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Evaluating future nanotechnology: The net societal impacts of atomically precise manufacturing

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ABSTRACT

Atomically precise manufacturing (APM) is the assembly of materials with atomic precision. APM does not currently exist, and may not be feasible, but if it is feasible, then the societal impacts could be dramatic. This paper assesses the net societal impacts of APM across the full range of important APM sectors: general material wealth, environmental issues, military affairs, surveillance, artificial intelligence, and space travel. Positive effects were found for material wealth, the environment, military affairs (specifically nuclear disarmament), and space travel. Negative effects were found for military affairs (specifically rogue actor violence) and AI. The net effect for surveillance was ambiguous. The effects for the environment, military affairs, and AI appear to be the largest, with the environment perhaps being the largest of these, suggesting that APM would be net beneficial to society. However, these factors are not well quantified and no definitive conclusion can be made. One conclusion that can be reached is that if APM R&D is pursued, it should go hand-in-hand with effective governance strategies to increase the benefits and reduce the harms.

1. Introduction

Atomically precise manufacturing (APM) is the assembly of materials with atomic precision. APM is also known as molecular assembly or molecular manufacturing, and is a form of molecular nanotechnology. APM does not currently exist, and some nanotechnology researchers doubt that it is feasible (e.g., Smalley, 2001), but those who believe it is feasible anticipate a wide range of transformative societal impacts (e.g., Drexler, 2013a). The best-case scenarios are incredible, featuring benefits on par with the industrial and computer revolutions. Worst-case scenarios are catastrophic, with harms up to and including human extinction.

The uncertain feasibility of APM and the wide range of potential impacts make for a difficult governance challenge. It is hard to know whether APM research and development (R&D) should be encouraged, discouraged, or simply ignored. Thus Marchant, Sylvester, and Abbott (2008) argue that traditional risk management approaches cannot be applied to APM. For example, the precautionary principle could suggest that APM R&D should be discouraged until it is clear that APM could not cause catastrophe, or it could suggest that APM R&D should be encouraged on grounds that it could help prevent other catastrophes. To the extent that prudent risk management demands a full accounting of the risks, and, more generally, that prudent governance demands a full accounting of the relevant factors and issues, it is not readily clear what society should do about APM.

In order to bring some clarity to the issue, this paper characterizes the potential societal impacts of APM if it is developed. The paper examines impacts across the wide range of sectors that APM could affect, including the environment, the military, surveillance, computing, space travel, and general material wealth. It seeks to understand what the net impacts on society would be, in particular

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whether they would be positive or negative, and by how much. The impacts are not quantified with any significant precision, as would be unwarranted for such a complex and uncertain future technology. However, a broad and imprecise analysis can nonetheless shed some light on the impacts of APM.

The paper is motivated by the question of whether society should invest in APM R&D. Greater APM R&D investment could bring APM into existence sooner (if APM would have been developed anyway) or with higher probability (if APM might not have otherwise been developed). Whether society should invest in APM R&D depends in part on what the net societal impacts of APM would be. If the net impacts would be negative, then arguably there should be no R&D investment. If net impacts would be positive, then there may be a case for R&D investment, though it would also depend on other factors, including the size of the net impacts, the cost of APM R&D, and the attractiveness of alternative investment opportunities. Thus, while this paper's analysis can inform APM R&D investment decisions, it cannot give definitive answers to how such decisions should be made.

This interest in APM R&D decisions is a reason for the paper's breadth across the range of APM impacts. One might object that this breadth makes for shallow and thus lackluster research. However, decisions like whether to invest in APM R&D depend on the full breadth of impacts. Thus, there is a need for synthesis across the potential impacts. Such synthesis additionally can identify important points of uncertainty where more narrow research would be of greatest value. This paper considers prior literature on APM impacts (e.g., Altmann, 2006; Drexler, 2013a; Freitas, 2006, 2007; Hughes, 2007; Timmermans, Zhao, & van den Hoven, 2011) and extends this literature with original analysis on each major sector of APM impacts in order to make progress on the question of net societal impacts and key areas of uncertainty. The prior literature on APM was mostly written over 10 years ago, Drexler (2013a) being a notable exception. Much has changed since then, both in the world at large and the relevant literature available from other fields. This paper therefore offers important updates from the prior literature, in addition to its original contribution from aggregating a broad spectrum analysis across multiple sectors.

