Economic Impact of the Personal Nanofactory

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Is the advent of, and mass availability of, desktop personal nanofactories (PNs)[1] likely to cause deflation (a persistent decline in the general prices of goods and services), inflation (a persistent general price increase), or neither?

A definitive analysis would have to address: (1) the technical assumptions that are made, including as yet imprecisely defined future technological advances and the pace and order of their introduction; (2) the feedback-mediated dynamic responses of the macroeconomy in situations where we don't have a lot of historical data to guide us; (3) the counter-leaning responses of existing power centers (corporate entities, wealthy owners/investors, influential political actors, antitechnology-driven activists, etc.) to the potential dilution of their power, influence, or interests, including their likely efforts to actively oppose or at least delay this potential dilution; (4) legal restrictions that may be placed on the widespread use of certain technological options, for reasons ranging from legitimate public safety and environmental concerns to crass political or commercial opportunism; (5) the possibility (having an as yet ill-defined probability) that nanotechnology might actually "break the system" and render conventional capitalism obsolete (much as solid state electronics obsoleted vacuum tubes), in which case it is not clear what new economic system might replace capitalism; and (6) the changes in human economic behavior that may result when human nature itself may have changed.

A definitive answer is beyond the scope of this essay. Here, we take only a first look at the question.

Price/performance assumptions

Our preliminary analysis begins with an assumption that at the end of a 20-year period of introduction, almost every household in a given developed country has purchased a PN. The PN will be capable of building any manner of consumer goods using simple molecular feedstock such as acetylene or propane gas that will be piped into the home via a utility connection, similar to present-day hookups that deliver natural gas, water, and electricity. There are other

[1] K. Eric Drexler, *Nanosystems: Molecular Machinery, Manufacturing, and Computation*, John Wiley & Sons, NY, 1992, Section 14.4.

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delivery scenarios such as bottled gas feedstock, and more self-sufficient feedstock provisioning scenarios such as nanoblock premanufacturing, solar-powered recycling, biomass/biowaste extraction, or even atmospheric extraction, but these will be set aside here both in the interest of simplicity and because they may be heavily regulated[2] or in some cases even declared illegal.[3]

If we further assume that (1) the price to acquire the PN is approximately US$4400 (see below), (2) the PN has a mass of 10 kg and produces consumer products at the rate of 1 kg/h,[1] and (3) the PN is operated 50% of the time throughout a useful lifetime of 10 years, then the PN during its useful life produces 44,000 kg of consumer products which then have an amortized capital cost of $0.10/kg, a cost that is built into every product manufactured by the PN.

The $4400 price point for the PN was taken as a plausible figure that might reasonably be chosen by a U.S. manufacturer. This price point cannot be too cheap or there is no profit, nor too expensive or there are no buyers. For comparison, $4400 will purchase a good quality large-screen TV, a high-end refrigerator/freezer, or a topnotch laptop computer in the U.S. today. The PN will be a versatile appliance, able to manufacture whatever is deemed legal in the 21st century such as: (1) consumer goods including nondurables such as food and durables heavily laden with nanosensors, nanomotors, nanopumps and nanocomputers, (2) all the patterned sheets or chunks of diamond that anyone might want, and (3) some kinds of medical nanorobots for personal use, though these may be heavily regulated. We assume that the PN will not be allowed to manufacture contraband, nor various types of weapons systems including ecophages,[4] or more PNs (which would nullify the R&D funding and manufacturing business model). If the public is not allowed to manufacture PNs using PNs,[5] then the production cost of a PN using a

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[2] A simple calculation (http://www.nanomedicine.com/NMI/6.5.7.htm#p4) of the hypsithermal limit for Earth, when combined with a few other reasonable assumptions, suggests that a per capita allocation of about 10 kg of active nanomachinery will generate about the maximum amount of extra thermal pollution that our planet can handle without sustaining ecological damage. This limit or something like it may someday be enshrined in international law.

[3] For example, consider the case of a private individual who sets up equipment to extract CO_2 from the air and combine it with water to synthesize his own acetylene gas. Authorities may not allow individuals to set up unregistered and unregulated systems (i.e., acetylene generator + PN) that are capable, in effect, of metabolizing air into diamond. Such a system would amount to the construction of an aerovore (http://www.rfreitas.com/Nano/Ecophagy.htm#Sec8-2_GrayDust)—a free-range replicator that can copy itself by feeding on air—because it would be fairly trivial to miniaturize the proposed acetylene synthesis system down to a micron scale system, and because basic scaling designs for submicron-size self-replicating molecular assemblers that use acetylene as feedstock have already been published (http://www.MolecularAssembler.com/KSRM/4.11.3.htm). Since the proposed system, once miniaturized, could be used to effectuate a "gray dust" scenario thus precipitating a global ecological catastrophe, it is likely that systems of this type (and their obvious precursors) may be deemed illegal except when deployed in highly regulated and extensively monitored (probably government) facilities, probably with an international supervisory body such as the IAEA continuously watching the entire proceedings via ubiquitous cameras. Because of the ecophagic risks, the building of such a device by an unauthorized and unsupervised person might even be viewed as an act of terrorism.

[4] Robert A. Freitas Jr., "Some Limits to Global Ecophagy by Biovorous Nanoreplicators, with Public Policy Recommendations," Zyvex preprint, April 2000; http://www.rfreitas.com/Nano/Ecophagy.htm.

[5] It seems unreasonable to presume that the existing capitalist power structure will knowingly fund the development, and then later willingly allow the widespread sale and unrestricted use, of a product which has no economic value whatsoever to capitalist manufacturers – and even worse, will likely

PN becomes almost irrelevant to the retail price of a PN. The manufacturer may charge $4400 for a PN even if it only costs them $10 to make one (see below), using the difference to pay for showrooms and sales staff, marketing and advertising, legal costs for defending the brand and a monopolistic pricing regime, product liability insurance costs (which could be substantial), warranty and servicing costs, online and print publications including consumer how-to books and magazines, websites and online help desks, executive overhead and corporate perks, and perhaps modest dividends from profits for the shareholders.

Assuming the average person in the developed world consumes 2000 kcal/day of food, and taking the average energy density of food (arbitrarily weighting protein:carbohydrate:fat in a 4:3:3 ratio) as 24 million J/kg,[6] then the person is consuming about 130 kg/yr of food. Further assuming this average person consumes four grocery bagfuls per week of nondurables with each bag containing 2 kg of useful product, then the average person requires 400 kg/yr of consumer nondurables (of which 130 kg/yr is food). The PN is assumed to produce 4400 kg/yr of consumer products. Given that the average person in an industrialized economy needs 400 kg/yr of nondurables, or 1600 kg/yr for a household of four people, this leaves 2800 kg/yr either for increased nondurables consumption or for the manufacture of desired consumer durables. Durables might include clothing, appliances, furniture, and cars. Large automobiles that weigh 2000 kg today might weigh as little as 200 kg if made of much stronger diamondoid materials,[7]

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threaten the economic value of all other product lines of *all* manufacturers. It may be hard to make money selling a product to consumers that can build more copies of itself, thus obviating future sales. This is amply demonstrated by the commoditization of agriculture, a "(bio)manufacturing" sector of the economy that relies heavily on self-replicating (bio)machinery. (Observe that big agribusiness survives in part by selling farmers new seeds each growing season.) It is unlikely that PNs will be sold that can make other PNs, because these could be a serious threat to the existing capitalist system and thus will be vigorously resisted by all possible means, once the power structure fully appreciates the threat and believes the threat to be both possible and imminent. Hacker-proofing is likely to be strictly enforced; the technologies that will make this possible are already being developed in the private sector IP area today. And governments of all types will be motivated not to let their citizens have too much freedom to manufacture whatever is locally defined as "contraband" or "taboo", so a fair degree of international cooperation in enforcing these restrictions can be expected. Consequently, restricted-use (and monitored-use, perhaps even publicly-published use) technologies in the personal manufacturing area cannot be ruled out and in fact seem highly probable in view of the security and economic risks.

