiconductor processing, Moore's law provides incontrovertible evidence. Semiconductor processing is, however, subtractive (along with most traditional metalworking and sculpture), whereas nanoassembly is additive—objects are made by the accretion of individual atoms on nanoblocks. This concept has already been realized macroscopically in additive manufacturing (the "3D printer"). A far as the environment is concerned, the main advantage of additive manufacturing over subtractive is that there is no waste. If, indeed, we ultimately acquire the ability to routinely assemble artefacts atom-by-atom, we should be able to disassemble them in a similar fashion, which means that every discarded object could be recycled. This raises the intriguing possibility of reversing the present trend of diminishing garbage recycling, because as objects become miniaturized, it becomes more and more difficult to usefully separate their components using conventional methods.

In summary, it is far from self-evident that nanotechnology will repair the environment to a pristine state. The main contribution is simply through the general increase of manufacturing efficiency (including the contribution of vastly increased computing power), requiring less energy and less waste to produce an artefact. But in many cases where nature competes (such as green plant photosynthesis vs photovoltaic solar panels) it is doubtful whether, taking everything into account (which is, of course, really difficult) the artificial system is superior; many of the arguments put forward by Pirie almost 25 years ago still seem valid, despite the enormous progress on the artificial side.[49]

[48] T. Hogg, Evaluating microscopic robots for medical diagnosis and treatment. *Nanotechnol. Perceptions* **3** (2007) 63–73.

[49] N.W. Pirie, Leaf protein as a food source. *Experientia* **38** (1982) 28–31.

## 6. Can nanotechnology placate Gaia?

This question needs to be formulated more precisely as "can nanotechnology ensure that the planetary system remains within the degree of directive correlation with respect to the focal condition of continuing life?" (see Figure 1). One way to approach this question is to attempt a blow-by-blow accounting of the contribution, rather like the procedures prescribed by ISO/TS 14067:2013 for quantifying the carbon footprint of products.[50] There are, however, some doubts about the value of this approach because of inadequate attention to uncertainty.[51] Therefore, it seems to be more fruitful to address the issue at a higher level.

Overwhelmingly, the greatest issue is one of population. All the trends of concern track population, and it seems reasonable to infer that Gaia could best be placated by reducing the population, back to the levels it had between 150 and 200 years ago. At first sight this seems paradoxical. If the focal condition is the maintenance of life, surely the more life there is, the better. This seems to be the premiss underlying the phrase "be fruitful and multiply",[52] on which the churches have battened. It is of course entirely appropriate in a relatively empty environment and probably remained appropriate for humanity until the late 18th or early 19th centuries. It is a moot point whether one should search for triggers of the rapid population growth that ensued around that time—such as advances in agricultural technology, the general rise of prosperity due to the Industrial Revolution, advances in medicine (decreasing mortality but also helping to decrease birthrate), as well as the increased demand for industrial labour (albeit offset by decreasing demand for agricultural labour)—or whether the natural tendency of any population to grow exponentially was simply following its course. Since we do not yet have a definition of "life" it seems premature to attempt to quantify it. Malthusian predictions of famine and pestilence were never really borne out; the so-called "green revolution" and antibiotics came to the rescue. The deep-rooted feeling that human ingenuity will ever thus overcome problems appears to have strong empirical support, although a more careful analysis has shown that the effect of all this ingenuity is, actually, remarkably slight.[32] And, in fact, the green revolution basically substituted quantity for quality. Not only has the flavour of food been sacrificed, but also its nutritional value. Antibiotics have given us resistant bacteria (and agricultural pesticides resistant pests) and as for general health, the trends of rising obesity, diabetes, allergies and mental disorders belie the notion that general health has increased. Furthermore, the effect of intensive agriculture on the environment is unsustainable, to say nothing of the vast quantities of energy required to sustain modern agricultural production.

Even if the apotheosis of nanotechnology is the synthesis of food in abundance from a simple carbon feedstock,[46] the problem of population would not be solved. Indeed, it might enable a still greater increase, further exacerbating the problems of crowding. For sure, ways can be found for giving shelter to all, if only in underground cells,[5] but how will man then retain an appreciation for the rest of the living world? Most rivers in populated areas are too polluted for swimming—instead artificial swimming pools have been created, but the mental construct associated with the latter is very different from that associated with

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[50] *Product Carbon Footprinting for Beginners*. London: British Standards Institute (BSI) (2014).
[51] For example, the word "uncertainty" does not even appear in ref. 50.
[52] Genesis 1, 22.

the former.[53] If one spends one's entire life in the built environment, surely it is inevitable that the deeply rooted appreciation of the entire living world that is doubtless necessary to "rescue" Gaia can never properly develop. Crowding also leads to a general intensification of life. Ideally parents should only have as many children as they can properly bring up, above all by devoting sufficient time to their education. The State has intervened by providing public centres of education—schools—but typically only from age six onwards, by which time the main features of a child's character are likely to have been formed. There is a tendency to provide facilities for younger children, but the younger the child, the more important the environment, hence providing nurseries from age four onwards still leaves untouched the even more crucial early years, and the same from age two: the logical conclusion of this line of reasoning is that children should be taken from their mothers from birth and placed in the care of the State. This has, indeed, been tried in some societies, but always the crucial question of *quis custodiet ipsos custodes* is given inadequate attention.

