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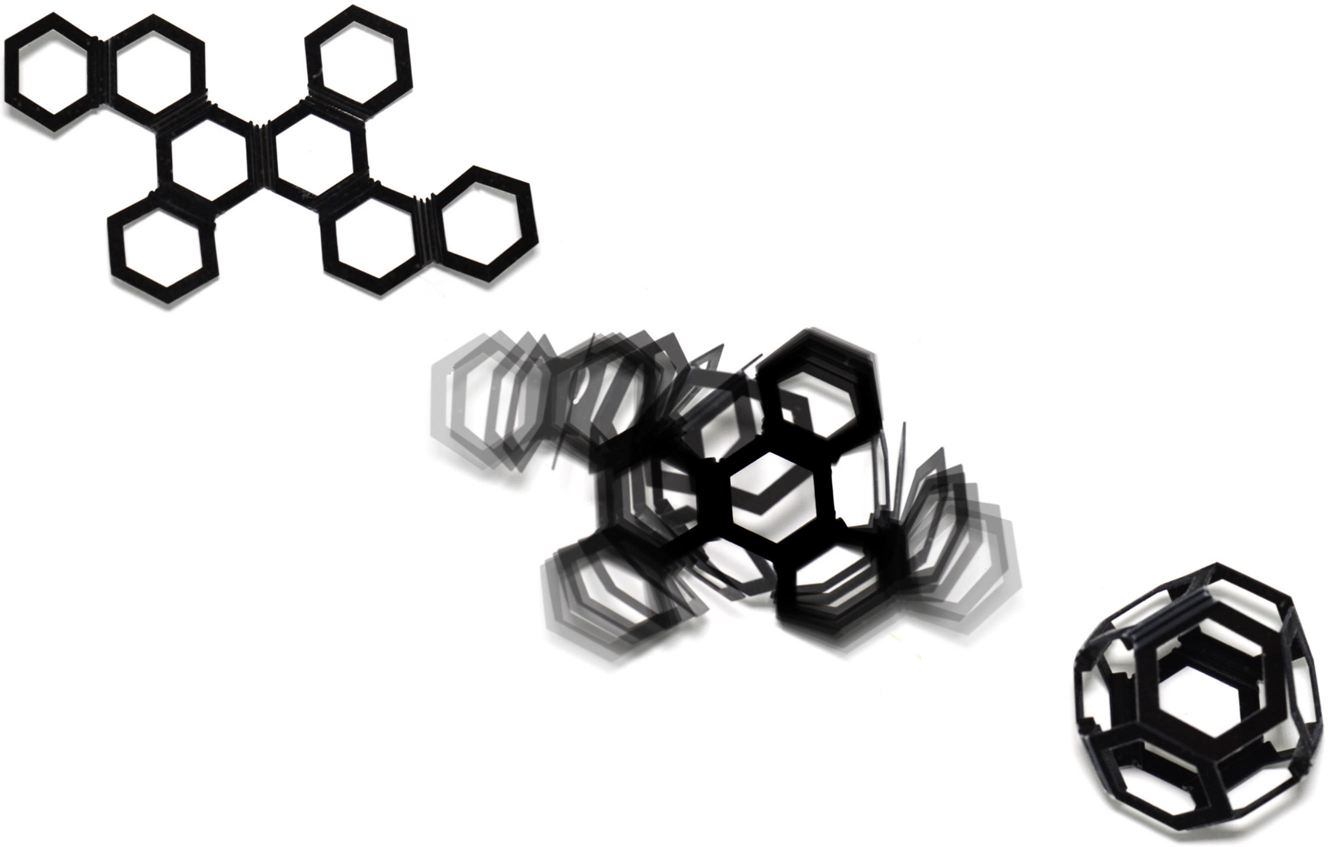
THE NEXT WAVE: 4D PRINTING
PROGRAMMING THE MATERIAL WORLD



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THE NEXT WAVE: 4D PRINTING
PROGRAMMING THE MATERIAL WORLD

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Cover: A 4D Printed flat surface was produced using the Stratasys Connex Multi-Material Printer. When dipped in water, the flat surface self-transforms into a rigid surface cube, without human intervention. Although a first step, this demonstrates the potential of 4D printing to create material objects that change form and function in response to external stimuli, whether a signal from a human or a reaction to changes in the environment (temperature, moisture, light, current, etc.). Image credit: Self-Assembly Lab, MIT + Stratasys Ltd. + Autodesk Inc.

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The Next Wave: 4D Printing and Programming the Material World

3D printing has been around for nearly three decades, but only in the last year has it captured the imagination of millions of people, including the president of the United States.[1, 2] Industry, government, and public awareness have reached a "tipping point," and now recognize 3D printing's current impact and future potential. Now a new disruptive technology is on the horizon that may take 3D printing to an entirely new level of capability with profound implications for society, the economy, and the global operating environment of government, business, and the public. Programmable matter (PM), here described as 4D printing (4DP), has the economic, environmental, geopolitical, and strategic implications of 3D printing while providing new and unprecedented capabilities in transforming digital information of the virtual world into physical objects of the material world.[3] The fourth dimension in 4D printing refers to the ability for material objects to change form and function after they are produced, thereby providing additional capabilities and performance-driven applications.

Imagine a world in which solid material objects can morph into new shapes or change properties at the command of an individual or in pre-programmed response to changing external conditions like temperature, pressure, wind, or rain. That world—in which things are not quite what they seem—is on the horizon. It is a world of potentially huge benefits, from airplane wings that change form in flight to furniture and even buildings that self-assemble and reassemble for different functions. Moreover, our planet's limited resources could be better conserved. Material objects could be recycled not by saving some of the materials such as plastic to be melted down and reused, but by commanding the object to decompose into programmable particles or components that then can be reused to form new objects and perform new functions. The long-term potential of PM/4DP thus could be a more environmentally sustainable world in which fewer resources are necessary to provide products and services to a growing world population and rapidly expanding global middle class.

While PM could have significant benefits for nations as well as businesses and individuals, it could also create new uncertainties and even insecurities, especially for policymakers. The Internet and social media have created an ever-widening sphere of activity outside government control in the virtual world. Now imagine a material world that can change in ways that are unpredictable by governments and potentially threatening to national security. While your bank account can be hacked and your identity stolen

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[1] While 3D printing is formally known as "additive manufacturing," the two terms are often used interchangeably and for this report the authors use 3D printing as the more popularly known term.