It is possible to imagine an alternative scenario in which PNs are given away for free, but cannot build anything unless you pay a subscription fee for software and product-build instructions for all the products you want, similar to the situation today in some companies where cell phones are given away free as a marketing ploy to sell subscription services. The success of this business model applied to PNs would strongly depend on the manufacturer having absolutely secure control over the source, and the use, of the purchased software and product-build information. We will not further evaluate here the economic consequences of this or other alternative business models for PNs.

6 "Table 6.1 Energy Storage Density for Various Chemical Fuels," in Robert A. Freitas Jr., *Nanomedicine, Volume I: Basic Capabilities*, Landes Bioscience, Georgetown, TX, 1999, p. 141; http://www.nanomedicine.com/NMI/Tables/6.1.htm.

7 The mass of diamondoid products whose utility is primarily a function of their strength may decrease by between two and three orders of magnitude. (If we are manufacturing food, there will likely be almost zero mass reduction in the products.) The only published detailed design analysis for the comparative mass reduction of any diamondoid products is for the respirocytes (http://www.foresight.org/Nanomedicine/Respirocytes/index.html), which are calculated to achieve a 1620-fold

so the production budget would allow up to 14 diamondoid cars per year to be built. Thus, a single PN per household with the above parameters is probably sufficient to satisfy all reasonable household needs for residents of industrialized countries.

Cost of PN-manufactured goods

The base operating cost of a working PN, and hence the price of anything that can be manufactured by the nanofactory, should approximate the cost of the material and energy inputs. Of course, "cost" is not price—in a capitalist economy, prices of goods are set by competitive markets. In a stable equilibrium economy, the price of manufactured goods that are

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mass reduction compared to a volume of red blood cells of equal functional capacity. But respirocytes are a microscale durable product. As of late 2005, no similar detailed analysis had yet been undertaken for macroscale consumer durables such as shoes, bicycles, automobiles, and the like. So, while it is reasonable to assume a 10-fold mass reduction in consumer durables, our ability to achieve 1000-fold mass reductions in macroscale durables (e.g., a 10-gram bicycle) remains somewhat speculative.

Another scaling issue is whether future consumer durables, fabricated using molecular manufacturing (MM) techniques, will be given the same functionality as today's products, or somewhat greater functionality, or will have dramatically augmented functionality (superfunctionality) due to the incorporation of a significant mass fraction of active nanomachinery. Over time, products will probably emerge across the entire spectrum, ranging from current functionality to superfunctionality.

In the case of MM-fabricated superfunctional nanomachinery-rich consumer products, a possible further complication of reducing product mass is the reduction in thermal capacity that this causes. Thermal capacity can be recovered by incorporating high heat capacity bulk materials such as water into the product or adding extra conductive structures in contact with external heat sinks, but either solution increases total product mass. Additionally, a superfunctional macroscale product containing a large quantity of active simultaneously-actuated nanoscale machinery can generate significant waste heat (http://www.nanomedicine.com/NMI/6.5.3.htm#p11)—mainly from computational tasks by nanocomputers but also from some kinds of mechanical tasks, both of which may employ power densities many orders of magnitude larger than those commonly found in biological systems. The fraction of active nanocomponent mass that is present in a superfunctional nanomachinery-rich macroscale product is a design decision. This fraction may range from 0% (e.g., the product is purely passive nanomaterials with no active nanocomponentry) to 100% (e.g. the product is purely active nanocomponentry as is approached by 'utility fog'), depending on the application and the objectives of the designer and his customers. For example, a respirocyte will have 8.37×10^{-17} kg of active nanocomponents (e.g., computers, sensors, pumps, and engines) for every 3.56×10^{-16} kg of total dry mass of final product (which includes inactive mass such as hull and other support structure), so 24% of the respirocyte dry mass is active nanocomponent mass. The problem of heat removal for a superfunctional product of size-independent power density grows more restrictive as product size increases (the familiar Square-Cube law), making this a more important issue for superfunctional macroscale products than for superfunctional microscale products such as medical nanorobots (e.g. respirocytes). Design solutions for superfunctional macroscale products incorporating large mass fractions of active nanomachinery may include: (1) reducing overall power density of the product, (2) reducing the fraction of active nanomachinery present in the product, (3) operating active nanomachinery present in the product at less than a 100% duty cycle, or (4) adding cooling systems such as onboard refrigerators coupled to radiators, disposable cooling packs, or hookups to external sources of cooling fluids or other heat removal systems.

In the case of MM-fabricated consumer products having similar functionality to present-day durable goods, cooling will be no more difficult for these products than it is today—and may, in fact, be easier because of the increased efficiency of nanoscale machinery compared with traditional macroscale machinery. Cooling only becomes an extra consideration when the designer adds significant new functionality that doesn't exist in today's consumer products.

in demand cannot long persist below the base cost of the material inputs. But added to those base input costs, and hence indirectly added to the price of a good, will also be various intangible costs, which for the PN might include some or all of the following:

(1) acquisition financing or opportunity costs;

(2) PN licensing costs;

(3) the cost of product-description information not in the public domain (e.g., IP fees, per-use fees, per-bit fees);

(4) communications toll charges for PN data links, with flat baseline fee varying by transmission speed, fidelity, security, and availability for product data downloads;

(5) fee for dangerous-product construction blocking (e.g., governmental, parental);

(6) fee for contraband or socially-taboo construction blocking (e.g., governmental, parental, religious, etc.);

(7) regulatory costs (e.g., environmental impact/mitigation, thermal pollution credits, content policing, federal mandates enforcement);

(8) federal/state taxes (e.g., sales/use, value-added, property, excise, luxury, inheritance, estate, gift, etc.), State Nanofactory Commission tax, and surcharges for unrelated social purposes;

(9) local taxes (e.g., feedstock fire services, toxic gas mitigation, metering services, low-income subsidies, universal access subsidies, 9-1-1 emergency phone number fees);

(10) federal protective trade and domestic subsidy-support tariffs;

(11) federal economic stabilization surcharges;

(12) fee for regular government-mandated safety inspections, analogous to annual smog inspections commonly required for automobiles;

(13) international surcharge for disadvantaged nations, administrated through United Nations auspices (perhaps imposed as single fee collected at time of sale, or paid as annual international tax);

(14) registration fee for all PNs, analogous to automobile registration fees;

(15) the cost of government mandated insurance for accidents or injuries to others as a result of products manufactured by the PN, similar to the automobile personal injury insurance required in many states; and

(16) miscellaneous other fees and expenses.

