A NEW FRAMEWORK FOR A NOVEL LATTICE: 3D PRINTERS, DNA FABRICATORS, AND THE PERILS IN REGULATING THE RAW MATERIALS OF THE NEXT ERA OF REVOLUTION, RENAISSANCE, AND RESEARCH

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I. INTRODUCTION

The Legos of the universe are within reach.[1] Self-contained, accessible machines are rearranging matter at every level of structural organization.[2] Shapes thought expressible only through mathematics are somehow finding form.[3] Digitized models and simulations look and act more realistic than ever before. The world of matter and the world of information are increasingly symmetric and convergent—able to mimic and translate between one another. How is this happening?

Computer-aided design ("CAD") is capable of modeling a large subset of reality, from molecules to skyscrapers.[4] Recent advances in computer-aided manufacturing ("CAM"), including accessible 3D printers and DNA synthesizers, are catching up in capability.[5] Ordinary people are being empowered to make

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1. *See* Matstermind, *LEGObot 3d Printer*, INSTRUCTABLES, http://www.instructables.com/id/LEGO-bot-3d-printer (last visited Mar. 6, 2015).

2. *See infra* Part III.

3. HOD LIPSON & MELBA KURMAN, FABRICATED: THE NEW WORLD OF 3D PRINTING 176 (2013).

4. *See, e.g.*, 4D-xD Solutions for Sketchup, *4D Construction Sketchup Plugin— Scenes in 4D*, YOUTUBE (May 27, 2009), https://www.youtube.com/watch?v=mRxtDx9fzYc; *Molecular Modeling in CAD*, MACHINE DESIGN (Sept. 28, 2006), http://machinedesign.com/archive/molecular-modeling-cad.

5. *See infra* Part III.

extraordinary things, from toys that resemble family members[6] to bespoke organisms.[7] While the technology is still in its infancy, some believe that it will give rise to a new industrial revolution that returns the means of production to individuals.[8] CAM is already stimulating fresh art[9] looks to be a tool of valuable scientific research.[10]

Speculation is mounting as to the technology's disruptive effect. There has been a stream of surprises for lawmakers, from especially well-made counterfeit paintings[11] to functional plastic handguns.[12] Scholars have proposed a number of regulation points, some focused on the digital world and others on the physical.[13] One of the latter strategies is to regulate raw materials that form the underlying structure of problematic objects.[14]

When CAM's accessibility and power incite raw material regulation, policymakers will encounter challenges that require a new framework to responsibly analyze the next era's infinite shades of objects and materials. First, this Article fundamentally re-characterizes CAM, not only as a technology that translates information into reality (bits-to-atoms), but one that transitions one organization of matter to another (atoms-to-atoms). New forms of matter that arise from these accessible tools could cause policymakers to entertain regulation of raw materials. Secondly, this Article describes three regulatory challenges in such an approach. There may be a mismatch in regulatory perspective that

6. Rebecca Borison, *All the Ways Your Kids Can Now Customize Their Toys*, BUSINESS INSIDER (Sept. 2, 2014, 12:53 PM), http://www.businessinsider.com/3d-printing-toys-2014-8.

7. Michael Gelphman, *Programming *Living* Things: The Next Generation of Computing?*, KCITP (Mar. 9, 2014, 3:35 AM), http://www.kcitp.com/2014/03/09/andrew-hessel-compute-midwest-conference-kansas-city (recording Andrew Hessel speaking at Compute Southwest Conference).

8. *See infra* Part IV.

9. *See infra* Part V.

10. *See infra* Part VI.

11. Andrew Liszewski, *3D Printing and Scanning Can Now Produce Near Flawless Art Forgeries*, GIZMODO (Aug. 26, 2013, 12:30 PM), http://gizmodo.com/3d-printing-and-scanning-can-now-produce-near-flawless-1201525111.

12. Andy Greenberg, *Meet the 'Liberator': Test-Firing the World's First Fully 3D-Printed Gun*, FORBES (May 5, 2013, 5:30 PM), http://www.forbes.com/sites/andygreenberg/2013/05/05/meet-the-liberator-test-firing-the-worlds-first-fully-3d-printed-gun.

13. Deven R. Desai & Gerard N. Magliocca, *Patents, Meet Napster: 3D Printing and the Digitization of Things*, 102 GEO. L.J. 1691, 1714–16 (2014).

