

Nanotechnology and the Commons: Implications of Open Source Abundance in Millennial Quasi-Commons

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Abstract. *Considering the implications of nanotechnology helps explore the prospects for common property institutions. Open source approaches to developing computer software create new commons in shared intellectual property. Applying open source principles to the development of nanotechnology and biotechnology might accelerate the growth of freely available knowledge. Increasing resource reuse and abundance may shift the balance between private benefits and broader interests in ways that favor the creation of commons. Users of shared spaces that are formally public or private property already assert increasing roles in governance, constituting quasi-commons. Longer lifetimes may encourage the crafting of new commons on a millennial time scale. Nanotechnology opens interesting opportunities for constituting new commons.*

Keywords: *nanotechnology, molecular engineering, common property resource management, new commons, open source software, cyberspace governance, intellectual property, genetic resources, recycling, flow and stock resources, quasi-commons, life extension, post-scarcity*

INTRODUCTION

What might be the prospects for the commons in a future of expanding cyberspaces, material abundance, and long life? Thinking about the implications of nanotechnology research and development offers a stimulating way to explore some of the challenges and opportunities facing management of common property resources in the new millennium.¹ Nanotechnology is a strong candidate to drive a future wave of change in technology and society, following and amplifying waves of change from information technology and biotechnology.²

Three routes to nanotechnology. Development of molecular machinery is scientifically feasible,³ though decades of scientific and engineering work may be needed before it is widely applied. At least three routes lead to nanotechnology,⁴ defined as precise control over the construction of molecular systems at the nanoscale of billionths of a meter. The computer industry is investing heavily in learning how to build smaller and smaller devices, shrinking manufacturing towards the atomic scale, (the top-down route). Biotechnology is discovering how to tailor the molecular machinery of DNA and proteins, (the wet route). Manipulation of individual atoms with atomic force microscopes foreshadows molecular assemblers which could build materials atom by atom, (the bottom-up route).⁵ Nanotechnology will probably be developed, one way or another. The challenge for speculation, and for technical and social invention, is how it may be used.

Potentials. The potential impacts of nanotechnology are immense. Shrinking computer components to atomic scale could enable computers to continue to grow cheaper, smaller, and more powerful for decades hence. Tiny nanomachines could monitor and make repairs inside cells, curing disease and extending life.⁶ Molecular assemblers might build materials to order, making matter as controllable and easily reproduced as software,⁷ while also disassembling wastes and pollution to recover elements and compounds for reuse. How these potentials are developed, and who has access to them, depends on social institutions. These institutions include not just private ownership and state regulation, but also collective action in the management of common property, old and new commons.

Nanotechnology scenario. An accelerating rate of technological change may lead to a singularity, a point beyond which it may be impossible to even foresee what might follow.⁸ However this paper suggests that efforts to create and manage common property will persist, however drastic the changes which may occur. Scenarios are useful tools for formulating ideas and policies that will be more resilient in the face of inevitable surprises.⁹ Nanotechnology, and particularly the vision of nanotechnology laid out in Eric Drexler's book, *Engines of Creation*, offers a feasible scenario of possible changes in technological capacity. Considering the implications of nanotechnology challenges some of the current conceptions and preoccupations in the study of common property. The point of this paper is not to make specific predictions, but to explore some possible consequences of technological change, using the example of nanotechnology, and to identify some possible implications for the study and management of common property.

Organization of the paper. The first section of this paper looks at "open source" approaches to the collective production and management of intellectual property in a commons of freely shared information resources. Molecular engineering may transform the use and reuse of natural resources, and the second section raises questions about the implications of abundance for management of common-pool resource stocks and flows. Nanotechnology may further expand capabilities to create shared spaces, both physical structures and cyberspaces. The third section notes how stakeholders reconstitute the governance of shared spaces as quasi-commons, mixing modes of private and public property with the influence of stakeholder voice and exit. The fourth section outlines how health, wealth and long life might bring increased attention to long-term endeavors, encouraging the crafting of common property institutions for millennial projects.

OPEN SOURCE IN INFORMATION COMMONS

Most studies of common property have focused on common pool resources, such as forests, fisheries, rivers and pastures in which a group of users share rights to use the resource. For such common pool resources, one person's use subtracts from the amount available for others to use, so users are rivals to some degree. By contrast, information can usually be duplicated at little or no cost, without necessarily diminishing its value to existing users. This potential for non-rival use and sharing is a distinctive characteristic of intellectual property. Conventionally, intellectual property rights, embodied in patents, copyrights and legally protected trade secrets, have been seen as necessary incentives to promote the production of knowledge, especially commercially useful knowledge. Such views emphasize the need to reward individual creativity, and tend to neglect the cumulative and collective processes through which knowledge is created.¹⁰ The emergence of open source software illustrates how an alternative approach to sharing information resources has enabled and accelerated the creation of a new commons.

Open source software. The Linux computer operating system has emerged as a serious challenger to the near-monopoly of Microsoft Windows. Linux exemplifies the strengths of collective action by a swarm of volunteer programmers to create freely available software. While Linux may be the best known example in the wider world, it is only one of many such efforts, ranging from the EMACS word processor pioneered on mainframe computers to the Apache software running the majority of web servers. Open source approaches have had surprising success in overcoming problems of coordination, diseconomies of scale and scope, which had been seen as inevitable constraints on large software projects, even well-funded programming projects managed by large corporations such as IBM or Microsoft.¹¹ Eric Raymond's essay, "The Cathedral and the Bazaar" analyzed the differences between the centralized planning of conventional software, prone to delays and errors (bugs), with the decentralized vigor of open source approaches for creating sophisticated, reliable programs.¹²

Open source software has characteristics of common property, in being freely available for use, nowadays posted on the internet where anyone can download it. It is the collective product of a community of programmers working together, most of them helping refine only a small piece of the overall project. Certain individuals may have "ownership" rights, based on initiative and community reputation, to decide what changes will be included in new releases of the software.¹³ Raymond argues that reputation is the key incentive underlying the post-scarcity "gift culture" of computer programmers participating in open source efforts, competing for status by giving things away.

As with other forms of common property, open source communities face conflicts concerning how to institutionalize access to common property. Intense debates have raged about how to provide a legal basis for open source software which will preserve accessibility while maintaining incentives for continued development.¹⁴ Legally the software is placed in the public domain, with licenses which allow others to use and modify the software. Licensing provides a legal mechanism for defining the boundaries of the group of legitimate users. In practice, membership is largely constituted through the electronic mailing lists used to discuss and announce improvements.