A precise quantification or estimate of all these costs cannot easily be made, but prorated intangible costs of at least \$0.20/kg appear plausible.[8]

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[8] What is the impact of government taxation and regulation on the cost of goods? There are many possible estimates, none of them very precise but all suggesting a consistent range of impact on costs. Starting with the broadest view, in the U.S. National Accounts for 2005QIII the "taxes on production and imports less subsidies" were 6.8% of Gross National Product [see Note 21 infra], implying an equivalent load on a \$1/kg PN product of about \$0.068/kg. Alternatively, in 2005QIII the total of "personal current taxes" plus "contributions for government social insurance" were 20.4% of Personal Income [21], which would imply an equivalent load on a \$1/kg PN product of about \$0.204/kg. The average effective state and local tax burden in the U.S. is 10.0% of income [34], which equates to a prorated \$0.10/kg assuming the value of PN output is treated as income at \$1/kg. Academic and institutional sources [35] estimate the economic cost of all U.S. federal regulations during the 1995–2005 period as \$0.865T-\$1.27T/yr, equivalent to a \$0.07–\$0.10/kg regulatory burden on a \$1/kg product.

This means that even if the cost of material and energy inputs fell to essentially zero—say, through the use of recyclable nanoblocks that could create the potential for cheap disassembly and re-use of nanoblocks, thus recovering the majority of the energy investment in a given amount of diamondoid mass—there would still be an amortized capital cost of $0.10/kg plus a fixed intangible cost of $0.20/kg built into all products manufactured by the PN, giving an irreducible total minimum cost of $0.30/kg. (The fixed intangible $0.20/kg component should prove relatively insensitive to fluctuations in the general price level.)

Bulk petroleum-based hydrocarbon gases like methane (CH_4) or propane (C_3H_8) can cost as little as ~$0.17/kg [9a] or ~$0.31/kg, [9b] respectively, at wholesale, but the retail price for home

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In the author's home state of California (USA), vehicle registration fees are based primarily on purchase price. According to the state's online vehicle registration fee calculator [36], the purchase of a new gas-powered vehicle in El Dorado County having a purchase price of $4400 (identical to the purchase price posited for the PN) would require payment of a total first-year registration fee of $409, which includes a one-time sales/use tax of $319 on the initial purchase and $90 for the first annual registration fee. Over the 10-year useful life of a PN requiring registration, this would amount to a total of $1219 in fees, which implies a registration fee of $0.028/kg when amortized over the lifetime PN product output of 44,000 kg. A listing of the items comprising the annual automobile registration fee (most of which are suggestive or have obvious analogs to a PN purchase) include Current Registration ($31), Vehicle License Fee ($29), California Highway Patrol ($9), Smog High Polluter Repair Fee ($6), Smog Abatement ($6), Air Quality Management District ($4), Abandoned Vehicle Fee ($1), Auto Theft and/or DUI Crime Deterrence Program ($1), County Service Authority for Freeway Emergencies Fee ($1), Fingerprint ID Fee ($1), and Reflectorized License Plate Fee ($1).

The author's review of personal residential landline telephone and electric bills for 2005 reveal essentially fixed government fees, taxes, and other surcharges averaging $6/mo and $45/mo, respectively, regardless of quantity consumed. Applying these amounts to a PN producing 367 kg/mo would imply a minimum fixed burden of $0.02–$0.12/kg, or higher if the full 367 kg product mass budget for the month was not manufactured. Property taxes are usually imposed on a per-parcel or per-house (or per floor-area) basis, regardless of the level of use (e.g., ignoring number of occupants, children, cars, etc.) of the real estate. An additional 1%–3%/yr personal property tax imposed on a PN costing $4400 producing 4400 kg of products annually would equate to a $0.01–$0.03/kg tax. Property taxes based on property market value range from 0.13%–2.3% in the U.S. [34], 0.1%–2.0% in Russia [37], and 1.4%–2.1% in Japan [38]; or as a percentage of national income (GDP), ~1% in Germany, ~3% in France, and ~4% in U.K. [39]. The City of Baltimore, MD, also assesses a 5.77% personal property tax and a 5.77% utility tax [40].

Copyright royalties for owned written intellectual property (IP) are typically 10%, which might suggest an additional $0.10/kg of IP-related costs on products initially priced at $1/kg, except that user fees might here be calculated according to the level of use (e.g., the number of users or "seats" authorized to operate the PN, as is common in commercial software contracts) rather than as a percentage of sales, hence might not be tied to unit price of product like a sales tax would be.

Financing a $4400 capital expenditure on an interest-only basis at a 5% interest rate for a device producing 4400 kg/yr equates to a minimum $0.05/kg financial overhead if the device is always operated at the 50% production rate. The cost of lost opportunity is calculated similarly, with the interest rate taking the role of a discount rate on foregone alternative uses of the capital. Note that the additional amortized capital cost of $0.10/kg still applies because interest-only financing means the borrower still owes the $4400 after 20 years of paying only interest. (These are only crude estimates; an explicit calculation of discounted future value, etc. would be needed to establish more precise estimates.)

Based on the above considerations, an irreducible intangible cost of at least $0.20/kg for government fees, IP rights, and financing costs seems plausible.

9 (a) Sudheer Indala, "Appendix A: Cost Estimation Procedure For Carbon Monoxide," Development and Integration of New Processes Consuming Carbon Dioxide in Multi-plant Chemical Production

delivery—as would be required to supply a PN—was \$2/gallon for liquefied propane gas in December 2005, or \$0.90/kg. Nanofactories may need to be restricted to such feedstocks for reasons of public safety (because development of more flexible feedstock technologies might facilitate malicious development of self-replicating systems,[10] e.g., by using nanofactories to construct them). For a complete PN feedstock gas, small amounts of other gases containing additional non-carbon atoms needed for mechanosynthetic processes still must be added to the mix, raising feedstock costs by an additional but unknown amount—for example, \$1.50/kg for hydrogen (H_2) gas, \$110/kg for Si atoms in silane (SiH_4), \$354/kg for P atoms in phosphine (PH_3), and \$1150/kg for Ge atoms.[11]

Theoretical studies of diamond mechanosynthesis[12] often assume the use of a more chemically convenient carbon-rich hydrogen-poor precursor carbon-source molecule such as acetylene (C_2H_2). Note that the chemical energy of all the interatomic bonds in one kilogram of acetylene is about 67 MJ, implying a relatively low theoretical cost of \$1.85/kg at the current electricity price of ~\$0.10/kW-h, even though large-volume commercial acetylene prices are typically \$18/kg[13] because of costly special tanks required by law for the safe transport of this unstable high-energy gas.