[2] President Barack Obama cited 3D printing in his February 2013 State of the Union as a technology that has "the potential to revolutionize the way we make almost everything."

[3] We recognize that some PM can be made without 4D printing, but we have conflated the terms PM and 4DP toward the goal of readability.

in cyberspace, your physical safety could be endangered in a world of PM. Morphable wings could be hacked to crash airplanes while buildings could be commanded to "disassemble" with you inside. Anticipating such dangers, however, should enable protective measures to be "baked-in" to PM rather than recognized only after the fact.[4] Some cybersecurity experts maintain that the structural vulnerabilities of the Internet could have been anticipated and designed out of the system from the beginning. Such considerations are even more paramount with the potential for the hacking of physical objects made by PM. Intellectual property (IP) rights could also become more complex, as products are able to morph from one form to another, thus directly challenging patent rights for multiple product lines.

While this new technology certainly qualifies the often-quoted quip that "any sufficiently advanced technology is indistinguishable from magic," policymakers need to understand the basics of this emerging technology and to get ahead of the curve on PM, as it offers both significant opportunities and unprecedented dangers.[5] It will take time and greater resources (researchers, manufacturing and measurement equipment, funding, etc.) before PM's full potential begins to be realized. In the meantime, there have already been successful prototypes proving PM's viability, and it is likely that PM will begin to appear in real-world applications in the next few years.

A Printable World

3D printing is a general-purpose technology that is being used in an extraordinarily wide range of applications—from potentially printing replacement human organs to wings of airplanes and even much of a nuclear weapon, potentially including the extraordinarily difficult-to-manufacture "implosion sphere." 3D printing builds objects layer-by-layer, thereby enabling the

Programmable Matter

Programmable matter (PM) is the science, engineering, and design of physical matter that has the ability to change form and/or function (shape, density, moduli, conductivity, color, etc.) in an intentional, programmable fashion. PM may come in at least two forms: (1) objects made of pre-connected elements that are 4D printed* or otherwise assembled as one complete structure for self-transformation, and (2) unconnected voxels** that can come together or break apart autonomously to form larger programmable structures. PM encompasses, yet goes beyond, a range of technological capabilities—including 3D printing, micro-robotics, smart materials, nanotechnology, and micro-electromechanical systems (MEMS), to name a few.

* 4D printing, where the fourth dimension entails a change in form or function after 3D printing, is one recent example of PM that allows objects to be 3D printed and then self-transform in shape and material property when exposed to a predetermined stimulus, such as being submerged in water or exposed to heat, pressure, current, ultraviolet light, or other energy source.

** A voxel is a volumetric pixel, often used to define the fundamental unit of digital space and Programmable Matter. Voxels can be both digital and physical. Digital voxels are computational representations in 3D models. Physical voxels may be comprised of materials as diverse as basic raw materials (e.g., titanium), nanomaterials, integrated circuits, biological materials, and micro-robotics, among others.

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[4] PM security concerns are analogous to ongoing discussions about the need for enhanced cybersecurity within the Internet of Things (IoT)–e.g., Haynes & Campbell, 2013, "Hacking the Internet of Everything," *Scientific American*, http://www.scientificamerican.com/article.cfm?id=hacking-internet-of-everything.

[5] Arthur C. Clarke, *Profiles of the Future*, (New York: Harper & Row, 1962).

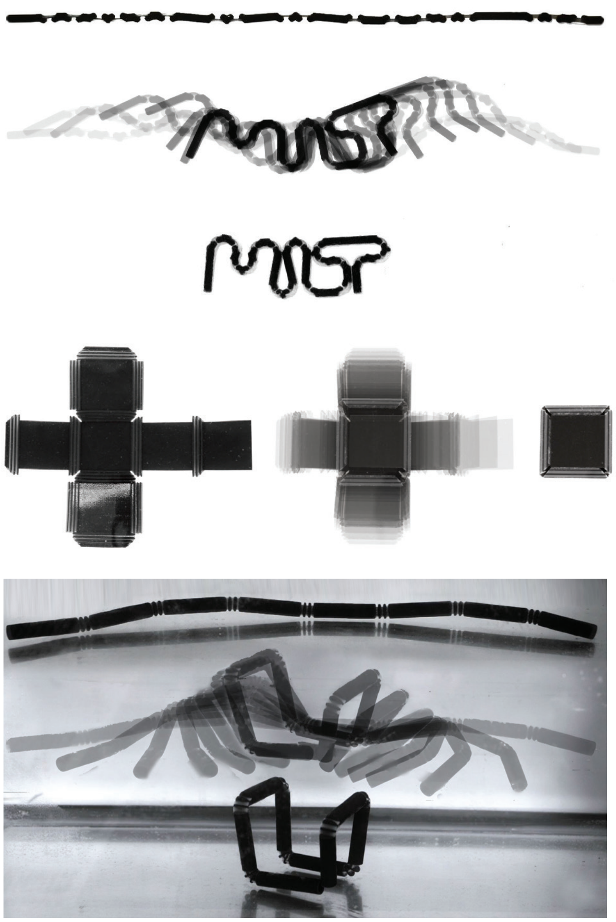

Figure 1. 4DP examples that show a single strand that self-folds into the letters "MIT," a flat surface that self-folds into a closed cube, and a single strand that folds into a wireframe cube. Developed by the Self-Assembly Lab, MIT; Stratasys, Ltd.; and Autodesk, Inc.

fabrication of virtually any geometry, including objects that are impossible to create using any other manufacturing means.[6, 7]

Programmable Matter at DARPA

The Defense Advanced Research Projects Agency (DARPA) ran the"Programmable Matter" program in 2007. This forward-thinking program had the goal of creating PM by shrinking robotics and thereby enabling new functionality at the millimeter scale, e.g., the width of a pencil. The DARPA report "Realizing Programmable Matter" laid out a multiyear plan for designing and constructing microscale robotics systems that could morph into larger military systems. An example achievement is the "**milli-motein**" (mechanical-protein) designed and built by MIT. Millimeter-sized components and a motorized design inspired by proteins created a system that can naturally fold itself into complex shapes. A group at Cornell also developed a **self-replicating reconfigurable robotic system**. Later, **micro-robotic systems** (M-bricks) were created that have the ability to move independently and relocate within a larger assembly.