Programming has strong roots in academia, partaking of scientific traditions for sharing knowledge. However open source software has proven able to thrive in commercial domains where one might usually expect proprietary software to be the rule. Raymond argues that a key reason for the economic viability of open source software comes because the vast majority of software is actually not sold directly, but instead written for internal use in producing goods and services.¹⁵ The businesses that pay the programmers who write the software are not concerned to maximize sales value. Instead, those businesses, and others who use open source software, are more concerned about reliability, quality, compatibility with popular standards, availability from multiple sources, and other factors, among which cost is often a relatively minor consideration. In some cases, companies may use a strategy of freely releasing software which enables them to profit from sales of related equipment or services. Open source strategies build on the potentials for easy sharing of electronic information, emerging through individual and organizational incentives that encourage communities of software writers and users to create and share new information commons.

Open source for nanotechnology. The increasing ability to precisely control the assembly of matter at the molecular and atomic level (one definition of nanotechnology) promises to make matter like software.¹⁶ Building equipment, food and other materials might become as easy, and cheap, as printing on paper is now. Just as a laborious process of handwriting texts was transformed first into an industrial technology for mass production and then individualized in computer printers, so also the manufacturing of equipment and other goods might also reach the same level of customized production. If “assemblers” could fabricate materials to order, then what would matter would not be the materials, but the design, the knowledge lying behind manufacture. The most important part of nanotechnology would be the software, the description of how to assemble something. This design information would then be quintessentially an information resource, software.

The same principles which have promoted the rapid development of accessible, affordable and innovative open source software might also be applied to the creation of knowledge for nanotechnology.¹⁷ Nanotechnology could maintain the paradigms of openness, public criticism and development as a community effort which are already part of its foundations in current nanoscience, rather than assuming that proprietary secrecy is the only route to further development.¹⁸ This could accelerate research and development, and promote accessibility, while also promoting safety.

Opening up intellectual property. Raymond argues that the advantages of closed source come through profiting from specific secret information, and that what has not been adequately appreciated is the extent to which the advantages of open source may far outweigh the potential profits of such proprietary information. He suggests that five factors may favor the choice of open source:

we can expect that open source has a high payoff where

(a) reliability/stability/scalability are critical, and

(b) correctness of design and implementation is not readily verified by means other than independent peer review. . . .

- [c] *when the software is a business-critical capital good [due to the desire not to be dependent on a single supplier] ...*
- [d] *in software that establishes or enables a common computing and communications infrastructure. ...*
- [e] *when key methods (or functional equivalents) are part of common engineering knowledge.¹⁹*

These criteria can be applied to nanotechnology. For nanotechnology, reliability and stability are crucial. For computers scalability means being able to expand to deal with more users and more information, and somewhat similar concerns arise if designs are used to produce multitudes of tiny nanomachines. Peer review may be essential to detect and correct errors. Companies using nanotechnology to produce other goods and services may prefer open source, to avoid dependence on a single supplier who keeps software secret. Common standards and infrastructure would promote cumulative development of the technology. It is not yet clear the extent to which nanotechnology may rely on commonly known procedures or unique techniques, but most of the foundations may well be developed as openly shared scientific knowledge.²⁰ It would seem that the rationale for open source would apply strongly in the case of nanotechnology, particularly if the principal products will not be the production equipment, assemblers, but rather designs for producing materials and machines, i.e. software.

An obvious starting point would be to promote open source approaches in developing modeling software for nanotechnology design. Such design is already being done on an exploratory basis, largely in a scientific mode, to see what sorts of molecules might be build for nanomachines. Creating commitment to open source in modeling software for the longer term, even after commercialization, would establish a foundation for accessible information. This would gain the advantages of peer review to examine design safety issues. It would build a coalition of individuals and organizations interested in supporting open source software for modeling nanotechnology designs. Such an initiative would benefit from first-mover advantages, and could establish standards, creating the intellectual infrastructure for a new field.

A further rationale for open source, especially when viewed from a wider societal perspective, comes from the much lower transactions costs of managing an open information commons, compared to the higher costs of establishing and protecting private intellectual property. Open source offers an alternative approach, applicable in at least some interesting cases, where it may well be in the public interest to promote (or at least avoid discouraging) common property institutions for information commons, rather than relying only on private forms of intellectual property.

The strategy of openness. Public sharing of information could also help to deal with some of the hazards that may accompany nanotechnology. Initially, and by analogy with biotechnology, concerns about the safety of nanotechnology focused on containment, avoiding nanomachines that might run wild and dissolve the world into “gray goo.”²¹ However over time it has become clearer that safety can be built into the design of nanomachines so they are easily shut down, and dependent on specialized inputs (artificial “vitamins”). Deliberate design could make nanomachines far more controllable than the viruses and bacteria used in biotechnology. The risk of

nanotech going wild could be made as unlikely as worrying that automobiles will go feral, stealing gasoline and reproducing themselves in the wild.²² The dangers that would remain would be ones of deliberate abuse, scenarios of hackers, terrorists and warfare. These risks are real and need to be addressed.²³ The methods already developed to cope with atomic, biological and chemical technologies could help to deal with these risks, but open source approaches might make some further contributions.

One of the arguments for open source software has been that a big and diverse group of people can quickly identify flaws, whether bugs or weaknesses that might be misused. Open source advocates argue that collective efforts to develop robust software, resistant to hacker vandalism, outpace individual or proprietary efforts. In the case of nanotechnology, safety protocols could be built into the core of designs. If these designs have the first mover advantages of widespread backing, then those who might wish to abuse the technology would be at a great disadvantage, with little choice but to use software which already has safety designed in from the beginning.²⁴

In addition to internal design characteristics such as making the technology failsafe, failsoft and dependent on scarce and controlled inputs, a key requirement might be transparency to external monitoring in key applications, particularly for any technology capable of self-replication. Openness to inspection is already a key part of international regimes for controlling atomic, biological and chemical technologies. An emphasis on transparency would use a strategy of openness.²⁵ Rather than emphasizing secrecy and restriction of information to the police and other government authorities, the strategy would be one of transparency, making monitoring information available to whoever is interested. Enforcement then need not be limited to narrow efforts by police, but would draw on the interests of a broad community, including media as well as commercial and political competitors with a strong interest in detecting and deterring illegitimate use. (This has obvious parallels to the ways in which users of common pool resources often monitor each others' use, and deal with violations, rather than relying only on specialized enforcers.)