Complexes, Master's Thesis, 18 December 2003; http://etd.lsu.edu/docs/available/etd-01212004-125820/unrestricted/14Appendix.pdf. (b) "Table 6.1 Current bulk prices of nanoscale-structured products," in Robert A. Freitas Jr., Ralph C. Merkle, *Kinematic Self-Replicating Machines*, Landes Bioscience, Georgetown TX, 2004, p. 203; http://www.MolecularAssembler.com/KSRM/Tables/6.1.htm. (c) Is the cost of housing really irreducible? It is true that personal residences of current design, if constructed using diamondoid materials, might be buildable using an order of magnitude less processed mass (possibly incorporating water, dirt, or stone ballast to provide wind-resistance bulk) than present-day houses, hence reducing homebuilding costs tenfold assuming a \$1/kg rate. However, opposing this deflationary factor will be consumers' inflationary desire for houses with more square footage and more extensive features – such as pools and saunas, interior waterfalls and decorative ponds, reconfigurable rooms, escalators and elevators to upper floors, greenhouses and extensive outbuildings for hobby purposes, home theaters, ubiquitous fireplaces and wall-sized 'view' windows, hurricane and earthquake-proofing, and so forth. And it is likely that any remaining savings in house construction costs may be spent to bid up the price of scarce land to build upon in desirable locations, since lower house prices would increase the demand for more houses.

[10] Robert A. Freitas Jr., Ralph C. Merkle, *Kinematic Self-Replicating Machines*, Landes Bioscience, Georgetown TX, 2004; http://www.MolecularAssembler.com/KSRM.htm

[11] Hydrogen (http://www.solartoday.org/2004/may_june04/h2_afford_it.htm), silane (http://microlab.berkeley.edu/text/2K4YER/bob.html), phosphine (http://www.aciar.gov.au/web.nsf/att/JFRN-6BN95D/$file/wp16.pdf), germanium (http://www.answers.com/topic/germanium).

[12] Ralph C. Merkle, Robert A. Freitas Jr., "Theoretical analysis of a carbon-carbon dimer placement tool for diamond mechanosynthesis," *J. Nanosci. Nanotechnol.* 3(August 2003):319–324; http://www.rfreitas.com/Nano/JNNDimerTool.pdf. David J. Mann, Jingping Peng, Robert A. Freitas Jr., Ralph C. Merkle, "Theoretical Analysis of Diamond Mechanosynthesis. Part II. C_2 Mediated Growth of Diamond C(110) Surface via Si/Ge-Triadamantane Dimer Placement Tools," *J. Comput. Theor. Nanosci.* 1(March 2004):71–80. Jingping Peng, Robert A. Freitas Jr., Ralph C. Merkle, James R. Von Ehr, John N. Randall, George D. Skidmore, "Theoretical Analysis of Diamond Mechanosynthesis. Part III. Positional C_2 Deposition on Diamond C(110) Surface using Si/Ge/Sn-based Dimer Placement Tools," *J. Comput. Theor. Nanosci.* 3(February 2006):28–41; http://www.MolecularAssembler.com/Papers/JCTNPengFeb06.pdf.

[13] "Price List: Millennium Acetylene Cylinders," Taylor-Wharton/Harsco, 10 November 2005; http://www.taylor-wharton.com/pricing/current_pricing_master/current_pricing_master.pdf and http://www.taylor-wharton.com/Pages/HP&A/Acetylene.htm. Price is \$17.91/kg for acetylene in largest

If electricity could be obtained more cheaply, then in principle the cost of acetylene could fall accordingly. For instance, if electricity costs dropped 10-fold to \$0.01/kW-h, then acetylene costs could fall to \$0.185/kg, and ignoring the cost of ancillary non-hydrocarbon gases the minimum total cost of PN manufactures would then decline to \$0.185/kg + \$0.10/kg (capital cost) + \$0.20/kg (intangibles) = \$0.485/kg. If electricity costs dropped 100-fold to \$0.001/kW-h, then acetylene costs could fall to \$0.0185/kg, implying a total cost for PN manufactures (again ignoring the cost of ancillary gases) of at least \$0.3185/kg. The cost of electricity cannot as a practical matter decline to zero[14] because energy is an inherently scarce resource, electrical generators have input material costs and fixed capital/site expenses, transmission lines require maintenance, waste heat and other pollution byproducts must be properly disposed of, natural environments should not be despoiled, and so forth. But even if the cost of electricity did fall to zero, the total cost of PN manufactures would still be at least ~\$0.30/kg as noted earlier.

Supporting the plausibility of our assumption of a future ~\$0.10/kW-h electricity price is the historical fact that U.S. prices of electricity in nominal dollars have been remarkably constant over the last 100 years. This period has seen economic booms and depressions, war and peace, and tremendous technological change and gains in industrial productivity. Specifically, the average price in nominal dollars for delivered U.S. residential electricity was \$0.105/kW-h in 1907[15] and \$0.099/kW-h in August 2005[16]—that is, no change. (The U.S.

WM-420 tank, capacity 13.0 kg of commercially pure acetylene gas at 250 psig and 70 °F. Calcium carbide may be purchased (http://www.chembargains.com/inactive-chemical-supplies-11359.php) at \$400 per 100 kg, which when reacted with water (assumed free) and the acetylene thus generated is collected (also assumed free), the cost for the 40.56 kg of liberated gas would be \$9.86/kg, not counting the additional disposal costs for the calcinated sludge byproduct.

[14] An uncritical optimist heedless of many technical, political, public safety, and other practical obstacles might propose obtaining almost zero-cost energy by employing a single well-shielded 2500 micron^3 selenophage of mass ~10^{-11} kg that is delivered to the Moon by hitchhiking for free on the next scheduled lunar lander mission that someone launches. The minimum possible energy cost for such a launch approximates the gravitational potential energy of a selenophage resting on Earth's surface, or $-GM_{Earth}m_{Selenophage}/R_{Earth} \sim 1.7 \times 10^{-10}$ kW-h which would cost ~\$$1.7 \times 10^{-11}$ assuming today's energy price on Earth of \$0.10/kW-h. The pure energy cost to manufacture the one selenophage unit in a PN, assuming \$1/kg, is also \$$10^{-11}$. Using lunar-available visible-spectrum solar energy (25 W/m^2 on cloudless Moon [17]) absorbed on the device's surface (184 micron^2) and local materials, the device replicates copies of itself (at 64 MJ/kg, 6.7×10^{-5} J needed per copy; 4.6 nW available to the device via solar energy; assume only 1/6 is used for replication/mechanosynthetic activities) at a leisurely rate of 1 day per copy cycle. Acceleration of each selenophage to the required average diasporic speed of 1.5 m/sec across the lunar surface costs (1/2 mv^2 =) 0.01 nJ, demanding only 0.002 sec of available onboard power, a negligible drain from replicative activities. After 81.2 doubling times, say 82 days, the entire lunar surface is coated with solar-electricity-producing selenophages. Conservatively assuming a solar-electric lifetime of only 10 years before replacement is needed, the circumlunar selenophagic layer now generates a total output of 500 terawatts (current human energy use ~ 10 terawatts worldwide) at a net cost to the original human instigator of (~\$$10^{-11}$) / [(500 terawatts)(10 years)] ~ \$ 2×10^{-28} / kW-h.

[15] U.S. Bureau of the Census, *Historical Statistics of the United States, Colonial Times to 1970*, Washington, D.C., 1976; "Average Prices for Electric Energy," Series S 116, p. 827; "Money Stock, M2 Money Supply," Series X 415, pp. 992–3; "Currency Stock and Currency in Circulation, Total Currency in U.S.," Series X 420, p. 993.