More fundamentally, one might object that APM is too speculative and not imminent enough to merit attention. Indeed, while the prospect of APM was central to the establishment of nanotechnology as a research topic, the nanotechnology scientific community has more recently downplayed APM in favor of more modest and immediately achievable forms of nanotechnology (Selin, 2007). Additionally, some ethicists argue that APM does not merit ethical analysis because it displaces attention from analysis of near-term nanotechnology and gives credibility to speculative future scenarios that may not come to be (e.g., Grunwald, 2010; Jones, Whitaker, & King, 2011; Nordmann, 2007; Nordmann & Rip, 2009).

One response to these concerns is that APM is perhaps not so speculative after all. As proof of principle, APM already exists in nature in the form of biomolecules such as ribosomes, which "manufacture" protein molecules as per the "instructions" they read from RNA molecules (Drexler, 1986; Freitas & Merkle, 2004; Jones, 2004). Additionally, rudimentary forms of artificial APM are now possible via scanning tunneling microscopy and atomic force microscopy, which are both capable of accurately analyzing and determining the atomic structure of samples. In fact, scanning tunneling microscopes can even move atoms to precise locations, building elemental atomic structures, an important step towards APM (e.g., Farrell & Levinson, 1985; Gomer, 1986; Møller et al., 2017). Progress towards APM can also be seen in the 2016 Nobel Prize in Chemistry, which was awarded to Jean-Pierre Sauvage, Sir J. Fraser Stoddart and Bernard L. Feringa for their work on controllable molecules. While these advances fall short of the advanced APM discussed in this paper, they do suggest its feasibility. It still remains possible that APM may never be built, but the possibility should not be dismissed.

Roache (2008) provides two additional reasons for early attention to speculative future technologies like APM. First, analysis of the merits of R&D can be of particular value while the science and technology remain immature and thus more governable. Once a field of science and technology grows large, it gains inertia in the form of institutional buildup and scientists' and technologists' professional investment. This makes it harder to restrict, even if analysis finds it to be dangerous. To be sure, early analysis is also more ambiguous, since important details of the science and technology have not yet been established. This is the well-known Collingridge dilemma between information about a technology and the power to control it (Collingridge, 1980). This underscores the importance of early analysis of the potential impacts of a technology: to the extent that information can be obtained early, it is especially valuable.

Second, Roache (2008) argues that seemingly unlikely future scenarios can still be worth attention if their potential consequences are large enough. Similarly, Ćirković (2012) argues that improbable theories can merit attention when they would have high stakes if they turn out to be true. As noted above and discussed in detail throughout this paper, the potential consequences of APM could be quite large indeed. The combination of APM being potentially feasible, at an early stage of R&D, and potentially highly impactful render it a worthy focus of research, especially for research that is, such as this paper, oriented towards assessing its overall merits.

In order to determine the net social impacts of APM, this paper aggregates the net impacts that APM has to various spheres. First, the value that APM has to general society, particularly the social impacts of APM generated abundance. Secondly, how APM affects the environment, most notably how APM can be used in carbon dioxide removal and the fabrication of photovoltaics. Thirdly, the impacts of APM on the military and the manufacturing of new weapons systems will be analyzed. Fourthly, the value of APM to other surveillance technologies like cameras and mass surveillance networks will be discussed. Finally, the impact that APM has on the development of artificial intelligence (AI) as well as space travel will also be looked at in order to determine whether or not APM merits further investment and R&D.

2. Evaluative framework

This paper's framework is essentially consequentialist, aiming to assess the various consequences of APM in terms of benefits or harms to society. This is not to say that consequentialism is necessarily the only correct framework for evaluating APM; we only claim