Patents represent a well-established form of intellectual property which compromises between the goal of providing incentives to innovators, while requiring them to make their new knowledge publicly available and limiting the period where the inventor controls rights to use of the new ideas. Similarly, environmental concerns have brought increasingly strict requirements that industries make publicly available information about what substances they release into the environment. It seems reasonable to expect that regulation of nanotechnology might reach similar compromises between private and public interests, including strong requirements that key applications of nanotechnology be subject to open monitoring.

Open source and biotechnology. It may be interesting to consider the extent to which open source principles could apply to the case of biotechnology, (particularly since this paper is being presented in a conference panel along with several papers on intellectual property in genetic resources.) Genetic engineering obviously has evoked strong concerns about safety, for which reliability and stability of the technology are crucial. Like nanotechnology, biotechnology is very concerned with the ability to produce its products billions of times over. Peer review may play a similar role in enhancing biotechnology, and safety concerns might reinforce preferences for open approaches, rather than proprietary secrecy. Companies using biotechnology to deliver other services, such as health care, rather than just selling genetic products (i.e. seeds) might well prefer

open source suppliers.²⁶ It is less clear how the principle of a common infrastructure might apply, though demonstrating compliance with safety standards might be important. Many forms of biotechnology rely on well-known processes, found in biology rather than being invented, while others make more use of “unique or highly differentiated services. It would appear that open source approaches might be relevant for many aspects of biotechnology, although there would likely still be major areas where proprietary approaches would retain advantages.

At a minimum, open source approaches might offer some useful options concerning the regulation of intellectual property rights related to genetic resources. The example of computer code shows how collective open source efforts can thrive, even while knowledge is produced and used within commercial activities. Similar principles might apply concerning genetic codes. Rather than a purely proprietary or purely public approach to intellectual property in genetic resources, a more differentiated approach might be feasible. Such an approach might facilitate collective action to discover and make available genetic knowledge in ways that would be difficult through purely public or private approaches. In at least some cases, proprietary rights may be neither necessary nor even the best way to promote innovation, while open source approaches could facilitate broader access to useful knowledge about genetic resources.

Information resources differ from common pool resources since information can be easily shared and duplicated, without subtracting from its availability to the original user. Both common-pool and non-rival resources may sometimes benefit from institutional arrangements that allow a diverse group of users to share in the production and governance of the resource, in ways which differ from public or private ownership. The principles of openness and cooperative effort which have promoted the growth of open source software might also foster the growth of nanotechnology design information, and assist in promoting safety, transparency (monitorability) and access to biotechnology and nanotechnology.

IMPLICATIONS OF ABUNDANCE

Much thinking about management of the common property resources such as water, forests and fisheries is driven by assumptions of increasing scarcity. Assumptions of increasing scarcity may underlie arguments that resources must be privatized in order to internalize externalities, create incentives for better management, and prevent a “tragedy of the commons.”²⁷ Students of common property have challenged such arguments, emphasizing the difference between commons where access and aspects of usage are regulated, versus “open access” resources with no such controls on how the resource is used. Research has documented the capacity of resource users to jointly organize common property institutions that regulate access, mediate conflicting claims and sustainably manage shared resources. The potential economic value of the resource is a major factor, inducing conflict, raising incentives for private appropriation, and possibly justifying the transactions costs involved in defining private rights over a resource such as water, fisheries, forest or range land. In contrast to prevalent scenarios of increasing scarcity, the potentials of nanotechnology might instead lead to increasing abundance, and increased capability for environmental regeneration. This shift in relative resource costs could then influence choices between the three broad institutional alternatives of public, private and common property resource management, in ways that might well favor common property institutions.

Elementary recycling. The ability to precisely control the assembly of matter at the molecular level also implies the capacity to disassemble materials, purify air and water, clean up pollution and possibly transform waste dumps into sources of valuable materials. Most recycling, of glass, paper or plastic for example, currently goes on at the chemical level of complex molecules and bulk materials. The presence of undesired elements and compounds often makes recycling difficult or uneconomic. Nanotechnology could make it easier to extract and reuse desirable atoms and compounds, and sort out temporarily unneeded elements for storage or use elsewhere. Properly deployed, nanotechnology could be a green technology, reducing the need for environmentally damaging resource extraction, enabling sustainable resource availability, and contributing to environmental restoration and regeneration.²⁸

From flow to stock. Water purification offers an example which can be used to explore possible implications of using nanotechnology for purification, and consequent changes in resource costs. Carbon nanotubes might not only enhance water purification technologies to the point where they far outcompete reverse osmosis or distillation in arid areas, but even become preferable options for water treatment in humid regions, at least for any place not too distant from the sea.²⁹ Water is normally managed as a flow resource, used once and then passed on, whether quickly along a stream or more slowly through recharge and extraction in aquifers. Rivers and seas tend to be treated as sinks, into which water can be dumped after use.

Tertiary wastewater treatment plants already can yield water with higher quality than the original sources used for urban water supplies. Many of the innovations in reducing industrial water use involve closing cycles, reusing water many times, or even indefinitely, with only occasional replenishment to compensate for minor losses such as evaporation. Fully implementing closed systems for urban water supply would likely face opposition due to attitudes about cleanliness and purity, especially for drinking water. A change might be more feasible with systems operating on “graywater” principles, distinct from water used for cooking, washing and bathing. Applying closed-cycle approaches to industrial and domestic water supply would mean that water in such systems would be managed primarily as a resource stock, rather than a transient flow. If implemented widely, such changes might dramatically reduce dependence of cities on upstream water sources. On the one hand this might reduce pressures to acquire new water sources, while on the other hand it might reduce the interest of downstream users in supporting improved watershed management upstream. Technological change would not only expand the envelope of technical possibilities, but could lead to changes in key characteristics shaping how the resource is managed, in this case, a shift from management of one-way resource flows to management of recycled resource stocks.