[16] "Table 9.9 Retail Prices of Electricity Sold by Electric Utilities," Energy Information Administration, *Monthly Energy Review*, November 2005; http://tonto.eia.doe.gov/merquery/mer_data.asp?table=T09.09.

Consumer Price Index (CPI) has risen 22-fold during this same period which means that the real cost of residential electricity has declined 22-fold over the last 100 years, but the nominal price has stayed constant at 10 cents. Industrial electricity prices have behaved similarly.) We can consider an idealized alternative scenario for decentralized energy production in which solar energy is captured by inexpensive thin solar panels placed as ground cover over cheaply-priced vacant rural land, initially bringing the cost of solar-derived electricity down to ~$0.001/kW-h.[17] Since this cheap electricity can be immediately resold at the prevailing $0.10/kW-h price in competition with existing utility suppliers, a likely rapid escalation of free-market vacant land values or the imposition of regulatory/protectionist tariffs by government should quickly close much if not most of the price gap. Of course, environmentalists may prevent the project from going forward at all for a variety of reasons – such as (1) the possible death of covered vegetation due to sunlight deprivation; (2) the alteration of local weather patterns and watershed hydrodynamics including soil drainage, erosion, and water tables; (3) the destruction of natural "view easements" with solar collectors that are aesthetic eyesores; (4) the interference with insect and bird navigation; and so forth. Ocean-based solar collection systems have similar costs with different sets of environmental issues.

Optimistically assuming that feedstock gases can be purchased by the consumer for a delivered price of $0.70/kg, and adding in the amortized initial capital outlay of $0.10/kg to buy the PN, and another $0.20/kg for prorated intangible costs, then the cost of manufacturing consumer products using a personal nanofactory should be about $1/kg. This is moderately cheaper than the current cost of nondurables like bread and meat at the grocery store ($3–$5/kg), [9b, 18] and 2–3 orders of magnitude cheaper than the current cost of commonplace durables such as a good pair of shoes ($100/kg) or a good laptop computer ($1000/kg).[9b] Supplemental licensing fees, intellectual property restrictions, taxes, regulatory tariffs and so forth may drive up the cost of some luxury or specialty items to well above the $1/kg price of manufactured goods, but the current prices of expensive items such as beluga caviar ($796/kg), pearls ($27,000/kg) and pharmaceutical interferon ($190,000,000/kg)[9b] (all made from intrinsically cheap atoms) also have room to fall many orders of magnitude. Over time, most basic consumer goods should

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[17] Taking average ground-level cloudless noontime optical-band solar intensity as 200 W/m^2 [41] and correcting for day/night cycles (0.5), cloud cover (0.5), solar angle (0.5), and 50% conversion efficiency (0.5), the panels deliver ~50 kW/acre (12.5 W/m^2) or ~4.4 million kW-h/acre over an assumed 10-year lifetime for the panels. Taking the average cost of vacant rural land as $500/acre [42], the carrying cost at 5% mortgage interest and a 1% property tax rate is $30/yr, or $300/acre for 10 years. Thin diamondoid solar panels with their support structures to cover 1 acre will have a total mass of ~2900 kg [43], costing $2900 if fabricated for $1/kg (see below), bringing total cost over 10 years to $3200/acre and thus the cost of energy to ~$0.001/kW-h. Cost is similar if the ground is first cleared by a bulldozer at $50–$150/h [44] plus move-in/out fees, allowing laying solar collectors on the ground without supports. This analysis also ignores any additional costs of local energy storage or transmission to a distant site.

[18] Even if the base cost of molecular manufacturing using PNs was lowered to $0.30/kg, food prices would always have less far to fall than durable goods prices because nondurables made using current production methods such as agriculture start out from a cheaper price base. Agriculture may be regarded as a form of biology-based nanotechnology (the plant or animal cells do most of the work of creating the molecular structure of the food, not the farmer) whose prices already have much of the manufacturing cost advantages of nanotechnology built into them.

become commoditized with prices asymptotically approaching production + capital + intangibles costs, though perhaps with some government tariffs on personal manufacturing zeroed out on basic staples and necessities to accommodate the neediest citizens.

A sudden lowering of manufacturing costs might lead to deflation. An interesting historical precedent for technology-driven hyperdeflation of a commodity price is the example of aluminum metal. During most of the 1800s, aluminum could only be produced commercially using an expensive chemical process involving highly reactive alkali metals. As late as 1884, the pure element still was regarded as a precious metal with a price of $16/pound, equivalent to $23/oz in current 2006 dollars. Aluminum was used for fine tableware (much like sterling silver, then and today) and the metal was chosen to cast the small pyramidal cap atop the Washington Monument.[19] In 1886 a cheap new electrolytic technology called the Hall process was discovered which by 1914 had sent the price of the pure metal plunging to just $0.19/lb, a price floor determined by the cost of electricity. This represents a nearly 100-fold single-commodity price hyperdeflation in less than 3 decades – the technology-enabled price drop could occur because aluminum atoms are plentiful and widespread in nature, unlike, say, gold atoms [see Footnote 24 infra]. Still, a bit of perspective is needed here. Average U.S. consumer prices have only risen 50-fold during the last 300 years and 10-fold in the last 60 years,[20] a +4%/yr long-term rate in modern times; the U.K. has a similar record. The sharpest general price deflation in U.S. history occurred during 1780–89 when prices declined 100-fold from temporarily inflated Revolutionary War profiteering highs.[20] But except in similar cases involving bursting economic bubbles, deflations are generally mild and rare – across the worldwide Great Depression during 1920–1933, U.S. consumer prices dropped by –35% (not even 2-fold).[20]

In light of the above considerations, a conservative assumption is that the introduction of personal nanofactories over a time period lasting, say, two decades will result in the average prices of consumer nondurables falling perhaps 5-fold from today's prices, and the average prices of consumer durables falling perhaps 100-fold.

How will this affect the overall inflation rate? Perhaps surprisingly, not much.

The deflationary impulse

In the 2005 U.S. economy, consumer durables accounted for 12.8% of all Personal Consumption Expenditures (PCE), nondurables were 29.0% of PCE, and services were 58.2% of PCE.[21] If the aforementioned 5-fold and 100-fold price declines occur over a 20-year period during which PNs are introduced at a linear rate of market penetration growing from 0% to

[19] George J. Binczewski, "The Point of a Monument: A History of the Aluminum Cap of the Washington Monument," *JOM* 47(1995):20–25; http://www.tms.org/pubs/journals/JOM/9511/Binczewski-9511.html.

[20] U.S. Bureau of the Census, *Historical Statistics of the United States, Colonial Times to 1970*, Washington, D.C., 1976, Series E 135 (CPI All Items, p. 211) and Series Z 557 (Wholesale Price, Colonial and Pre-Federal Years, p. 1196); current CPI and employment data from Statistical Abstract of the United States, various years.

[21] "Personal Income and Outlays: October 2005," U.S. Bureau of Economic Analysis, Dept. of Commerce, 1 December 2005; http://www.bea.gov/bea/newsrel/pinewsrelease.htm. See also: "Gross Domestic Product and Corporate Profits: Gross Domestic Product: Third Quarter 2005 (Preliminary)," U.S.