A Programmable World

PM adds the capability of *programming* the fundamental materials used in 3D printing and is thus a logical complement and extension of 3D printing (see our formal definition of PM in box below). Making PM a reality has been made possible by the development, synergy, and convergence of a number of technologies. Substantial improvements have been made in 3D printing with the fabrication of 3D objects from metals, ceramics, plastics, and even multi-material capabilities. Smart materials are similarly getting better and more affordable, while computing and electronics continue to become smaller and cheaper. Introducing programmable capabilities into 3D-printed materials could enable robot-like capabilities embedded directly into the materials, without the need for energy-intensive and failure-prone electro-mechanical devices. Such capabilities could be greatly beneficial to society, but also open the potential for new risks.

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[6] Thomas A. Campbell, Christopher B. Williams, Olga S. Ivanova, Banning Garrett, "Could 3D Printing Change the World? Technologies, Potential and Implications of Additive Manufacturing," Strategic Foresight Report No. 1, October 2011, http://www.atlanticcouncil.org/images/files/publication_pdfs/403/101711_ACUS_3DPrinting.PDF.

[7] 3D printing is part of larger trend of digital fabrication. Hod Lipson (of Cornell University) writes in his book, "The next revolution after 3D printing will be the transition from analog to digital materials." [Hod Lipson, Melba Kurman, *Fabricated: The New World of 3D Printing* Indianapolis: Indiana: John Wiley & Sons, 2013].

Objects created today, including by 3D printing, are primarily designed to be stable and static—that is, they are unable to change their form or function after fabrication.[8] PM material would change this inert world into a dynamic one, enabling a wide range of capabilities—see box for comparative advantages of 3D printing vs. 4D printing. PM would allow changes in material properties (e.g., flexibility, porosity, conductivity, optical properties, magnetic properties), and it would create objects that could be assembled, disassembled, and then reassembled to form macroscale objects of desired shape and multifunctionality.

Examples of 4D Printing

One recent approach to PM is 4D printing. An example of 4D printed objects that were pre-programmed to respond to a stimulus—water—and change into other shapes is shown in Figure 1. The top figure demonstrates a 1D object morphed into a 2D object— when inserted into water, the snake-like object forms the letters "MIT." The bottom two figures demonstrate how one can also create self-folding cubes from both flat and wireframe structures. Other applications in Figure 2 demonstrate a single strand that self-transforms from the letters "MIT" into the letters "SAL," a flat surface that self-folds into a truncated octahedron, and a flat disc that self-folds into a curved-crease origami structure. These experiments were conducted by one of the authors (Skylar Tibbits) along with Stratasys, Ltd. and Autodesk, Inc. using Stratasys' Connex multimaterial printer and a new polymer developed to expand 150 percent when submerged in water. A new application was embedded into the Autodesk software, Project Cyborg, to simulate the dynamics of 4D printed objects and their material optimization.

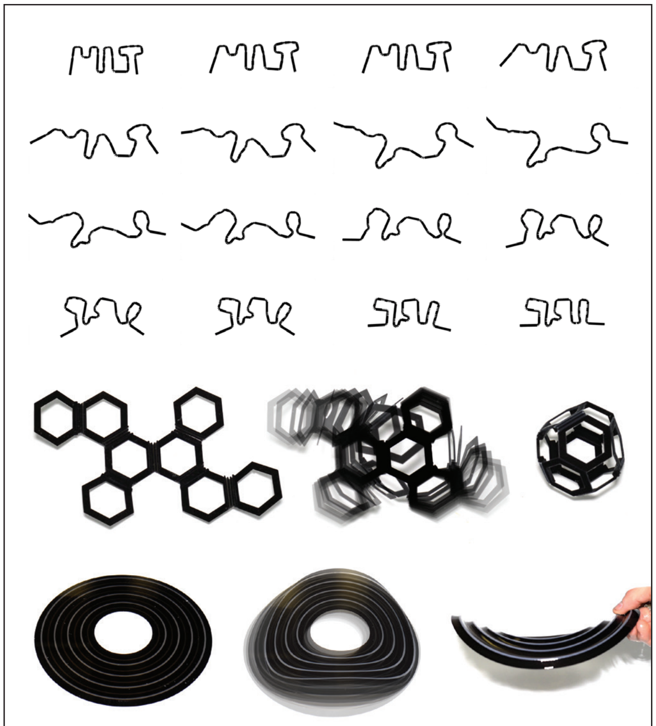

Figure 2. 4DP examples that show a single strand that self-transforms from the letters "MIT" into the letters "SAL"(Self-Assembly Lab), a flat surface that self-folds into a truncated octahedron, and a flat disc that self-folds into a curved-crease origami saddle structure. Developed by the Self-Assembly Lab, MIT; Stratasys, Ltd.; and Autodesk, Inc.

This technology has attracted substantial press attention around its potential for manufacturing.[9]

Another 4D printing technology involves embedding wiring or conducting parts into special compliant components during the 3D printing

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[8] A traditional solution toward enhanced capabilities is that of robotics, even micro-robotics—see box below for DARPA program description. While certainly promising in initial research, there are drawbacks and fundamental limitations that researchers encountered with micro-robotics, including fabrication expense, component failure, challenges in fabricating motors and batteries at the microscale, difficulty in interacting with micro-components for new programming and repair, and overall weight of fully assembled systems with numerous micro-robots.

[9] Tibbits, Skylar. 2013. '4D Printing: Multi-Material Shape Change', in Bob Sheil (ed), Architectural Design: High Definition, pp 116–121; John Breeden II, "3D printing is yesterday's news—time for 4D?," http://gcn.com/blogs/emerging-tech/2013/04/4d-printing.aspx; Robert Petterson, "What is 4D Printing?," http://quartsoft.com/blog/201304/what-is-4d-printing; "4D Printing: Multi-Material Shape-Change," http://additivemanufacturing.com/2013/04/07/4d-printing-multi-material-shape-change/.