Atmospheric commons. Improvements in purification technology might also drive changes from a “use it once and pass it on” approach for indoor air. Outdoor air quality in wealthier countries has already improved dramatically, much of this driven by regulation of air as a public resource.³⁰ Indoor air quality is a more recent concern, and struggles over its management are shown, for example, by changing social norms and legal restrictions on smoking cigarettes. Concern for energy conservation has already driven much greater attention to improving insulation

and reducing unwanted air loss in temperate climates, and much potential for further such improvements exists, reducing flows relative to stocks.³¹ Nanotechnology would represent an ultimate purification technology, capable of removing radon, formaldehyde and other such pollutants, and making total recycling at least conceptually feasible, as well as the elimination of unwanted emissions. Increasing ability to recycle air within a building might lead air to be managed even more as a stock, with the flow element of the resource playing a smaller role.³² Private business, and common property organizations such as condominiums, would gain greater capacity to manage the resource themselves, reducing (for better or worse) their dependence on public management of air quality. At the same time, eliminating emissions and recapturing pollutants such as sulfur and carbon dioxide could become much more feasible and affordable. Depending on costs, this might reinforce or undermine schemes for tradable emission rights. How such changes might play themselves out is hard to predict, but emphasizes the importance of not assuming that choices between state regulation, common property management and market approaches will always face the same structure of costs and technologies.

Paper problems. The paperless office has so far proved elusive, with paper consumption increasing, though recycling has also risen. Improvements in the ability to create and restore useful molecules could further reduce the need to harvest wood or other natural fibers.³³ Other technological innovations, such as display screens which look and act like paper, would have similar effects. Reduction in demand for wood products would reduce one incentive for state control or private ownership of forests. Where control over forests is contested, this might allow more space for retaining communal forms of ownership, able to regulate diverse users without splitting up the resource into individualized units. However, demand for “natural” materials may well persist or increase, even if commodity prices continue to decline. Resource abundance is unlikely to eliminate struggles over control of forests and other natural resources, but could reshape the economic value of the resources at stake. Struggles over forests, seashores, lakes, mountain valleys and other areas might be increasingly driven not by resource extraction, but by other forces, particularly the demand for positional goods such as resorts and second homes.³⁴

Diamonds and water. Economists are fond of using the comparison between diamonds and water to illustrate how economic value depends on scarcity. Water is essential to life, but relatively abundant, while diamonds are not essential, but scarce and prized. The ability to recycle materials at the elemental level could well transform scarcity into abundance.³⁵ Similarly, the choice between private property, common property and state institutions for managing resources is influenced by the value of resources and the transactions costs of different institutions for managing them. Over a range of resources, the potentials of nanotechnology could enable recovery and reuse of materials which are currently disposed into the environment, reducing demands for extracting resources from natural sources. Elementary recycling may drastically reduce demand on natural resources, and so reduce their economic value. It may reduce the incentives for individuals and states to seek control over such resources. In some cases, common property institutions might offer lower transactions costs, equitable access, and more effective means for a community of users to jointly manage a shared resource.³⁶ The declining value of private benefits, compared to the stakes a broader community of users have in the resource (externalities), thus

might induce a relative shift from away from private proprietorship.³⁷ In many cases, this could come through increased assertion of public state rights over private owners, mediated by government action. However, in some cases this might, also lead to efforts by specific groups of users to create new commons, following contemporary examples such as land trusts and wetlands protection.

Inclusive entitlements. Cheap does not mean free. Abundance does not assure access. One of the cruelest problems of the contemporary world is the persistence of famine, in an era of abundant food production, set amidst broader juxtapositions of poverty and prosperity. Amartya Sen (1981) analyzed how famine comes not from lack of food, but from lacking the capability to obtain food. Food is present in times of famine, but too many people lack the entitlements, the socially established command over resources, that would enable them to obtain food. Similarly, the technological potentials created by nanotechnology will not automatically be available to all. The previous section argued that open source approaches could contribute to the accessibility of nanotechnology. The institutional arrangements through which people become capable of obtaining goods and services would still play a powerful role. Common property institutions offer further lessons about how access can be shared, while still managing resources sustainably. Such principles might be used to organize access to the fruits of material prosperity, and those resources which are still scarce. Between the exclusiveness of private ownership, and the bureaucratic limitations and flawed incentives of state provision, common property institutions may offer one way to to expand access to abundance. As with earlier commons, membership in institutions organized on such principles might offer inclusive entitlements, bringing both capabilities and responsibilities.

Innovation and abundance. Even without nanotechnology, there are strong grounds to hope for a future of increasing relative abundance for natural resources, rather than the conventional presumptions of increasing scarcity. Julian Simon's book, *The Ultimate Resource* offers both theoretical explanations for innovations that promote resource efficiency and substitution, and abundant empirical documentation of declining commodity prices, increasing abundance relative to the cost of labor and capital, and of the ability to sustain such trends. From another perspective, in *Natural Capital*, Paul Hawken, Amory Lovins and Hunter Lovins outline creative, "green" innovations available for multiplying efficiency and drastically reducing resource use. From either perspective, the potential exists for sustaining the world's growing population at levels of material comfort that exceed those of currently affluent nations, while protecting and restoring natural habitats.³⁸ The prospects for nanotechnology further reinforce the arguments for continued technological innovation which, if wisely applied, can generate resource abundance, and facilitate environmental restoration. It then becomes even more important to consider the role common property institutions might play in the management of resources such as water, forests and seas, especially where the economic gains which might be extracted by individual proprietors are low relative to the externalities affecting other stakeholders who have strong concerns about management of commons or other shared spaces.

CONSTITUTING QUASI-COMMONS

Nanotechnology may bring increasing capacity to cheaply construct and reconstruct the built environment of physical spaces, as well as expanding the diversity and accessibility of cyberspaces. Much thinking about management of traditional commons has been rooted in conceptions of egalitarian communities, small face-to-face groups cooperating democratically to manage a shared local resource. However, in thinking about new commons and other shared spaces, it may be important to reconsider the relevance of familiar assumptions about commons, communities, how roles in governance are constituted, the relative importance of voice versus exit, and the interaction of pluralistic communities. A few examples may help introduce the complexities of quasi-commons:

- The resort town of Seaside, Florida is one of the landmarks of the “New Urbanism,” a school of architects designing attractive mixtures of spaces for living, working, shopping and playing. The park at the center of Seaside is marked by a semicircle of shops, framing a green commons, where children play and people can gather to listen to concerts, watch movies, and enjoy other community events.
- In suburban shopping malls, walkers often gather in the morning to exercise in a safe, climate controlled space. Political campaigners and others have sought to ensure that they can speak, distribute leaflets and exercise other rights of speech on the nominally private grounds of malls. Teenagers often make malls a place of their own, (if not inhabiting the electronic spaces of chatrooms or networked videogames).
- In early 2000, there was an uproar that a prominent agency placing advertising on websites might be gathering names, e-mail addresses and other personal information about website visitors without their knowledge or permission. Whatever the fine print of legal “agreements” supposedly consented to by entering a website, many felt concerned to assert and protect their “rights” to privacy.