100%, and if the services component of PCE continues to inflate at the long-term historical +4%/yr rate, then the net inflation rate for all of PCE falls from +4%/yr in the last year prior to PN introduction to +1.4%/yr during the 20 year period in which PNs are introduced into the economy. In other words, there is no actual deflation, just –2.6%/yr worth of disinflation. By the end of the 20-year PN introduction period, services make up 95.5% of the private consumption economy, nondurables are 4.4% of PCE, and durables have almost vanished at 0.1% of PCE. In year 21, inflation returns to the long-term historical +4%/yr trendline.

It's unclear what effect PNs might have on inflation in the service sector.[22] On the one hand, it can be argued that services may experience some disinflation during the PN introduction period because PNs in the hands of service providers will make those businesses more efficient, hence able to lower their prices for competitive advantage. On the other hand, the principal determinant of the price of services is the cost of human labor. With workers generally more affluent and less desperate for necessities, labor wage rates might actually need to rise, not fall, to induce PN-goods-satiated indolent citizens to remain in, or return to, the workforce. Of course, if most services no longer needed to be provided by humans – e.g., if most services could be provided by AI-enabled robotic slaves cheaply manufactured by PNs, thus allowing humans to become pure consumers with no need to produce anything of value or to serve anyone – then the value of human labor would have effectively fallen close to zero and the cost of services would then fall to the same degree as durable goods, since robots and AI-embedded computers are also durable goods. The degree to which humans will find robot-only services to be socially and aesthetically acceptable is unclear, as is the legal status of enslaved AI-enabled robotic "persons" [see Footnote 52 infra], and both issues are beyond the scope of this essay.

The inflationary impulse

However, this is not the end of the story. Much like the extreme but narrow economic dislocations experienced by developed countries when suddenly confronted with cheaper external sources of goods (often causing companies to outsource), personal nanofactories are the economic equivalent of below-cost trade competition for most retail manufactured products. One likely result is that much of the manufacturing, agriculture and wholesale/retail trade sectors (about 40% of all employment in developed economies[20]) could face continuing downsizing pressures throughout the 20-year introduction period of the PNs. Up to 40% of all workers could be affected and they may experience wage stagnation, job loss, and a need for

Bureau of Economic Analysis, Dept. of Commerce, 30 November 2005; http://www.bea.gov/bea/newsrelarchive/2005/gdp305p.htm. PCE represents ~70% of the U.S. Gross Domestic Product (GDP), with the balance of GDP consisting of private domestic investment (~15%) plus government consumption expenditures, government investment, and the import/export trade deficit.

[22] The impact of PNs on the food sector is illustrative. PNs may bring down the prices of basic food and food products 5-fold, with basic nutrition becoming public domain. But food with a strong service component may not suffer and might even thrive. For example, visiting a restaurant is mainly experiential service consumption, not nondurable goods consumption. Served food derives much of its value from ambiance, service, and variety. The restaurant chef may be fabricating all the food using a PN in the back of the kitchen, but the PN will be running specialized software that allows the chef to synthesize each course using unique molecular recipes he's written himself incorporating the latest flavors, smells and textures, and to create a dazzling variety of special effects.

additional education or retraining for gainful employment in the service sector—much as displaced agricultural workers fled to the manufacturing sector a century ago.

Consider the likely governmental response to these displacements. If a significant fraction of manufacturing-sector employees lose their jobs and thus have no money to pay for necessities, then as their unemployment or union benefits and savings become exhausted these people will naturally turn to the government for further assistance during their period of career realignment. They will demand to receive transfer payments of subsistence cash to buy the commodity goods (e.g., food, clothing) and services (especially nanomedical care) that they need but can no longer afford. Politicians will feel little restraint against printing money as fast as it is needed to make voters whole, equivalent to Milton Friedman's famous proposed "helicopter drop" of cash.[23]

This forced expansion of the money supply will be inflationary. But by how much? In the scenario analyzed earlier, over a 20-year PN introduction period the economy loses a combined average of $160B/yr in consumer spending on durables and nondurables, rather than gaining a combined average of $220B/yr that would have occurred in the absence of the PNs. In the simplest case, the government (using the United States as an example) would just issue the swing difference ($380B/yr) as direct grants to displaced people in the affected industries. This would increase the current growth rate of the 2005 U.S. M2 money supply from $300B/yr (+5%/yr) to $680B/yr (+10%/yr), perhaps adding about +5%/yr to the annual CPI inflation rate (assuming for simplicity no multiplier effect) during the 20-year PN introduction period. Combining this new government-induced inflation with the disinflation of –2.6%/yr caused by the rapid fall in the prices of PN-manufactured goods (see above) gives a net inflation rate increase of +2.4%/yr, i.e., from the current +3%/yr rate to a slightly higher +5.4%/yr rate of U.S. consumer price inflation. The macroeconomic effects of this change might be hardly noticeable to non-economists.

Even this small increment to the CPI inflation rate can be entirely neutralized (at least on an economy-wide basis) if the government increases the M2 money supply growth by only an average of $200B/yr (rather than $380B/yr) of direct grants of assistance to displaced workers. In this case, the +2.6%/yr inflationary impact of increased government outlays would exactly counterbalance the –2.6%/yr deflationary impact of the PNs on the general price level, resulting in a zero net change in the overall inflation rate. The missing $180B/yr not directly paid to the displaced workers would be offset in most cases by the incremental appreciation of tangible assets owned by them, that cannot readily be manufactured by nanofactories with any clear cost advantage (e.g., houses (whose conventional manufacturing cost is already $1/kg[9c]), land and other real estate, precious metals,[24] and so forth). The 2004 U.S. national home ownership rate was 69.0%,[25] and an extra +2.6%/yr of general inflation applied to the current $19.1T worth of owned residential real estate[26] amounts to an annual appreciation gain of $500B/yr.

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[23] Milton Friedman, "The Optimum Quantity of Money," in Milton Friedman, ed., *The Optimum Quantity of Money*, Aldine Publishing Co., Chicago, 1969.

[24] Robert A. Freitas Jr., "Tangible Nanomoney," *Nanotechnology Industries Newsletter*, Issue II, July 2000, pp. 2–11; http://www.rfreitas.com/Nano/TangibleNanomoney.htm.

[25] "Table 15. Homeownership Rates for the United States, by Age of Householder and by Family Status: 1982 to 2004," U.S. Census Bureau 2004; http://www.census.gov/hhes/www/housing/hvs/annual04/ann04t15.html.

[26] "Table B.100 Balance Sheet of Households and Nonprofit Organizations," FRB Release Z.1, 8 December 2005; http://www.federalreserve.gov/releases/z1/current/z1r-5.pdf.

Deflation and inflation can be balanced through government action

Note that because government has the ability to "lean against the wind," then, within broad limits, the inflationary effects of increased government outlays can always absorb the deflationary effects of PNs, even if cheaper electricity allows the cost of PN-made goods to fall from \$1/kg to the irreducible minimum of \$0.30/kg. The same result occurs if PNs are introduced into the economy over a period substantially shorter than 20 years. For example, a faster 10-year introduction period produces a mild –0.8%/yr deflation over that period.[27] In this case, the +4.8%/yr inflationary impact of \$365B/yr of increased government outlays would exactly counterbalance the –4.8%/yr deflationary impact of the PNs on the general price level, again resulting in a zero net change in the overall inflation rate.