Life feeds on negentropy, hence ultimate ruin is inevitable. All that can be done is to stave off that moment. Kaku's solution is to expand into the rest of the universe;[37] it should be achievable with advanced technology, of which nanotechnology is the ultimate realization (since manipulating with subatomic precision hardly makes sense). Lovelock focuses on keeping the Earth's temperature under control.[36] In both these works there is a hint that some kind of regimentation will be necessary to keep unruly humanity under control. This was the method adopted in the Bronze Age empires, and it led to sterility of thought—quite the opposite of what one needs to creatively develop ever more advanced technologies as a means to prolong life on Earth.

Maybe the problem of crowding (overpopulation) is not so much the pressure on resources (food and environment)[54] as the mental pressures resulting from the intensification of living in society; "intensification" means having thousands of "friends" via social media, having to deal with an intrusive, impersonal bureaucracy for all matters concerning the State, being flooded by thousands of cheap plastic artefacts of no real use, and so forth. It is extremely worrying that there appears to be evidence that our intelligence is declining.[55] This bodes extremely ill for our continuing ability to develop advanced technologies.

## 7. What is technology?

But what is technology? It appears to be difficult to define; Brian Arthur remarks that "Technology in fact is one of the most completely known parts of the human experience. Yet of its essence—the deep nature of its being—we know little".[56] Unfortunately Arthur does not

[53] Cf. Hans Andersen's fairytale "The Swineherd": the princess rejects the swineherd's gift of a live nightingale, preferring an artificial musical box.

[54] V.D. Markham (ed.). *AAAS Atlas of Population & Environment*. Washington, DC: American Association for the Advancement of Science (2000).

[55] M.A. Woodley, J. te Nijenhuis and R. Murphy, Were the Victorians cleverer than us? The decline in general intelligence estimated from a meta-analysis of the slowing of simple reaction time. *Intelligence* **41** (2013) 843–850.

[56] B. Arthur, *The Nature of Technology: What It Is and How It Evolves*. New York: Simon & Schuster/ Free Press (2009).

address the question of its essence in his book; the main point appears to be the proposition that technology develops by a process of combinatorial evolution. Several decades earlier, however, Oswald Spengler had presented a remarkably insightful view of technology's essence:[57] in brief, man is a predator and the purpose of technology is to dominate nature. Technology is, therefore, inevitably opposed to Gaia, even though technology was nurtured by Gaia. Nevertheless, it is not unreasonable to suppose that intelligent man will seek to use technology to avoid destroying the environment on which is survival depends.

Sheer survival, under possibly quite unpleasant conditions, might not be motivating enough to drive such a development of advanced technology. Lovelock writes that "what is most in danger is civilization";[36] what we need to preserve is that. But what is civilization? This is more elusive to define then technology. It is inextricably tied up with values. Values can motivate, can elevate, and without such elevation humanity may feel that survival is not an inspiring goal.

Surprisingly (for it appears to be a very crude measure) the degree of civilization appears to be correlated with per capita energy use. This compounds the difficulties associated with population growth. Not only does mankind become more numerous, but his degree of civilization increases and if both are roughly exponential, total energy consumption increases superexponentially. It is an intriguing question whether this increasing per capita energy use is actually driven by the exigencies of collective living. The lone subsistence farmer has few organizational constraints, but enabling collective urban living implies a great variety of energy-consuming installations, including street lighting, underground railways and elevators in high-rise dwellings.

To conclude, advanced technology, which is most completely exemplified by nanotechnology, could be intelligently applied to preserve Gaia and keep the Earth a pleasant dwelling place for man. But for this to yield any results, there needs to be some consensus about a core set of values. The real challenge is how to achieve that, for it cannot be done by regimentation. And, with due regard to the heterarchical nature of science and society, society needs to appreciate what science—knowledge—can achieve.[58]

[57] O. Spengler, *Der Mensch und die Technik*. Munich: C.H. Beck (1931).
[58] J. McCreesh, Why bother about science? *New Scientist* (15 March 1973) 612–613.