14. *Id.*

fails to respect individuals as manufacturers and researchers. There is a heightened risk to innovation when restricting materials that form the basis or building blocks for other innovations. And regulators will face extreme difficulty in classifying and specifying objects when everything, including raw materials, can be unique. Finally, this Article presents a specialized object theory for understanding the atom-to-atom transition of CAM. It describes best practices to protect the foundational raw materials of the next era of revolution, renaissance, and research.

Part II describes the development of CAD and CAM as interfaces, CAM's ability to translate bits (information) to atoms (reality), and an increasing symmetry and convergence between the information world and the physical world. Part III introduces CAM as a process not only of translation but of transition between organizations of matter. It describes the structure of matter as levels of organization in a hierarchy and explains CAM's rapidly developing capability to define every level of that hierarchy.

Part IV introduces the Next Industrial Revolution in which CAM, and especially 3D printers, is causing a shift in the means of production to individuals. Part V describes a new renaissance in art, fashion, and cuisine, along with the new capability to reflect personality in customized things. Part VI presents CAM's potential, especially in conjunction with accessible distributed computing, to enable valuable research by individuals and small groups. Part VII explains the current fears of democratized creation such as the destruction of intellectual property and creation of weapons.

Part VIII proposes a specialized object theory to approach both "finished" objects and "raw materials," which may become increasingly difficult to distinguish. Part IX introduces three primary challenges in regulating raw materials and applies the specialized object theory to provide guidelines to protect essential or promising raw materials that will define the new era.

II. TRANSLATION

In the 1950s, information theorists concluded that matter and information are synonymous.[15] They postulated that information was a physical thing as measurable as mass or flux,

15. JAMES GLEICK, THE INFORMATION: A HISTORY, A THEORY, A FLOOD 7–11 (2011).

with its smallest unit being a "bit," which is the amount of information needed to distinguish between two alternatives—an up or down, a one or zero.[16] Every collection of matter is merely a bunch of bits, from particles to planets, and the universe is a giant state-processing computer.[17] The view from the ivory tower is that the tower is made of information.

Standing at the tower's base, looking up, it still appears to be ivory. If not theoretically discrete, the physical and information worlds are practically segregated for most people—a shadow of what is "real" rather than a reflection or extension. Still, as data pervades, it is easier to see that the worlds are connected.

There are portals, or "interfaces," that bridge the information-reality divide.[18] They translate atoms to bits or bits to atoms, sometimes abstracting during the process.[19] In fact, the success of computing and the expansion of the digital domain can be largely attributed to interfaces. Programming languages, a system for translating raw machine language into human-readable instructions, changed computers from mere machines for churning out artillery trajectories to essential tools of science and business.[20] The graphical user interface ("GUI") went a step further, making computers accessible to a vast number of non-technical people by abstracting software code into familiar metaphors, such as desktops and file folders.[21]

There are other interfaces with more power to influence the physical world. Around the same time that Apple introduced the GUI to the public in 1984,[22] Digital Equipment Corporation and others developed relatively small and inexpensive "minicomputers" that, unlike costly mainframes, could be economically dedicated to a single task.[23] Computers began to

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16. *Id.* at 9–10.

17. *Id.* at 10.

18. *See Media Lab Creates Center for Bits and Atoms with NSF Grant*, MIT NEWS (Nov. 28, 2001), http://newsoffice.mit.edu/2001/bits-1128.

19. *Id.*

20. PAUL E. CERUZZI, A HISTORY OF MODERN COMPUTING 24–27, 79–84 (I. Bernard Cohen & William Aspray eds., 2d ed. 2003).

21. *See* Jeremy Reimer, *A History of the GUI*, ARS TECHNICA (May 4, 2005, 1:40 AM), http://arstechnica.com/features/2005/05/gui.

22. *Id.*

23. *Smaller Is Better*, Exhibit to *Minicomputers*, COMPUTER HISTORY MUSEUM, http://www.computerhistory.org/revolution/minicomputers/11/332 (last visited Feb. 20, 2015).

monitor reaction chambers and automate factory floors.[24] In addition to coordinating the physical world, they started shaping it. Minicomputers were used to direct cutting tools along a programmable tool path using a process called computer numeric control ("CNC").[25] CNC made it possible to precisely carve curves that were easy to describe but difficult to make;[26] a small step toward theory-reality convergence.