Quasi-commons. Malls are usually private property.³⁹ New urbanist planners may embed their rules in the legal foundation of government-issued building codes, or the covenants of a homeowners’ association, while nominally “public” spaces are actually under private ownership.⁴⁰ Websites exist in the evolving legal context of cyberspace. Such spaces can all be viewed as quasi-commons if they are formally under private ownership but share characteristics of commons, especially if this concerns not just how they are used, but how they are governed.⁴¹ Governance includes not just making and enforcing rules, but the constitutional level of rules for making rules: determining who has voice and authority to enact or adjust rules, how leaders and managers should be chosen, and how disputes should be resolved. In quasi-commons, users act not as co-owners of common property, but as stakeholders. However the characteristics of such spaces, and the ways in which users assert claims over their governance lead them to take on elements of commons, becoming quasi-commons.⁴²

Stakeholder monitoring. One of the advantages of common property resource management has been that a community of users is much more able to monitor use, and detect abuse, than a private owner dependent on their own abilities or those of agents. Cheap, widespread videocameras change the cost of surveillance.⁴³ This undercuts one of the advantages of common property management, to the extent that potential violators are deterred by the threat of detection. Other forms of automation and computerization also lower the relative costs of private management compared to collective action. Nanotechnology would reinforce these reductions in the costs of private monitoring. However to extent that norms are created and enforced not through explicit rulemaking and formal enforcement, but rather mainly through interaction with other people, then other users still play a major role, even if the space is formally private or public property. Thus other users not only have a stake in being able to use and enjoy such spaces, but they play an important role in creating and maintaining rules, primarily informal, about how such spaces are used. Furthermore, and crucially for their influence in governance, without their presence the common space loses its value.

Coevolving communities of choice. Users choose whether or not to use quasi-commons. Rather than a community of fate, tied together by mutual interdependence, often within the confines of a small locality, and highly dependent on a single resource, these quasi-commons reflect the multiple, voluntary affiliations of an urbanized culture (though they may be physically located in the more dynamic and conducive conditions of “edge cities”).⁴⁴ Exit by users is an important sanction, though its impact might mainly work through the concerns of merchants who want to maintain an attractive place to market their wares. Communities sharing commons and quasi-commons interact with each other, creating their mutual environment.⁴⁵ Individuals and families usually maintain multiple affiliations. Principles are applied across different realms of experience. Standards emerge from debate and dialogue, and evolve over time. Such spaces, and their governance, are dynamic.

Constituting governance in quasi-commons. Bringing together these ideas, the influence of users as stakeholders in quasi-commons, affiliation by choice and coevolution among communities, implies that management of commons or quasi-commons is likely to be dominated not by direct democracy within small communities where everyone knows everyone else and works out problems through consensus. Instead, management is likely to mix modes of common property (such as homeowners associations), state regulation, and private enterprise, with stakeholder participation in governance of quasi-commons. Users’ choices regarding entry and exit may have a bigger influence than voice on how quasi-commons are managed. The role of those sharing common spaces would come not as co-owners, but as stakeholders.

CRAFTING COMMONS FOR MILLENNIA

Healthy, wealthy and wise? Nanotechnology promises material abundance. In the longer run it offers tools for curing illness, restoring health, and greatly prolonging life, the prospect of living for hundreds or even thousands of years. Further enhancement of computers and communications should make data, information and a wealth of knowledge widely available. Long life may bring a

much longer time horizon for considering self-interest.⁴⁶ On the other hand, accelerating change may further reduce time horizons for investments, emphasizing the importance of ephemeral commons, quickly created and perhaps quickly disappearing. In information commons, a reputation for honesty, creativity and other intangible assets may be much more important than material or financial wealth. If opportunities are less and less constricted by material constraints, the most important challenges may concern choosing what to do from a widening array of choices, and creating new choices, including new commons. Fundamentally, nanotechnology may offer the time and the capabilities to explore the potentials for being human, or more than human.⁴⁷ It is hard to know what directions these may take, but they may well return to the central concerns of religion and philosophy, and the mundane arts of living a satisfying life among family and friends.

Collective enterprises. However it is almost inevitable that many of these activities will be collective, bringing together groups of people larger than families and smaller than nations to undertake joint enterprises. While governments and corporations are unlikely to wither away, they are likely to be accompanied by a greater variety of other institutions, already flourishing in the “Third Sector” of associations, clubs, trusts, foundations and other forms of organization for pursuing interests other than money and power. Knowledge about how to manage common property will continue to be useful, although as noted above, it may take forms distinct from more traditional institutions for managing common pool resources.

Visions. Nanotechnology is protean enough that it could serve many visions:

- The development of nanotechnology may be strongly influenced by the underlying ideas of those who develop the technology, whether soft paths to green sustainability, hard-edged aspirations for high tech expansion, pursuit of personal immortality, or various amalgams and alternatives. The evolution of computer technology was strongly influenced by those who pioneered personal computers, inspired by visions of individual empowerment, affordability and freedom from dependence on corporate resources. To the extent those involved in the development of nanotechnology share a similar individualistic or libertarian ethos, this may shape the way the technology is developed.
- Edward Regis’ exploration of nanotechnology explains the conceptual foundations, describes protagonists and outlines amazing potentials, but ends with a suggestion that much of the future might be captured by a vision of (an American) Sunday afternoon in the suburbs.⁴⁸
- Some may strive to employ nanotechnology and other technologies to deal with what they see as major threats to the human species, whether preventing future ice ages, fending off asteroid impacts, or expanding humanity beyond a single vulnerable planetary ecosystem.