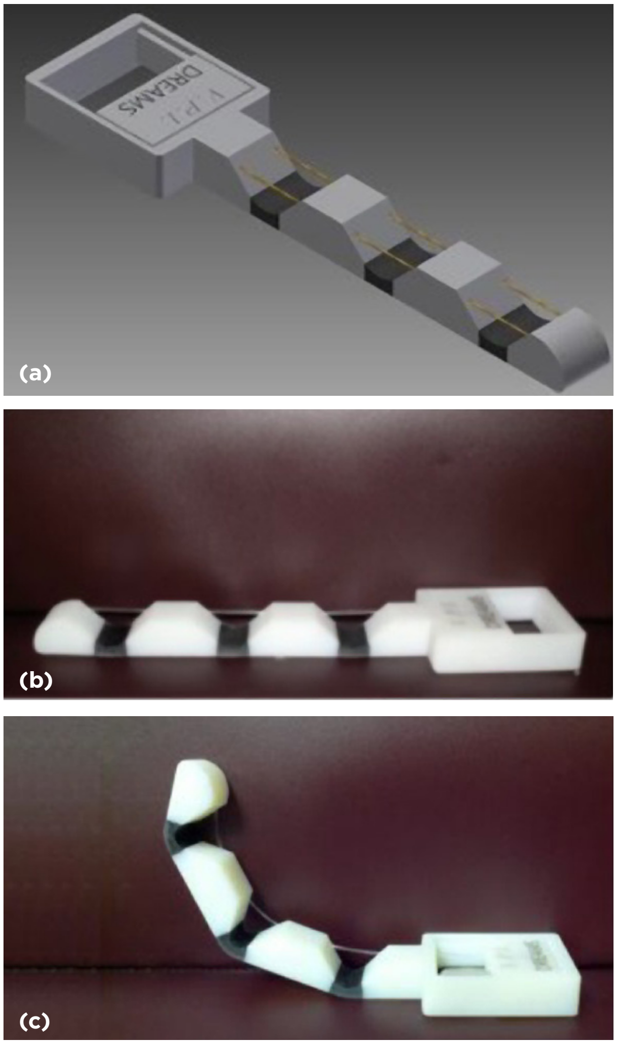

Figure 3. Robotic finger designed and created via in situ embedding with an additive manufacturing process: a) computer-aided design (CAD) representation, b) finger as-built (with embedded monofilament fiber), and c) finger actuated via a sliding joint.[10]

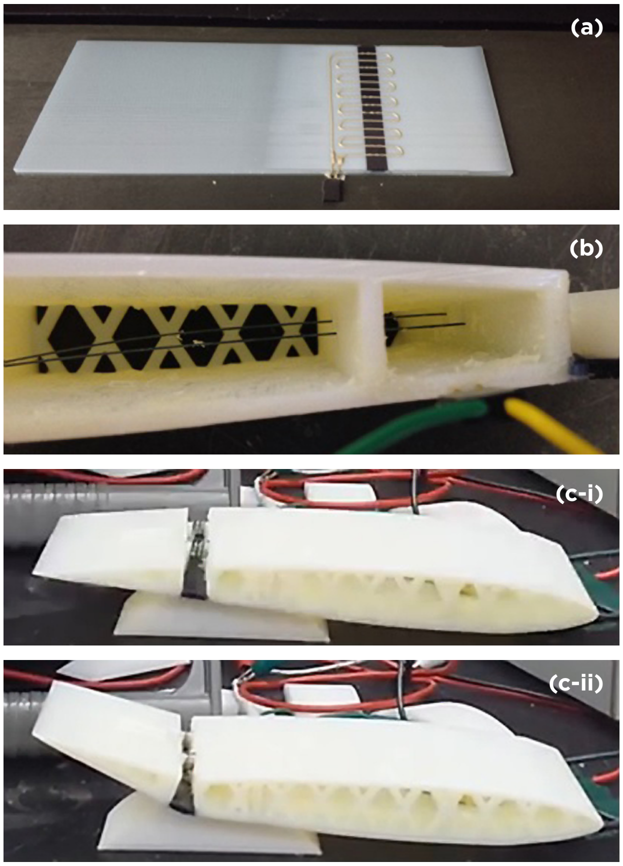

Figure 4. Integrated sensing and actuating wing flap manufactured via a materials jetting process: (a) Embedding plane and geometry of directly written conductor shown on build tray during the mid-print deposition step (DuPont 5021 conductive silver ink; conducting lines are 700 µm wide and 32 µm tall); (b) Detailed view of embedded, actuating shape memory alloy wire within final printed geometry; (c) Integrated sensing and actuating wing flap (i) before, and (ii) after electrical current application. Wing is 7” long, 2.5” deep, and 0.75” tall at its widest point.[11]

job. After the object is printed, the parts can be activated by an external signal to trigger full assembly actuation (e.g., Figure 3 and Figure 4). This approach has potential implications for areas such as robotics, furniture, and building construction.

Other 4D printing approaches include composite materials that can morph into several different, complicated shapes based on a different physical mechanism and heat activation.[12] Also, demonstrations have been made of materials that self-fold due to light exposure.[13]

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[10] Justin L. Stiltner, Amelia M. Elliott, and Christopher B. Williams, “A Method for Creating Actuated Joints via Fiber Embedding in a Polyjet 3D Printing Process,” 22nd Annual International Solid Freeform Fabrication Symposium, 2011.

[11] With permission from Dr. Christopher B. Williams, DREAMS Laboratory, Virginia Tech, http://www.dreams.me.vt.edu.

[12] Q. Ge, H.J. Qi, M.L. Dunn (2013), “Active materials by four-dimension printing,” *Applied Physics Letters, 103, 131901-131901-5*.

[13] Ying Liu, Julie K. Boyles, Jan Genzer, Michael D. Dickey, “Self-folding of polymer sheets using local light absorp-

Programmable Matter as Sensors

Embedding sensors into 3D printed objects would also open new avenues for PM. The insertion of nanomaterials into 3D printed objects can create multifunctional nanocomposites that can change in properties in response to electromagnetic waves—e.g., visible light and ultraviolet light.[14, 15] Figure 5 shows an example of what can be done with nanomaterials and a typical 3D printing resin.[16] When lit by visible light, the letters are gray, but when lit by ultraviolet light, the letters glow red. While this is a simple example, more complex capabilities are feasible with greater three-dimensionality and other nanomaterials. For example, sensors could be embedded into medical devices to test for extremes in blood pressure, insulin levels, and other important medical metrics.