Most CNC processes work by subtracting material from a work piece.[27] But one bit-to-atom interface of the 1980s, called stereo lithography, was fundamentally different. It was built by adding material layer by layer, each layer fusing to form a three-dimensional object.[28] As long as the shape was within the machine's resolution, that shape could be any geometry, no matter how complex.[29] It was one of the best ways yet that reality could mimic information. But it was too early for "additive manufacturing." Stereo lithography, and later developed additive technologies, remained behind industry doors, quietly building prototypes next to the rest of the cumbersome CNC equipment.[30]

The GUI, our window into the world of information, has proliferated to the point where we have portholes in our smartphones and peepholes in our "wearable tech." But at the beginning of the twenty-first century, the doors that allowed information to take form in atoms, arguably the most powerful interfaces, remained the pretension of industry. They were not fit for small-scale production or lay experimentation. As computing power steadily rose, the garage entrepreneur could create his or her vision with CAD. Unprecedented processing speeds tightened

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24. Michael Churchman, *CNC Programming and Computer-Aided Manufacturing/Design*, UDEMY BLOG (Apr. 8, 2014), https://blog.udemy.com/cnc-programming.

25. *Id.*

26. *See generally* Yoram Koren, *Interpolator for a Computer Numeric Control System*, c-25 IEEE TRANSACTIONS ON COMPUTERS 32 (1976) (comparing increase in curve accuracy through CNC processes versus pre-computing techniques).

27. *CNC Machining*, MFG.COM, http://www.mfg.com/manufacturing-knowledge-center/mechanical/cnc-machining-quotes (last visited Mar. 26, 2013).

28. Elizabeth Palermo, *What Is Steriolithography?*, LIVESCIENCE (July 16, 2013, 2:39 AM), http://www.livescience.com/38190-stereolithography.html.

29. *Id.*

30. *See Technology Mapping: The Influence of IP on the 3d Printing Evolution*, CREAX (July 14, 2014), http://www.creax.com/2014/07/technology-mapping-influence-ip-3d-printing-evolution.

the digital mesh around surface models and rendered tantalizing digital pinups. The information world was getting much better at mimicking reality. But it was too expensive to wrest the vision from bits. For most, timid emissaries conducted exchange between worlds: the keyboard, the inkjet printer, and the business card scanner.

In 2005, additive manufacturing emerged under the popular synonym "3D printing."[31] A project called RepRap that aspired to make a machine that could copy itself[32] began to experiment with the technology. Other open source communities followed.[33] After a key patent expired in 2009, additive manufacturing poured into the public domain.[34] The price of 3D printers dropped dramatically while quality increased.[35] Most consumer-available 3D printers continue to print low-resolution plastics, but sophisticated metal 3D printers are accessible through online printing services.[36] "Makerspaces" and "hackerspaces" offer membership-based access,[37] and 3D printers are showing up in office supply stores,[38] public libraries, and elementary schools.[39]

Additive manufacturing can build items using a variety of materials, including plastic, ceramics, composites, and metals like stainless steel and gold.[40] New 3D printers can build items in

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31. LIPSON & KURMAN, *supra* note 3, at 11.

32. *See* Adrian Bowyer, *RepRap*, VIMEO (June 17, 2009, 10:57 AM), https://vimeo.com/5202148.

33. *See, e.g.*, *Home*, FAB@HOME, http://fabathome.org (last visited Apr. 1, 2012).

34. *See* CREAX, *supra* note 30.

35. *See* Agam Shah, *3D Printer Price Drops Could Lure Home Users*, PCWORLD (Apr. 4, 2014, 4:10 PM), http://www.pcworld.com/article/2140360/3d-printer-price-drops-could-lure-home-users.html.

36. *See, e.g.*, *About Us*, SHAPEWAYS, http://www.shapeways.com/about?li=footer (last visited Mar. 6, 2015); I.MATERIALISE, http://i.materialise.com (last visited Mar. 6, 2015).

37. CHRIS ANDERSON, MAKERS: THE NEW INDUSTRIAL REVOLUTION 18 (2014) (placing the number of shared production facilities just under one thousand); *see, e.g.*, HACKER DOJO, http://www.hackerdojo.com (last visited Mar. 6, 2015); NOISEBRIDGE, https://www.noisebridge.net (last visited Mar. 6, 2015); TECHSHOP, http://techshop.ws (last visited Jan 20, 2015).