- The Martian settlers in Kim Stanley Robinson’s science-fiction trilogy add nanotechnology to their toolkit, but focus their livelihoods on smallholder agriculture as part of ecopoiesis, with plenty of leisure for pastimes such as hiking, sailing, and flying.⁴⁹
- Richard Norgaard’s book, *Development Betrayed* stands out from most critiques of development in its attempt to reexamine the conceptual roots of the modern project of universalist development, and to go beyond criticism to make some initial suggestions about an alternative prospect for a “patchwork discourse of coevolving communities.” Just as the educational and emancipatory opportunities of computers and the internet have been incorporated in green visions, soft versions of nanotech may well find a welcome among those concerned with sustainable communities and ecological regeneration.
- When asked what he thought of western civilization, Gandhi is said to have replied that “western civilization would be a good idea.” Around the world, diverse cultures have aspirations that go far beyond their current achievements, and much that could be done to work towards realizing those aspirations. While current conceptions of nanotechnology are heavily framed by Western and particularly American ideas of progress, it is not necessarily restricted to the implementation to any specific cultural agenda, nor limited to the intellectual projects of the Enlightenment and Modernity.
- The continued development of computer technology may make it possible to transfer human minds into a computers.⁵⁰ If nanotechnology helps make such “uploading” possible, then the governance of cyberspaces would become even more crucial. Living in virtual realities at computer speeds would also make it possible to experience subjective millennia in relatively short periods of objective time.
- Quite likely, future enterprises may take forms hard to envision now, but still face challenges of how to create and manage common property.

Institutional architecture. Long life and prosperity may make it possible to explore an expanding diversity of ways to live, whether pastoral or high tech, earthbound or traveling to the stars. These various enterprises all face the challenges of organizing collective action in shared spaces, commons, whether in the material world or cyberspace. Long life could make it possible to undertake truly long-term projects. Managing coexistence among diverse communities may pose major challenges. Structuring incentives, assuring cooperation, become even more important in the design of institutions for the long term, including the ability to reconstitute institutions in the face of unforeseen challenges. Longer-term perspectives could stimulate greater interest in the art and science of institutional architectures for common property, the challenges of constituting commons.

CONCLUSIONS

Exploring a few of the many possible consequences of nanotechnology indicates how it might bring profound implications for the management of existing commons and the creation of new commons. Prediction is impossible, but scenarios show how it may be important to reconsider some of the assumptions that underlie much study and management of common property. Nanotechnology itself could be developed as an abundant common property information resource, a new commons, applying the principles behind open source computer software. Recycling at the elemental level, assembling and disassembling materials out of their constituent atoms, may promote resource abundance, converting one way flows from extraction, consumption and disposal into closed cycles, reusing and managing resource stocks. If this furthers declining prices for commodities, then it may reduce incentives for private appropriation, and sometimes favor common property management. Stakeholders may become even more assertive in reconstituting governance of shared private and public spaces as quasi-commons, mixing modes of state, private and common property management. Lifetimes measured in centuries or millennia, are likely to encourage new projects, collective enterprises pursuing goals distinct from private profit or state survival, some of which may well be governed as common property. Nanotechnology may make common property more common, not less, with commons, in physical space and cyberspace, increasingly important in enabling people to pursue their dreams. The study of common property should continue to offer useful intellectual tools that people may use to craft their futures.

“The best way to predict the future is to invent it.”⁵¹

NOTES

- ¹ In addition to the published literature on nanotechnology, the paper draws on attendance at the Seventh Foresight Conference on Nanotechnology in October 1999, academic training in social science, experience as a consulting sociologist concerned with participatory development, and many years of reading science fiction. This paper has been prepared as part of a self-financed semi-sabbatical, and I am very interested in further exploring these issues. Future versions of this paper may be posted at www.BryanBruns.com. Comments, criticisms and suggestions are invited to: BryanBruns@BryanBruns.com
- ² This framework of three future waves of change draws on Davis and Davidson, 1991.
- ³ Feynman 1959.
- ⁴ The basic ideas, potentials and dangers of nanotechnology were laid out by Eric Drexler in his 1986 book, *Engines of Creation*. For less technical introductions, see Drexler and Peterson, 1991 and Regis 1995. Crandall (1996) has a good introductory essay, followed by articles on various possible applications.
- ⁵ Most attention on bottom-up assembly has focused on manipulation using the tips of atomic force microscopes. Laser technology might offer another option (Frank Underdown, personal communication, see also Underdown and Renn, 1999), and is a reminder that the exact routes actually taken to nanotechnology may turn out to be quite different from those currently envisioned.
- ⁶ *Nanomedicine*, by Robert Freitas (1999), analyzes in detail many of the technical problems and opportunities involved in applying nanotechnology for health.
- ⁷ Ellenbogen 1997.
- ⁸ Vinge 1993. Vernor Vinge is a professor of computer science, as well as a leading science fiction writer. For a discussion of his concept of a technological singularity, see Hanson 1998. For a list of science fiction novels dealing with nanotechnology, see www.erinet.com/prass/nanowars/ninsf/n_in_sf.html
- ⁹ Schwartz 1991.
- ¹⁰ Boyle 1996.
- ¹¹ Brooks 1995
- ¹² This essay was first published online in 1997. All three of the essays mentioned here were included in a 1999 book (Raymond 1999b). For links to the three papers and commentaries on them, see www.tuxedo.org/~esr/writings/homesteading. For further information on open source see www.opensource.org
- ¹³ Raymond 1998.
- ¹⁴ One view is to see open source licenses as defensive mechanisms to protect a distinctive gift culture of “copyleft” from the surrounding exchange culture (Russ Allbery <tra@stanford.edu> 05-Jul-1998 www.eyrie.org/~eagle/writing/homesteading.html).
- ¹⁵ Raymond, 1999a.
- ¹⁶ Ellenborg 1997.
- ¹⁷ Drexler (1986) stresses the benefits of public discussion and criticism for promoting safety and other aspects of nanotechnology research and development. In a posting on the usenet sci.nanotech newsgroup on Jan 5 1995, Sean Jackson (sdj1@cityscape.co.uk) suggested that nanotech designers could share their ideas via the same kind of public source licenses used for software, mentioning Linux, and Emacs and posting a brief version of the Free Software Foundation’s license. The Foresight Foundation is interested in applying open source ideas to its own organization and agenda-setting (Christine Peterson, personal communication) and to promote reliability of nanotech designs (Eric Raymond, personal communication).
- ¹⁸ In light of the analysis of the economics of open source by Eric Raymond in “The Magic Cauldron” one could argue that the first nanotech startup, Zyvex, has, by making its goal the production of an assembler, made the choice least likely to facilitate collaborative efforts. According to Raymond’s logic, industries using nanotechnology as means to produce other products (e.g. nanoelectronics) and services (e.g. designs for nanosystems, nanomedicine) would have strong incentives to support open source approaches which provided them with better tools than they could create by themselves.
- ¹⁹ Raymond 1999a. (Magic Cauldron, Section 10. “When To Be Open, When To Be Closed.”)
- ²⁰ The U.S. government recently proposed a \$500 million initiative to promote nanotechnology research. S. Milius. R&D Budget Should Ease Biomed Envy. *Science News* v. 157 February 12, 2000. V. 157. No. 7: 102.
- ²¹ Drexler 1986

22 For a recent, alarmist view of the hazards of self-replicating genetic, nanotech, and robotic technologies, see
Joy 2000. For an introduction to hazards of nanotechnology and ways to deal with them, see Drexler and
Peterson 1991, Chapter 12: Safety, Accidents and Abuse.