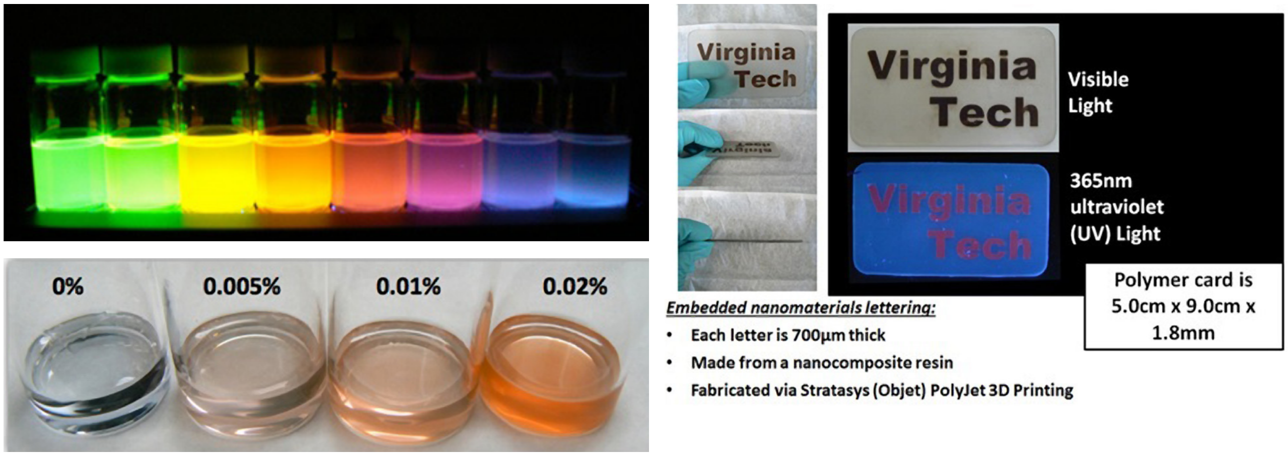

Figure 5. TOP–Cadmium selenide quantum dots (CdSe QDs) synthesized at Virginia Tech and suspended in toluene. Each vial contains a different size of QD (ranging from diameters of ~2.5 nanometers, dark green, to ~15.0 nanometers, dark blue), and thus emits a different color when under ultraviolet light. MIDDLE–As prepared nanosuspensions of photopolymer/CdSe QDs with different QD loadings (by weight percentage as listed); QDs in each vial are the same size. BOTTOM–Embedded quantum dot nanocomposites in a 3D printed part. The same part is shown under visible and ultraviolet (UV) lighting. Research is a joint effort by one author (Thomas A. Campbell) and Dr. Christopher B. Williams of Virginia Tech.

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tion," *Soft Matter*, 2012, 8, 1764-1769.

[14] "Nanotechnology is science, engineering, and technology conducted at the nanoscale, which is about 1 to 100 nanometers." http://www.nano.gov/nanotech-101/what/definition.

[15] Thomas A. Campbell, Olga S. Ivanova, "3D printing of Multifunctional Nanocomposites," *Nano Today*, 2013, Volume 8, 119-120.

[16] Cadmium selenide (CdSe) quantum dots are prepared synthetically via colloidal chemistry and embedded into a three-dimensional, business card sized, 3D printed object. Considered 'artificial atoms' as an assembly semiconducting material, quantum dots have the characteristic that their fluorescence is both light wavelength and size dependent. As shown in Figure 5, the same CdSe material, at different size scales, fluoresces in different visible wavelengths when lit by an infrared light source. This enables significant freedom in sensing capability.

More Capable Programmable Matter

Such demonstrations only just hint at the potential of PM. More complex assemblies, different nanomaterials and raw materials, and different activation energies (water, heat, light, etc.) could theoretically be utilized to create a potpourri of novel applications for PM. Much like one can build more complex structures with a variety of Lego^{TM} bricks—see Figure 6—only by having a wide collection of PM will a diverse set of capabilities for changing form and function be feasible.

One vision of the future is PM/4DP with a suite of multiple voxels with different forms and functions that are custom-designed, easily deposited, and then programmed for specific applications. Theoretically, one could have voxels made of metal, plastic, ceramics or any number of other materials. The potential can be better understood by reference to DNA-driven biological systems. In their recent book, Lipson and Kurman explain:

> Biological life is composed of twenty-two building blocks—amino acids—that arrange themselves in different permutations to give rise to a myriad of proteins and eventually life forms….This makes it possible for biological life forms to repair themselves. Animals and plants can consume each other and reuse the biomaterial because we are all made of the same relatively small set of just twenty-two building blocks. In the same way a pixel is a building block of an image, a bit is a unit of information, and an amino acid is a building block of biological matter, a voxel is a volumetric pixel (hence its name). The elementary units of physical matter are atoms. The elementary units of printed matter would be larger, a couple hundred microns, the size of a grain of sand. Like a few colors on an artist's palette, a few voxel types can take you far. If fewer than two dozen element types give rise to all biological life, a few basic voxel types can also open a large range of possibilities. To begin, let's combine rigid voxels and soft voxels. Using just those two types of voxels, it's possible to make hard and soft materials. Add conductive voxels, to make wiring. Add resistor, capacitor, inductor and

Figure 6. Diversity of bricks in Lego^{TM} store; Copenhagen, Denmark (photo by Thomas A. Campbell).

transistor voxels, to make electric circuits. Add actuator and sensor voxels and you have robots.[17]

Technical Challenges Ahead

Several PM technical challenges that need to be addressed in the coming years include (in no particular order):

- **Design**—How do we program future CAD software to encompass PM with multiscale, multi-element and dynamic components?[18, 19]
- **Materials**—How do we create materials with multifunctional properties and embedded logic capabilities?
- **Adhesions between voxels**—How can we ensure that adhesion among voxels is comparable to normally fabricated systems, while simultaneously allowing reconfigurability or recyclability after use?
- **Energy**—How can we generate, store, and use passive and abundant energy sources to activate individual voxels and PM?
- **Electronics**—How do we efficiently and effectively embed controllable electronics (or electronic-like capabilities) at the submillimeter scale?
- **Programming**—How do we program and communicate with individual voxels both physically and digitally? How do we program variable state-changes (3+ physical states)?
- **Adaptability to different environments**—How do we program and design environmentally responsive voxels?
- **Assembly**—What external forces would be needed to cause macro-scale self-assembly of voxels?
- **Standardization**—Can standards (e.g., as produced by ISO) be created to ensure seamless interaction among PM voxels and systems?[20]
- **Certifications**—Can PM systems be certified technically through normal channels, or will wholly new certifications be required (e.g., aircraft parts that require rigorous FAA certifications)?
- **Physical and cyber security**—How can we embed programmable capabilities into objects while still ensuring they are secure?
- **Affordable manufacturing techniques**—Can routine manufacturing of PM systems be made economically viable for small- and large-scale manufacturers?
- **Characterization**—How will we characterize dynamic systems of voxels? Will new metrology equipment be required?
- **Recycling**—How can we ensure the voxels can be disassembled and reconfigured for reuse or error-correcting for self-repair?