38. Mike Senese, *Staples Announces In-Store 3-D Printing Service*, WIRED (Nov. 29, 2012, 1:10 PM), http://www.wired.com/2012/11/staples-goes-3-d.

39. *See* LIPSON & KURMAN, *supra* note 3, at 153–54.

40. Pamela J. Waterman, *3D Printing's New Materials, Part 2: Metal*, DESKTOP ENG'G (Nov. 1, 2014), http://www.deskeng.com/de/3d-printings-new-materials-part-2-metal; Pamela J. Waterman, *3D Printing's New Materials: Plastics, Ceramics, Composites and More*, DESKTOP ENG'G (Oct. 1, 2014), http://www.deskeng.com/de/3d-printings-new-materials-plastics-ceramics-composites.

carbon fiber and Kevlar,[41] and print objects that are magnetic[42] and conductive.[43] Competing teams are working to employ nanomaterials like graphene.[44] There is also a movement to use widely available resources. For instance, the homemade Solar Sinter 3D printer focuses sunrays to make glass sculptures from dune sand.[45] The additive manufacturing materials market is rapidly expanding, and is estimated to grow at a compound annual rate of 20 percent, to over one billion dollars by 2019.[46]

The 3D printer is the lodestone of a new "maker" movement.[47] However, additive manufacturing is just one of many digital-to-physical interfaces with growing power, accessibility, and proficiency. The collection of these devices is referred to as CAM.[48] Traditional CNC tools, including mills, routers, and laser cutters, are being miniaturized into "desktop" versions.[49] Makerspaces provide industry-scale, bit-to-atom interfaces from automatic quilters to plasma cutters.[50] Perhaps far beyond the capability to make products, CAM tools may also be able to make life itself.

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41. *Materials*, MARKFORGED, https://markforged.com/materials (last visited Mar. 6, 2015).

42. Whitney Hipolite, *ProtoFlux's Magnetic Filament Allows for Incredible 3D Printed Data Storage & More*, 3DPRINT.COM (Nov. 25, 2014), http://3dprint.com/26823/protoflux-magnetic-filament.

43. Bridget Butler Millsaps, *Functionalize Launches Kickstarter Campaign for Super Conductive Filament for 3D Printing of Electronics*, 3DPRINT.COM (Nov. 10, 2014), http://3dprint.com/22669/functionalize-kickstarter.

44. *See, e.g.*, Kyle Maxey, *American Graphite to Develop Graphene 3D Printing Material*, ENGINEERING.COM (Apr. 26, 2013), http://www.engineering.com/3Dprinting/3DprintingArticles/ArticleID/5649/American-Graphite-to-Develop-Graphene-3D-Printing-Material.aspx.

45. Markus Kayser, *Solar Sinter*, MARKUSKAYSER.COM, http://www.markuskayser.com/work/solarsinter/ (last visited Mar. 6, 2015).

46. Davide Sher, *3D Printing Materials Market to Surpass $1 Billion Within 5 Years*, 3D PRINTING INDUS. (Dec. 9, 2014), http://3dprintingindustry.com/2014/12/09/3d-printing-materials-market.

47. *See generally* ANDERSON, *supra* note 37, at 20, 86; MARK HATCH, THE MAKER MOVEMENT MANIFESTO 87 (2014); Thomas MacMillan, *On State Street, "Maker" Movement Arrives*, NEW HAVEN INDEP. (Apr. 30, 2012, 11:00 AM), http://www.newhavenindependent.org/index.php/archives/entry/make_haven/id_46594.

48. *CAM / Computer-Aided Manufacturing*, SIEMENS, http://www.plm.automation.siemens.com/en_us/plm/cam.shtml (last visited Feb. 15, 2015).

49. ANDERSON, *supra* note 37, at 55–56.

50. *See, e.g.*, Vishal, *New Machines Are About to Come Online!*, MILWAUKEE MAKERSPACE (Feb. 6, 2015), http://milwaukeemakerspace.org/tag/plasma-cutter.