23 Recently, the Foresight Foundation has organized the preparation of guidelines on developing molecular
nanotechnology, currently under discussion. These will soon be posted, probably in May 2000, at
www.Foresight.org

24 An open source approach to developing nanotechnology might also offer much more rewarding opportuni-
ties (in reputation and money) to those tempted to indulge in abusive hacking.

25 Brin 1998. Kantrowitz, 1992.

26 Celera, the private company decoding the human genome is making the primary data from its genomic re-
search freely available to researchers, mainly aiming to profit from providing related services and equip-
ment. Celera is also filing for patents on some gene sequences, which it intends to license (Philipkoski
1999). On April 6, 2000, Celera announced it had completed sequencing the human genome, and Celera's
President, Craig Venter, reaffirmed that "we will publish the sequence of a human being and make it avail-
able on the Internet with no restrictions for researchers to use information." (Philipkoski 2000, see also
Reuters 2000). For further information also see www.celera.com/corporate/about/sbm.html

27 It should be noted that Hardin's original (1968) conclusion was not that tragedies were inevitable, but that
they needed to be avoided by "mutual coercion, mutually agreed upon." One of the key arguments of stu-
dents of common property has been that such collective action can be organized not just by the governing
apparatus of states, but also by many other forms of self-governing common property institutions (see for
example, Ostrom 1990, Bromley 1992).

28 See Drexler and Peterson (1991), especially Chapter 9 on "Environmental Restoration."

29 Warren 1999 and personal communication, Marc Adelman personal communication. See www.flowtc.com
and www.sabrex-tx.com The discussion here is intended to do no more than offer illustrative scenarios and
raise questions. Well before the time nanotechnology becomes widely available, declining energy costs for
pumping are likely to dramatically reshape technological options for water resources management, not to
mention the institutional reforms which are ongoing or under consideration in many countries.

30 Simon 1999.

31 Hawken, Lovins and Lovins 1999.

32 On a more speculative note, stronger materials produced with nanotechnology, might make possible en-
closing cities with domes, creating local atmospheric commons at an even larger scale than that of shop-
ping malls, covered stadiums and other contemporary structures.

33 See Hawken, Lovins and Lovins 1999, Chapter 9 for a discussion of potentials in production and use of fi-
bers.

34 Hirsch 1976. However Hirsch's "limits to growth" approach may neglect the extent to which substitution
and innovation could reduce constraints and diversify demand for positional goods. This includes more
immediate substitutes such as beachside condominiums and timeshares which offer many people beach
views and access, cruise ships, or factors such as shifts towards shorter vacations and increased preference for
electronic entertainment (videos or virtual reality) rather than travel.

35 Nanotechnologists suggest that diamond could be assembled from abundant carbon atoms (including excess
CO₂ in the atmosphere) to make a very strong, durable and cheap building material.

36 In some cases, material wealth may eventually enable a relaxed management of commonly shared resources,
tolerating multiple uses and minor abuses in casual prosperity, in ways not too dissimilar from how com-
mon property approaches have long been used to manage resources whose value was too small or too
widely dispersed in time or space to reward private appropriation or intensive state regulation.

37 Coase's (1990) ideas are often interpreted to mean that rights should be "privatized" so that market and le-
gal mechanisms could better resolve adverse impacts, internalizing externalities. However "privatization" of
rights can also take the form of assigning rights to common property institutions. Where impacts are spread
broadly among a community of users, such institutions offer a feasible and equitable alternative.

One could argue that the increasing assertion of environmental standards over private property owners in
countries such as the United States already reflects such a shift, where declining commodity costs mean that
resource owners have less incentive defending their private rights against public claims. Similar reasoning
might also be applied to the willingness to acknowledge indigenous land claims, as natural resources play
a declining role in wealth creation, and as the political role of primary producers (farming and mining) and
manufacturers declines in importance.

38 Those who find this too heretical a deviation from conventional thinking are strongly encouraged to read ei-
ther or both the cited books. Such ideas should not be taken as arguments for complacency about environ-
mental degradation, but rather reinforce the urgency of bringing about the institutional reforms needed to
39 realize the technical opportunities which exist for improving resource management and the environment.
Ruth Meinzen's objections to my characterizing malls as a form of common property stimulated my think-
40 ing about the concept of quasi-commons.
For a good introduction to ideas of the New Urbanism see Kunstler (1996). French (2000) points out some
of the common property issues involved in shared housing.
41 Similarly, spaces may formally be state property, but de facto be governed like common property, con-
trolled or strongly influenced by a much narrower group of users. Such spaces could also be characterized as
quasi-commons.
42 A further complication is that whether ownership is private, collective, or even public, management func-
tions may well be contracted out, so that users perceive and interact with similar agents (salaried profes-
sional managers, security guards, lawyers, public relations staff, caretakers, etc.) regardless of the underlying
ownership.
43 Brin 1998.
44 Garreau 1992.
45 The general concept of coevolving communities comes from Norgaard (1994), though his visions for the fu-
ture seem more oriented towards small, localized, bioregional communities, rather than cosmopolitan fluid-
ity.
46 Expectations of nanotechnology have stimulated interest in cryonics, freezing bodies immediately after
death, in hopes that life and health could be restored by future technologies. A consequent challenge for de-
signing long-term institutions is to create organizations which people would entrust with protecting their
frozen bodies and their assets (especially since potential heirs may have strong incentives to challenge such
arrangements).
47 There is a substantial overlap of those interested in the social implications of nanotechnology and interest
in science fiction-type speculation about futures for humanity. Extropian theories offer one example of such
ideas (www.extropy.com).
48 Regis 1995.
49 Robinson, 1993, 1995, 1997.
50 Kurtzweil, 1999.
51 Alan Kay (see www.smalltalk.org/alankay.html), as often quoted by Ralph Merckle, one of the leading
proponents of nanotechnology (for example, see www.zyvex.com/nanotech/howlong.html).