Of course, there are also fundamental limitations to PM based on the laws of physics. For example, conservation of energy and matter cannot be violated and voxel raw material cannot currently be changed from, say, titanium to plastics or ceramics; however, a material's property and behavior can easily be transformed.

These and other unknown challenges will need extensive research to pave the way for PM. Clearly, significant investment will be needed to make PM more technically feasible in numerous systems and thus widely adopted.

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[17] Hod Lipson and Melba Kurman, *Fabricated: The New World of 3D Printing*.

[18] Computer-aided design.

[19] Two authors (Thomas A. Campbell and Skylar Tibbits) recently attended a meeting to provide guidance to DARPA on "Rethinking CAD," which has the goal to advance software design and thus enable more complex, multimaterial, multifunctional 3D object fabrication.

[20] International Organization for Standardization, http://www.iso.org/iso/home.html.

Intellectual Property Implications of Programmable Matter

Intellectual property (IP) could be challenged by PM. Much like 3D Printing*, PM could make it difficult for consumers and lawyers to trace origins of products. Patents are founded on the irreproducibility of a given product. Via both 4D Printing and PM however, one could potentially make copies of objects with identical form and function, or guide the objects to make themselves. Legal implications for component failure could also become interesting with PM. Who would be responsible if a PM-fabricated component of an aircraft wing failed—the original manufacturer, the programmer, the producer of the new design or the smart material? Just as with 3D Printing, such questions should be considered as the new technologies of PM begin to be embraced by designers and manufacturers.

* Thomas A. Campbell, William J. Cass (2013), "3-D Printing will be a Counterfeiter's Best Friend—Why we need to rethink intellectual property for the era of additive manufacturing," Scientific American, **http://www.scientificamerican.com/article.cfm?id=3-d-printing-will-be-a-counterfeiters-best-friend**

A Disruptive Technology

History is replete with examples of new technologies disrupting global commerce and geopolitics (e.g., the telegraph and the Internet). 3D printing is already having such effects. PM/4DP will likely be more transformative as it enables 3D printed objects to not only be custom-tailored for their application, but also to be programmable for post-fabrication changes in shape and function—including adapting to changing environments—and then to be recycled, repaired, or reconfigured when no longer of use.

Programmable matter will have a wide range of military applications and implications. The US Army and Navy are already developing 3D printing for spare parts in the field or on ships as well as for design and manufacture of cheaper, lighter, and more effective weapons systems.[21, 22, 23] Not having to transport and store thousands of spare parts near the battlefield or on ships will save time, expense, and, for ships, space for warfighters. PM could take such defense benefits to an even higher level. Imagine having a bucket of voxels on a Hummer or submarine. If a part breaks or a specific tool is needed while away from the home base, one merely takes a collection of the voxels and programs them to form into that part or tool. When the tool is no longer needed, it can be commanded to disassemble itself; thereby leaving the voxels available for making other tools or parts. Beyond parts and tools, PM could enable uniforms that adjust insulation and cooling to the surrounding environment and the biometrics of the individual; and, perhaps the ultimate vision of some PM researchers, the morphable robot that can shapeshift around and through obstacles as imagined in the movie *Terminator 2*.[24]

Other examples further illustrate the potential of PM:

- Buildings or structures that takes on life-like qualities.[25, 26] Instead of casting brick or pouring concrete, we instead pour a building-size volume of PM into a foundation, and then program the

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[21] "Additive Manufacturing: Implications to the Army Organic Industrial Base in 2030," Col. Jon R. Drushal, 2013, http://public.carlisle.army.mil/sites/Landpower/Shared%20Documents/Drushal%20CRP.pdf.

[22] M. Llenza, "3-D printing will streamline the Navy's supply chain—and much more," *Armed Forces Journal*, May 2013, http://www.armedforcesjournal.com/print-when-ready-gridley/.

[23] "Need Ships? Try a 3-D Printed Navy," *Wired*, April 2, 2013, http://www.wired.com/dangerroom/2013/04/3d-printed-navy/?utm_source=feedburner&utm_medium=feed&utm_campaign=Feed%3A+wired%2Findex+%28Wired%3A+Top+Stories%29.

[24] The Army recently awarded $855,000 to look into dynamic camouflage and other possibilities with 4D printing. See http://www.engineering.pitt.edu/News.aspx?id=2147508574.

[25] Chris Arkenburg, "Cities of the Future: Built by Drones, Bacteria, and 3D Printers," http://www.fastcoexist.com/1681891/cities-of-the-future-built-by-drones-bacteria-and-3-d-printers.

[26] Michio Kaku, *Physics of the Future: How Science Will Shape Human Destiny and Our Daily Lives by the Year 2100*, (New York: Doubleday, 2011) Anchor, 2012.

PM elements to ‘grow’ into a full building with all the accoutrements of embedded electricity, plumbing, and information technology. Recent work by MIT on morphable cube-shaped PM could be a precursor to a new form of construction bricks for space applications or quickly deployable structures.[27]

- Airplane wings that change shape in flight to enhance performance as a result of a signal sent to the wings or an automatic response of the wing to changing air pressure, temperature, or other environmental conditions to minimize air resistance or maximize lift.
- Tires that change shape/traction depending on road/weather conditions and driving demands, as an automatic response from sensors.
- Shoes/clothes/gear that adapt to the user’s performance and the changing environment, thus offering enhanced performance, fit, or style.
- Furniture that is packaged flat, but self-assembles in your home after purchase; such assembly could be automatic as one opens the packaging or as the result of a signal sent by the owner. Similarly, one could have furniture that could disassemble itself for easier moving or different functionality.
- Self-healing materials, e.g., micro-cracks self-healing on aircrafts, roads, bridges, and equipment.
- Self-disassembling materials for recyclability or information security and protection of confidential materials.
- Bridges and roads that adapt to varying load conditions or weather.
- Smart valves, connections, and sensors for infrastructure lines that can fundamentally respond to control flow-rates and are adaptable for resilience and protection.