In a worst-case scenario, an unrealistically fast 1-year introduction period of PNs would produce a 1-year –33.5%/yr deflation rate (in the absence of any government response), almost exactly matching the total peak-to-valley deflation that was recorded during the Great Depression (see above). But rather than allowing money supply to naturally decline as in the 1930s (which enhanced the contraction in real economic growth), this time the governmental monetary authorities would probably increase the M2 money supply to match the \$3,320B in lost final sales. That's the equivalent of handing every man, woman, and child in the U.S. a check for \$11,600. The one-time stimulative action would increase the M2 money supply by about +50.1% in a single year.

Such stimuli are not unprecedented in U.S. economic history.[28] For instance, a two-year +50.1% M2 increase during 1942–44 at the beginning of WWII produced only +4%/yr CPI inflation in those years, in part due to the simultaneous implementation of price controls.[15, 20] A one-year +60.6% increase in total U.S. currency during 1862–63 at the beginning of the Civil War produced +23%/yr CPI inflation across those years, though by 1878 consumer prices had returned back down to 1862 levels.[15, 20]

In the above worst-case scenario, the one-time issuance of government largesse would permanently balloon federal debt[29] from \$7,900B (2005) to \$11,200B in a single year. Assuming interest rates remain roughly unchanged along with the inflation rate (since interest rates loosely track the inflation rate), federal interest payments on the debt[30] would only rise from \$350B/yr (2005) to \$500B/yr, a \$150B/yr federal budget expenditure increase that seems

[27] For a PN introduction period lasting τ years and assuming neutral fiscal and monetary policies and all else equal, a crude approximation of the inflation rate is $I_\tau \sim 100\% \, [\exp(\ln\{PCE(\tau) / PCE(0)\} / \tau) - 1]$, with $PCE(t) = ND(t) + D(t) + S(t)$ and taking t = 0 as Year 2005 data: NonDurable goods ND(0) = \$2566.8B, $ND(\tau) = ND(0)/5$, Durable goods D(0) = \$1129.9B, $D(\tau) = D(0)/100$, and Services S(0) = \$5159.8B, $S(\tau) = S(0)\,(1.04)^\tau$.

[28] Keynes [45] had argued in 1936 that public spending was a perfect substitute for private spending in terms of its effect on the overall economy. During the 1940s, the positive impact of WWII on the American economy was interpreted by many as a vindication of Keynesian economic principles, suggesting that it was possible to manage the overall economy through a judicious use of public spending.

[29] "Historical Debt Outstanding—Annual 1950–2005," U.S. Department of Treasury, 2005; http://www.publicdebt.treas.gov/opd/opdhisto4.htm.

[30] "Interest Expense on the Debt Outstanding," U.S. Department of Treasury, 2005; http://www.publicdebt.treas.gov/opd/opdint.htm.

modest in comparison to the usual $3,900B/yr (2005) in U.S. federal outlays.[31] Even a modest increase in long-term interest rates, due to the increased debt level, is probably tolerable to the federal budget. In the low-probability 1-year PN introduction scenario, federal outlays would spike +85%, from $3,900B to $7,220B for one year, but this is historically comparable to the +51% increase in federal outlays during 1862–63 and the +172% increase in federal outlays during 1942–44.

Conclusions

Deflationary forces driven by advances in molecular manufacturing (MM) can be opposed by inflationary forces competently initiated by governmental monetary authorities. This allows the two forces to remain roughly in balance, with the incremental inflation at the general price level remaining close to zero as PNs are introduced. Since an MM-rich economy will be dominated by services and information, not goods, our expectation is that the prices of services and information might rise very slightly as the prices of PN-manufactured goods falls significantly. For example, if services and information comprise 95% of the economy and goods are only 5% of all sales, then a deflationary –20% decline in the prices of goods can be largely offset by an inflationary rise of just +1% in the prices of services and information.

Manufactured goods will represent a decreasing portion of the total economy as PNs are introduced, hence the influence of such goods on the general price level in the overall economy will tend to decline as the diffusion of MM throughout the economy approaches saturation. Similarly, services and information will represent an increasing fraction of the total economy as PNs are introduced, eventually reaching near 100%. Hence the amount of incremental inflation in the prices of services and information that is required to offset the deflation caused by falling goods prices will also tend to decline toward zero as the diffusion of MM throughout the economy approaches saturation.[32]

[31] "Government Current Receipts and Expenditures," Bureau of Economic Analysis, 2005; http://www.bea.gov/bea/dn/nipaweb/GovView.asp

[32] Ray Kurzweil (personal communication, 21 December 2005) suggests that once a technology becomes an information technology, it becomes subject to the law of accelerating returns (LOAR) [46], which is a strongly deflationary force. Some technologies, he says, are already subject to LOAR such as computers and communications, while others are becoming subject to it such as drugs and medical technologies that are in the process of switching from the hit-and-miss paradigm of drug discovery to the information-driven paradigm of rational drug design. Information technology is now only about 10 percent of the economy but will grow substantially over the next 20 years, ultimately dominating the economy. However, Kurzweil adds: "There is a natural counterbalance to the deflationary effect of the LOAR, which is the tendency to increase consumption with greater price-performance. The price-performance of electronics (in terms of the cost per transistor cycle) has been coming down by half about every year. But our consumption of electronics has more than kept pace: the industry has grown by 18% per year in constant dollars over the past fifty years despite the fact that you can buy about twice as much capability each year for the same number of dollars. People didn't buy ten thousand dollar IPods ten years ago. We've seen that at each stage of automation. In the eighteenth century, few people could afford any well-made clothing. With the automation of the textile industry starting around 1800, the common man and woman could afford well-made clothes for the first time, and people were no longer satisfied with owning a single shirt. This led to the invention of fashion, in which people did not want to keep wearing the same clothes for very long. So this increase in consumption with increasing price-performance acts as a natural counterbalance so that the deflationary effect of the LOAR does not actually shrink the size of the economy as measured in constant currency."

Both deflationary and inflationary levers exist in the economy. Either may be pulled on harder, as needed, to maintain a stable price regime (or at least to ensure 'soft landings'), up to the point where the whole economic system breaks down. That is, a monetary expansion (possibly creating soaring public debt politically rationalized by a Presidential proclamation of a "War on Deflation") can continue until the required inflationary counterstimulus becomes so enormous that the financial stresses induced by large and rapid monetary flows literally break the economic system, possibly in an extended analog of the stock market crash of 19 October 1987.[33] Quantifying this threshold systemic breakage point—in both local and global economies—should be an urgent matter for future econometric and economics-history research.

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[33] Donald MacKenzie, "The Big, Bad Wolf and the Rational Market: Portfolio Insurance, the 1987 Crash and the Performativity of Economics," Economy and Society 33 (February 2004):303–334; http://www.sociology.ed.ac.uk/Research/Staff/Mackpaper5.pdf. See also: "Black Monday—the Stock Market Crash of 1987," http://www.stock-market-crash.net/1987.htm; "Lope Markets—1987 Stock Market Crash," http://www.lope.ca/markets/1987.html.

