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Programmable Matter: 4D Printing's Promises and Risks

By Nayef Al-Rodhan

A 3D printer in action at Makers Party Bangalore 2013, an event hosted by Mozilla India and Hive Learning Center. Despite its novelty, 3D printing has already been rendered yesterday's news by the development of 4D printing technology (Wikimedia Commons)

Three-dimensional printing, which has barely arrived on the scene, is already in danger of being eclipsed by another innovation that provides an upgrade to its functionality: Four-dimensional printing.

Three-dimensional printing entails printing finished objects from data sent to a 3D printer through a process of additive layering, in which successive layers of material are aggregated incrementally until the product is finished. The technology currently services both corporate manufacturing and private use, and is employed in multiple fields ranging from electronics, aerospace, and the automotive industry to medical efforts to create new human tissues, prostheses, and hearing aids. The housing and construction industries might well be next in line, following the recent full 3D printing of a house in China in the span of less than a day—and using waste-free materials to boot.

Four-dimensional printing goes a step further. Researchers at the Massachusetts Institute of Technology, where the technology was pioneered, have worked to incorporate an additional dimension into the 3D printing process: *time*. This not only allows objects to be custom-tailored but also makes them programmable for changes *after* fabrication. As MIT's Skylar Tibbits, one of the project's lead developers, recently explained, 4D printing is essentially nothing new—the innovation instead lies in what happens after printing has occurred.

While 3D printing is purposed around building static items, 4D printing employs dynamic materials that evolve or adapt to their external environment in real-time and in direct response to changing conditions. This ability to transform is embedded within the material itself. Objects created through 4D printing are programmed to self-assemble and alter their structure when the material of which they are composed comes in contact with different conditions, such as moisture or humidity. The ultimate goal is to create stimuli-responsive components, materials that modify their own form or self-assemble new patterns automatically and in predictive ways.

If 3D printing has broken ground by devising new methods to build objects from scratch, 4D printing's greatest innovation lies in the extraordinary potential of "smart" materials to incorporate the necessary information for self-assembly. Prior programming enables them to "learn" the thresholds of energy to which they then respond dynamically. The materials involved are not necessarily new; instead, they derive mostly from existing substances, such as plastics or fibers, combined in ways that change their properties under specific environmental conditions. Indeed, 4D printing can be viewed as simply a logical extension of its 3D counterpart and other existing technologies: As smart materials develop to the level of nano-composites and computing becomes both smaller and cheaper, programmable capabilities have emerged as a natural next step.

Experiments involving 4D printing have been quite limited to date. Nevertheless, both the constructive potential and disruptive capacity of the new technology have been taken seriously. The concept of "adaptive infrastructure" has already started to gain purchase in some businesses and industries, of which sportswear is one example. Four-dimensional programming has been tested to develop smart shoes with the ability to turn into running or basketball shoes or, alternatively, to become waterproofifit is raining or adapt according to the surrounding temperature, atmospheric pressure, or other external conditions.

Adaptive and biomimetic composites and responsive materials that react to external stimuli could revolutionize manufacturing by making it easier to build in extreme environments. In the realm of infrastructural projects, this is particularly relevant for the functioning of water pipes, which have long been considered a fixed capacity. Using 4D printing, pipes could be designed to adapt, expand, or contract based on their surroundings. Similarly, this adaptability could permit a range of innovative capacities such as "self-healing" pipes and equipment to counteract cracks or wear as well as "self-disassembling" materials to facilitate recyclability.

The U.S. military, which has previously invested in emerging innovations ranging from nanotechnology to camouflage and invisibility technologies designed to conceal objects and individuals from microwaves and the human eye, has also expressed interest in 4D printing. Four-dimensional printing is a natural extension of the military's underlying objective to maintain technological superiority on the battlefield and beyond, especially because it could optimize the functionalities of other emerging or existing technologies. For instance, uniforms made of 3D printed material could adapt to camouflage, cool, or insulate soldiers in different environments. Similarly, an adaptive printed metal could adapt to specific environmental conditions to improve the performance of vehicles like tanks or trucks.

The possibilities ushered in by 4D printing run much further afield, however. Ultimately, its frontiers are expected to shift from the inorganic world to the realm of organic life, where nanotechnology and the science of bio-programmable matter could converge to offer unprecedented solutions to current global issues. Smart pharmacology and personalized medicine are one such frontier. The so-called Autodesk Initiative has already embarked on an ingenious project called "DNA origami," which builds nano-scale protein structures whose purpose is to create nano-robots precisely designed to target and kill cancerous cells in the body. A part of this initiative called Project Cyborg similarly works on a meta-platform of programming matter to set parameters and create specialized designs for biomaterial that can then grow or change their properties. The use of these design platforms could vary widely, from tissue-engineering to the self-assembly of biomaterials.

Programming matter carries profound implications for industry, the military, and medicine. Its benefits, however—especially in terms of cost-savings, adaptability, and customization—are offset by many technical and legal challenges that need to be addressed. Particular areas of concern include design, standardization and certifications, affordability, and recycling. Like any emerging technology, 4D printing also brings to the fore numerous other risks, including possible dual-use or misuse for criminal or otherwise harmful purposes.

As with 3D printing, the problem of legal regulation remains overarching. Programmable matter prompts special concern for intellectual property law and patenting (particularly in terms of reproducibility). The question of responsibility, which often arises in debates regarding artificial intelligence and robotics, also looms large over 4D printing: which party is to blame, for instance, if an item or any one of its functions fails? Is it the manufacturer, the programmer, or the developer of the smart material employed?

These and other concerns must be integrated into the guidelines and regulatory frameworks that will come to govern 3D and 4D printing. Recent technological advances in material science, nanotechnology, and other fields have converged to unprecedented levels, enabling technologies such as programmable matter to become a real possibility. The world must be prepared to both welcome their benefits and, simultaneously, prepare to mitigate their potential risks.

Nayef Al-Rodhan *is a Philosopher, Neuroscientist and Geostrategist. He is a Senior Member of St. Antony's College, University of Oxford, UK, and Senior Fellow and Director of the Centre for the Geopolitics of Globalisation and Transnational Security at the Geneva Centre for Security Policy, Geneva, Switzerland. He is the author of The Politics of Emerging Strategic Technologies: Implications for Geopolitics, Human Enhancement and Human Destiny (sustainablehistory.com).*

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