Such is the world that is on the horizon with PM. A wide range of technologies are coming together now—software and design tools, new materials, advanced machines, information, and communication technology (ICT) capabilities, big data, advanced algorithms, and 3D printing—to open new possibilities that were only science fiction just a few years ago.

Conclusions

Programmable matter and 4D printing certainly have the potential to appear “magical,” but they are grounded in real engineering and science research that is only now emerging due to recent technological advances. Several near-term applications of PM are on the horizon. Nevertheless, we note that more substantial applications will require significant infusion of resources (greater funding, training of researchers, federal centers devoted to PM research, development of new fabrication and measurement equipment, etc.). As with 3D printing, the United States has the opportunity to lead in 4D printing research and applications, but this will require increased and sustained funding and policy support for programmable matter research and development.

Through programmable matter and 4D printing, there exists the potential to create a new class of disruptive technologies comparable to—and far beyond—3D printing. It does not seem fanciful to imagine a world in which a new form of matter formation could enable form and function modification at the flip of a switch—a world in which one could make intelligent Lego™-like bricks that can assemble, become multifunctional and morphable into almost any 3D object, and disassemble at will. Such a future—with both its promises and challenges—awaits us.

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[27] “4D printing and programmable matter,” http://boingboing.net/2013/04/05/4d-printing-and-programmable-m.html&ct=ga&cad=CAcQAhgAIAAoATAAOABAorKBi-wVIAVgBYgVlbi1VUw&cd=6OJEMOZolfA&usg=AFQjCN-HzR9p3dT_SMvq_6GwM2MOHBn-s4Q.

4D Printing/Programmable Matter—Steps Beyond 3D Printing[28]

Advantages over Traditional Manufacturing[29]	**3D Printing (3DP)**[30]	**4D Printing (4DP)**
Increased product design freedom	Traditionally, product designs are constrained by the limitations of the machines that will produce them. An immediate benefit of 3DP is the ability to create complex shapes that cannot be produced by any other means. Fundamentally, 3DP processes allow designers to selectively place material only where it is needed, thus saving weight and material by creating bone-like structures.[31] The design freedom thus extends to the internal structure of a product, not just its outside shape.	4DP could offer the ultimate state of design freedom. With the ability to shape-shift physical objects from one form to another at will, 4DP goes one step beyond the design of static objects by adding dynamics and performance capabilities into the material itself. Preliminary results shown by MIT already demonstrate significant adaptability from nearly any shape to any other. Further, 4DP will allow parts to adapt their geometry and structure, on-demand, as forces and requirements change, further increasing material efficiency.
No cost for complexity	In traditional manufacturing, the more complicated a product, the more expensive it is to manufacture. In 3DP, "fabricating an ornate and complicated shape does not require more time, skill or cost than printing a simple block."[32] 3DP is a "single tool" process—no matter the desired geometry, there is no need to change any aspect of the process. This, in effect, makes shape complexity free—there is no additional cost or lead time between making an object complex or simple.	Once processes are streamlined, 4DP would require no additional cost or time to embed actuation, logic, and sensing into printable parts. This has significant implications for electronics-like capabilities and manufacturing/assembly processes for robotics and other electromechanical devices.
On-demand production in batches of one	A given manufacturing facility is capable of printing a huge range of products without retooling—and each printing run can be customized without additional cost. Moreover, products can be printed on demand without the need to build-up inventories of products and spare parts.	Similar to 3DP, products can be customizable in batches of one or more since 4DP won't add complexity or cost to the printing process itself.

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[28] This comparison only offers contrasts of 4DP vs. 3DP and does not specifically note those inclusive solely of 4DP. For example, 4DP offers the potential of recyclability, unique actuation and sensing, and multiple functions/reconfigurations for products/systems, all of which 3DP does not necessarily provide. The categories are also not meant to be comprehensive, but merely a set of examples to illustrate how 4DP could go beyond 3DP.

[29] *See also* "The Ten Principles of 3D printing" in *Fabricated*, pp. 20-24.

[30] 3D printing points are taken from the recent report *3D Printing: More Opportunities Than Dangers*, Banning Garrett, Lawrence Livermore National Laboratory.

[31] For example, see the DREAMS Lab of Virginia Tech, www.dreams.me.vt.edu.

[32] *Fabricated*, op. cit., p. 20.

4D Printing/Programmable Matter *(continued)*

Advantages over Traditional Manufacturing[29]	3D Printing (3DP)[30]	4D Printing (4DP)
From mass production to mass customization	Since printing one-of-a-kind products is no more costly than mass-producing the same object, 3DP technology enables the design and efficient manufacture of personalized products. This unique capability of 3DP is driving a transition from mass production to mass customization, where each item produced is customized for the user at little or no additional production cost.	Personalizing products would be a particular strength of 4DP. Several examples discussed in the main text highlight the capabilities of 4DP—universal spare parts, morphable electronics, user-responsive products, environmentally adaptive structures, etc. — all these and more may be possible with 4DP.
Simplification of manufacturing process	Since 3DP creates physical products directly from a standardized digital file, these computer-controlled processes require a low level of operator expertise and reduce the amount of human interaction needed to create an object. In fact, the processes often operate unmonitored. This allows for overnight builds and dramatically decreases the time and human precision to produce products—thus reducing the time between design iterations.	With 4DP, the manufacturing processes become even simpler than 3D printing. Extremely simple structures can be printed and then activated by external stimulus to change into complex functional structures and systems. Further, the printed part can now be produced, shipped, and left unmonitored while it senses and responds physically to its surrounding environment.
From making prototypes to manufacturing finished products	As material properties and process repeatability improved, 3DP technologies' use has evolved from solely creating prototypes to fabricating parts for functional testing, to creating tooling for injection molding and sand casting, and finally, to directly producing end-use parts.	Once 4DP materials have been created and embedded with dynamic functionality, finished products would be more the expectation than the exception with 4DP.
Eliminating supply chains and assembly lines for many products	The final product—or large pieces of a final product such as a car—can be produced by 3DP in one process, unlike conventional manufacturing in which hundreds or thousands of parts are assembled. And those parts are often shipped from dozens of factories from around the world—factories that may have in turn assembled their parts from external suppliers.	Similar to 3DP, supply chains and assembly lines could dramatically change or, in some cases, become obsolete with widespread adoption of 4DP.
Designs, not products, move around the world	Digital files can be printed anywhere by any printer that meets the designed parameters. The Internet first eliminated distance as a factor in moving information instantly across space. Just as a written document can be emailed as a PDF and an identical copy printed in 2 dimensions, an "STL" design file can be sent instantly to the other side of the planet via the Internet and printed as an identical 3-dimensional physical object. A digital file of bits can be rematerialized into a physical object composed of atoms.	Designs and programs would digitize our world with 4DP. The ability to take a collection of voxels anywhere in the world, access the program in the cloud and then instruct those voxels to form a multifunctional object offers a game-changing design-to-production cycle.