REFERENCES

- Boyle, James. 1996. *Shamans, Software and Spleens: Law and the Construction of the Information Society*. Cambridge MA: Harvard University Press.
- Brin, David. 1998. *The Transparent Society : Will Technology Force Us to Choose Between Privacy and Freedom?* Reading, Massachusetts: Addison-Wesley.
- Bromley, Daniel W., et al., eds. 1992. *Making the Commons Work: Theory, Practice and Policy*. San Francisco: Institute for Contemporary Studies.
- Brooks, Frederick P., Jr. 1995. *The Mythical Man-Month: Essays on Software Engineering*. Addison-Wesley.
- Coase, R. H. 1990. *The Firm, the Market and the Law*. Chicago: University of Chicago Press.
- Crandall, B.C., ed. 1996. *Nanotechnology: Molecular Speculations on Global Abundance*. Cambridge, Massachusetts: MIT Press.
- Davis, Stan, and Bill Davidson. 1991. *2020 Vision: Transform Your Business Today to Succeed in Tomorrow's Economy*. New York: Simon and Schuster.
- Drexler, K. Eric. 1986. *Engines of Creation*. New York: Anchor Books. Available at www.foresight.org
- Drexler, K. Eric, and Chris Peterson, with Gayle Pergamit. 1991. *Unbounding the Future: The Nanotechnology Revolution*. New York: William Morrow.
- DuCharme, Wesley M. 1995. *Becoming Immortal: Nanotechnology, You and the Demise of Death*. Evergreen, Colorado: Blue Creek.

- Ellenbogen, James C. 1997. "Matter as Software." McLean, Virginia: Mitre Corporation. Presented at the Software Engineering and Economics Conference, April 2-3, 1997. www.mitre.org/technology/nanotech/downloads/Matter_As_S-W.pdf
- Feynman, Richard P. 1960. "There's Plenty of Room at the Bottom: An Invitation to Enter a New Field of Physics." *Engineering and Science*. www.zyvex.com/nanotech/feynman.html
- Freitas, Robert A. Jr. 1999. *Nanomedicine. Vol. I. Basic Capabilities*. Austin, Texas: Landes Bioscience.
- French, Susan F. 2000. "Common Interest Communities: The Dilemma of Shared Resources in Residential Housing." *Common Property Resource Digest* (51):4-5.
- Halperin, James L. 1998. *The First Immortal*. New York: Del Rey.
- Hanson, Robin. 1998. A Critical Discussion of Vinge's Singularity Concept. www.extropy.org/eo/articles/vi.html
- Hardin, Garrett. 1968. The Tragedy of the Commons. *Science* (162):1243-1248.
- Hawken, Paul, Amory B. Lovins, and L. Hunter Lovins. 1999. *Natural Capitalism: The Next Industrial Revolution*. London: Earthscan.
- Hirsch, Fred. 1976. *Social Limits to Growth*. Cambridge, Massachusetts: Harvard University Press.
- Hirschman, Albert O. 1970. *Exit, Voice, and Loyalty*. Cambridge, MA: Harvard University Press.
- Joy, Bill. 2000. Why the Future Doesn't Need Us. *Wired Magazine* 8.04. April 2000 www.wired.com/wired/archive/8.04/joy.html
- Kantrowitz, Arthur. 1992. The Weapon of Openness. In *Nanotechnology Research and Perspectives*, edited by B. C. Crandall and James Lewis. Cambridge, Mass: MIT Press. www.foresight.org/Updates/Background4.html
- Kunstler, James Howard. 1996. *Home from Nowhere: Remaking Our Everyday World for the Twenty-first Century*. New York: Simon and Schuster.
- Kurzweil, Raymond. 1999. *The Age of Spiritual Machines*. New York: Viking.
- Ostrom, Elinor. 1990. *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge: Cambridge University Press.
- Philipkoski, Kristen. 2000. "Celera: Genome Map Complete." *Wired News*. 8:35 a.m. Apr. 6, 2000 PDT www.wired.com/news/technology/0,1282,35479,00.html
- Philipkoski, Kristen. 1999. Final Stretch in the Genome Race. *Wired News*. 3:00 a.m. Oct. 25, 1999 PDT. www.wired.com/news/technology/0,1282,32076,00.html
- Norgaard, Richard B. 1994. *Development Betrayed: The End of Progress and a Coevolutionary Revisioning of the Future*. London: Routledge.
- Raymond, Eric. 1997. The Cathedral and the Bazaar.
- Raymond, Eric. 1998. Homesteading the Noosphere. www.tuxedo.org/~esr/writings/homesteading
- Raymond, Eric, 1999a. The Magic Cauldron. www.tuxedo.org/~esr/writings/magic-cauldron/
- Raymond, Eric. 1999b. *The Cathedral and the Bazaar: Musings on Linux and Open Source by an Accidental Revolutionary*. Sebastopol, California: O'Reilly, www.tuxedo.org/~esr/writings/cathedral-bazaar/
- Reuters. 2000. Celera Intentions Misunderstood. *Wired News*. 2:20 p.m. Apr. 6, 2000 PDT. www.wired.com/news/technology/0,1282,35500,00.html
- Regis, Ed. 1995. *Nano: The Emerging Science of Nanotechnology: Remaking the World-Molecule by Molecule*: Little, Brown.
- Robinson, Kim Stanley, 1993. *Red Mars*. Bantam.
- Robinson, Kim Stanley, 1995. *Green Mars*. Fanfare.
- Robinson, Kim Stanley, 1997. *Blue Mars*. Bantam.
- Schwartz, Peter. 1991. *The Art of the Long View*. New York: Doubleday.
- Sen, Amartya. 1981. *Poverty and Famines: An Essay on Entitlement and Deprivation*. Oxford: Clarendon Press.
- Simon, Julian L. 1996. *The Ultimate Resource*. Princeton, New Jersey: Princeton University Press.
- Underdown, Frank Jr., and Michael Renn. 1999. Laser Guidance of Mesoscopic Particles. Paper presented at the Seventh Foresight Conference on Molecular Nanotechnology. www.foresight.org/Conferences/MNT7/Abstracts/Underdown/index.html
- Vinge, Vernor. 1993. The Coming Technological Singularity: How to Survive in the Post-Human Era. www-rohan.sdsu.edu/faculty/vinge/misc/singularity.html
- Warren, William L., Bruce E. Gnadea, Lawrence H. Dubois, and John Pazik. 1999. Molecules Can Compute. Arlington, Virginia: Defense Advanced Research Agency. www.foresight.org/Conferences/MNT7/Abstracts/Warren/index.html