[34] "Effective State and Local Tax Burdens by State and Rank for Calendar Year 2005," Retirement Living Information Center, http://www.retirementliving.com/RLtaxburdens.html; "Taxes by State," http://www.retirementliving.com/RLstate1.html

[35] Clyde Wayne Crews Jr., *Ten Thousand Commandments: An Annual Snapshot of the Federal Regulatory State*, 2002 Edition, Cato Institute, Washington DC, 2002, http://www.cato.org/tech/pubs/10kc_2002.pdf; "Cost of Health Services Regulation: Working Paper Series," Center for Health Policy, Law and Management, Duke University, 26 December 2005, http://www.hpolicy.duke.edu/cyberexchange/Regulate/CHSR/CHSR.html; Richard K. Vedder, "Federal Regulation's Impact on the Productivity Slowdown: A Trillion-Dollar Drag," Center for the Study of American Business (CSAB), Washington University, St. Louis, Policy Study Number 131, March 1996, http://heartland.org/Article.cfm?artId=4677; Thomas D. Hopkins, "Regulatory Costs in Profile," Center for the Study of American Business (CSAB), Washington University, St. Louis, Policy Study Number 132, August 1996, http://wc.wustl.edu/csab/CSAB%20pubs-pdf%20files/Policy%20Studies/ps132%20hopkins.pdf; Peter Ferrara, "The Government Tab," Cato Institute, Washington DC, 26 June 1999, http://www.cato.org/dailys/06-26-99.html.

[36] "California Vehicle Registration Fee Calculator," California Department of Motor Vehicles, https://vrir.dmv.ca.gov/FeeCalculatorWeb/index.jsp

[37] Boris Vishnevsky, "Tax Reform: A Breakthrough?" The Moscow News, 10 December 2004; http://english.mn.ru/english/issue.php?2004-12-10

[38] "NNI Business Glossary, Tax: Property Tax," NikkeiNet Interactive; http://www.nni.nikkei.co.jp/FR/TNKS/TNKSHM/glossary/tax_03.html

[39] "General News: September could be bad for investments - papers 2nd Sept," IFAOnline, 2 September 2002; http://www.trustnet.co.uk/general/news/printable.asp?db=general&id=35552

[40] "2005–2006 County Tax Rates," Maryland State Department of Assessments and Taxation, 25 October 2005; http://www.dat.state.md.us/sdatweb/taxrate.html

[41] "Section 6.3.6 Photonic Energy Conversion Processes," in Robert A. Freitas Jr., *Nanomedicine, Volume I: Basic Capabilities*, Landes Bioscience, Georgetown, TX, 1999, p. 156; http://www.nanomedicine.com/NMI/6.3.6.htm#p5.

[42] U.S. rural farmland in 2004 ranged from \$265/acre in NM to \$10,200/acre in CT and RI; U.S. average is \$1360/acre [47]. Canadian rural farmland in 2004 ranged from \$350/acre in Saskatchewan to \$3337/acre in Ontario [48], with one writer reporting prices as low as \$188/acre in southeastern Saskatchewan [49]; Canadian average is \$927/acre [48]. In 2005, relatively inaccessible virgin Brazilian timberlands were available for \$18/acre in 10,000-acre parcels [50], remote but water-accessible Brazilian grasslands could be bought for \$200/acre in 200-acre parcels [50], and cattle grazing property was for sale in remote Arizona for \$125/acre in 20,000-acre parcels [50].

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[43] A solar-collector sheet of diamondoid material of dimension w = 67.1 m (edge length of 1 square acre), working strength $\sigma_w = 10^{10}$ N/m^2 (~0.2 times the failure strength of diamond; http://www.nanomedicine.com/NMI/10.3.1.htm#p3) and density ρ_{diam} = 3510 kg/m^3 frontally impacted by a wind of density ρ_{air} = 1.29 kg/m^3 at STP traveling at maximum gust velocity v = 44.7 m/sec (100 mph) must have thickness $t > \rho_{air} w v^2 / \sigma_w \sim 17$ microns to avoid tearing, giving a sheet of mass $M_{sheet} = \rho_{diam} w^2 t$ = 270 kg. Cylindrical diamond supporting columns (one at each corner) of length L = 10 m with Young's modulus $E_{diam} = 1.05$ ′ 10^{12} N/m^2 must have radius $R > (4L^2\ \rho_{air} w^2 v^2 / \pi^3 E_{diam})^{1/4}$ = 7.7 cm to avoid buckling (http://www.nanomedicine.com/NMI/9.3.1.2.htm#p2) under a maximum whole-sheet 1200 metric ton wind load, giving total column mass $M_{columns} = 4\ (\pi R^2 L \rho_{diam})$ = 2630 kg, hence total installed diamond mass $M_{diam} = M_{sheet} + M_{columns}$ = 2900 kg. (M_{diam} is minimized using the largest possible sheet rather than multiple smaller sheets because $M_{columns} \sim w^{-1}$.) The above estimate ignores possible damage from seasonal snow loads, an additional 400 metric tons per foot of snow depth assuming a snow pack density of ~300 kg/m^3 [51].

[44] "Machinery Rental, Wisconsin, 2004," Wisconsin's 2004 Custom Rate Guide, Wisconsin Agricultural Statistics Service, p. 9; http://www.nass.usda.gov/wi/custom_rate_2004.pdf; "Summary Of EERA Rates, Bulldozers," California Interagency Emergency Hire Of Equipment Rental Rates, New Agreement Period: May 1, 2005–April 30, 2008 , No. 29 April 2005, p. 3934–6; http://www.fire.ca.gov/php/fire_er_content/downloads/3934rev0405.pdf. See also: http://www.cityofmiddletown.com/Purchasing/Bids/2005-038.pdf.

[45] John Maynard Keynes, *The General Theory of Employment, Interest and Money*, Harcourt Brace, New York, 1936.

[46] "Chapter 2. A Theory of Technology Evolution: The Law of Accelerating Returns," in Ray Kurzweil, *The Singularity is Near: When Humans Transcend Biology*, Penguin Books, New York, 2005, pp. 35–110.

[47] "Table 9–14. Farm real estate: Average value per acre of land and buildings, by State, Mar. 1, 1970 and Jan. 1, 2000–2004," *Agriculture Statistics 2005*, U.S. Department of Agriculture, p. IX-9; http://www.usda.gov/nass/pubs/agr05/05_ch9.pdf.

[48] "Table 2. Value per acre of farm land and buildings," Value of Farm Capital, Agriculture Economic Statistics, November 2005, Statistics Canada; http://www.statcan.ca/english/freepub/21-013-XIE/2005002/t002_en.htm.

[49] "Farmland Prices on the Prairies," *Warren's Farm & Ranch Review*, Spring 2001, pp. 14–15; http://www.warrensdirectory.com/pdf/2001/getting_intense.pdf.

[50] "Land for sale, Farms for sale, Rural property for sale," *Rural Property Bulletin*, 17 December 2005; http://www.landandfarm.com.

[51] "Snow Cover. Properties of Snow Cover: Snow Density," *The Atlas of Canada*, 18 April 2005; http://atlas.gc.ca/site/english/maps/environment/climate/snowcover/1.

[52] Robert A. Freitas Jr., "The Legal Rights of Robots," *Student Lawyer* 13(January 1985):54–56; http://www.rfreitas.com/Astro/LegalRightsOfRobots.htm.