4D Printing/Programmable Matter *(continued)*

Advantages over Traditional Manufacturing[29]	**3D Printing (3DP)**[30]	**4D Printing (4DP)**
Instant production on a global scale	The representation of physical artifacts with a digital file enables rapid global distribution of products, thus potentially transforming product distribution much in the same way the MP3 did for music. The digital file can be sent to any printer anywhere that can manufacture any product within the design parameters of the file—i.e., which can print the size, resolution, and materials called for in the file.	Voxels and their respective designs and programs would decouple the need for traditional manufacturing on site through 4DP. Digital files would be sent anywhere in the world with the right collection of voxels to enable matter formation on demand. Recycling of voxels into other 3D objects, as described in the main text, could reduce the need for further shipping of additional voxels.
A major boost to innovation	The rise of 3DP will likely lead to the reinvention of many old products, as well as to extraordinary new innovations. Since 3DP processes can print virtually anything that can be designed on a computer—thus eliminating the limitations posed by machine tools, stamping, and molding—engineers and designers will no longer be limited in their designs because of previous manufacturing technologies. New hybrid materials, such as nanocomposites via 3DP, are being researched to take design and material properties manipulation even further.	4DP would inherently boost innovation. Design and fabrication of voxels would become a new industry as new materials and functionality are enabled beyond what exists today with traditional manufacturing processes. We are only just scratching the surface in imagining the possibilities of 4DP. The innovation created by 4DP and related disruptive industries and military applications will be profound.
Stimulation of new interest in design and engineering	The direct relationship between the designer and the product—a relationship that has been constrained by the past 200 years of industrial production methods—will be similar to the relationship between software engineers and their products. As a result, interest in engineering and industrial design has increased, as has happened in the field of computer science and software engineering over the last half century.	Freeing the student to think at the level of multifunctional dynamic objects and then full material programming through 4DP would stimulate a new generation of engineers and scientists. An entirely new field of “matter programmers” may emerge, similar to today’s computer programmers. Further, students and researchers can now learn and discover through dynamic and intelligent physical models—offering new educational models for the future.

About the Authors

Thomas A. Campbell is a nonresident senior fellow with the Atlantic Council and associate director for outreach and research associate professor with the **Institute for Critical Technology and Applied Science** (ICTAS) at Virginia Tech. His research specializations are future trends—disruptive/emerging/converging technologies, and national security; and advanced materials—additive manufacturing/3D printing, programmable matter, and nanomaterials. Dr. Campbell joined Virginia Tech from ADA Technologies, Inc. in Littleton, Colorado, where he was senior research scientist and nanotechnology program manager. Prior to ADA, he was with Saint-Gobain, Inc. as a research scientist, and an Alexander von Humboldt research fellow at the University of Freiburg, Germany. He holds a PhD and an MS in aerospace engineering sciences from the University of Colorado at Boulder (funded by a NASA Graduate Student Research Program fellowship) and a BE with honors in mechanical engineering from Vanderbilt University.

Skylar Tibbits is the director of the Self-Assembly Lab at MIT and the founder of a multidisciplinary research-based practice, SJET LLC. Mr. Tibbits is also faculty in MIT's Department of Architecture, teaching masters- and undergraduate-level Design Studios and co-teaching "How to Make (Almost) Anything" at MIT's Media Lab. Having studied architecture and computer science, Mr. Tibbits' research focuses on self-assembly and programmable material technologies for industrial applications in the built environment. He was recently awarded a 2013 Architectural League Prize, The Next Idea Award at Ars Electronica 2013, the Visionary Innovation Award at the Manufacturing Leadership Summit, a **2012 TED Senior Fellowship** and was named a Revolutionary Mind in SEED Magazine's 2008 Design Issue. He has designed and built large-scale installations around the world and exhibited at the Guggenheim Museum NY and the Beijing Biennale, and lectured at MoMA and SEED Media Group's MIND08 Conference.

Banning Garrett is the senior fellow for innovation and global trends for the Atlantic Council's Strategic Foresight Initiative (SFI). He directed the SFI's long-term cooperation with the US National Intelligence Council in production of the NIC's unclassified, quadrennial long-term global trends assessments, including *Global Trends 2030: Alternative Worlds*, released in December 2012. He also directed SFI's program on the foreign policy implications of emerging technologies, and the US-China Joint Assessment of long-term global trends project. Dr. Garrett was founding executive director of the Institute for Sino-American International Dialogue at the Graduate School of International Studies, University of Denver in 2007 and was director of the Initiative for US-China Cooperation on Energy and Climate at the Asia Society's Center for US-China Relations from 2008 until early 2009 when he rejoined the Atlantic Council. Prior to joining the Council in 2003, Dr. Garrett was a consultant for twenty-two years to the Department of Defense and other US government agencies carrying on a strategic dialogue with China. He was also a senior associate at the Center for Strategic and International Studies, a founding board member of the US Committee for Security Cooperation in the Asia Pacific, and an adjunct professor of political science at The George Washington University. Garrett received his BA from Stanford University and his PhD from Brandeis University.

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