The new interfaces may allow individuals or small groups to research biology. Additive manufacturing is already used to deposit cells to build living tissue.[51] Even more surprising, small machines could make genetic engineering accessible by allowing keyboard strokes to be translated into DNA.[52] Organic chemistry, the discipline used to make pharmaceuticals and other molecules, may not be far behind. Indeed, there are proposals for setting up chemical synthesis in 3D printed "reactionware."[53]

We should prepare for a steady stream of products from information-to-reality interfaces that are bizarre vis-à-vis the present. One giant 3D printer is erecting apartment buildings[54] while another reaches ten-micron resolution.[55] Additive manufacturing can build pre-assembled products,[56] such as a clock with all of its gears in position,[57] and may be able to produce finished circuits.[58] Some believe that in the coming decades almost anything could be the product of a moderately accessible CAM device.

Each generation of CAM manifests more intricate and theoretical models. Each generation of CAD models reality more precisely. This mutual mimicry creates symmetry.[59] At the same

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51. Sean V. Murphy & Anthony Atala, *3D Bioprinting of Tissues and Organs*, 32 NATURE BIOTECHNOLOGY 773 (2014).

52. Andrew Hessel, *The Dark Side of the Double Helix: When Good Molecules Do Bad Things*, TED[x] MARIN, http://www.tedxmarin.org/2012-speakers (last visited Mar. 6, 2015).

53. Lee Cronin, *Print Your Own Medicine*, TED (June 2012), http://www.ted.com/talks/lee_cronin_print_your_own_medicine.

54. *See* Michelle Starr, *World's First 3D-Printed Apartment Building Constructed in China*, CNET (Jan. 19, 2015, 7:05 PM), http://www.cnet.com/news/worlds-first-3d-printed-apartment-building-constructed-in-china.

55. *See* LIPSON & KURMAN, *supra* note 3, at 70.

56. *Id.* at 21.

57. Duncan Graham-Rowe, *3-D Printing for the Masses*, MIT TECH. REV. (July 31, 2008), *available at* http://www.technologyreview.com/Infotech/21152/?nlid=1244&a=f.

58. Pieter Hermans, *How Could the Electronics Industry Use 3D Printing?*, 3D PRINTING ELECTR. CONF. (Jan. 17, 2014), http://www.3dprintingelectronicsconference.com/3d-printing-electronics-conference/how-could-the-electronics-industry-use-3d-printing.

59. The information world and the physical world will never be perfectly symmetrical. The information world can create models that do not conform to the physical laws of our universe. At the same time, reality cannot be perfectly modeled. For example, the wave function cannot be solved precisely for any atom other than hydrogen with a single electron. *See* N. H. MARCH, W.H. ET AL., THE MANY-BODY PROBLEM IN QUANTUM MECHANICS 1 (1967) ("It is well known, even in classic mechanics, that the problem of interacting particles presents great difficulties when exact solutions are sought. Likewise, in quantum mechanics, there is hardly a single worthwhile problem with realistic interactions which we can solve precisely."). *See generally Many-body Problem*,

time, CAM and "reality capture" technologies, like medical imaging, breach the barrier: 3D scanners pull bits into atoms and 3D printers push them back out. Similarly, DNA can be sequenced, transmitted thousands of miles as electronic bits, and rebuilt.[60] Not only are these worlds becoming symmetric, they are converging.

CAM, especially as implemented in 3D printers and DNA fabricators, is a talismanic technology. But it is not merely a method that translates bits to atoms, it is also fundamentally a process that shifts matter from one state to another. Matter, and the process by which it is reorganized, will become central to CAM.

III. TRANSITION

Atoms are boring in isolation. It is their organization that gives rise to the rich properties in the objects around us,[61] from the elasticity of spandex to the hardness of sapphires. That organization is a set of relationships among other objects, and that organization occurs on many hierarchical levels.[62] Carbon and oxygen form carbonate, carbonate and calcium form calcite, calcite forms limestone, and finally, limestone is arranged into a pyramid. While CAM currently adjusts the shape of one material at one level, it will expand to every level of the hierarchy. The hierarchy will not only become an important concern for creators but a critical factor in regulation formulated by policymakers.

The boundaries between organizational levels, artificial and fuzzy, are crucial tools of classification and modeling.[63] Atoms, the root of the hierarchy, are seldom isolated. At a first level of

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WIKIPEDIA, http://en.wikipedia.org/wiki/Many-body_problem (last modified May 8, 2014) ("[T]he wave function of [a quantum system with more than two particles] . . . usually makes exact or analytical calculations impractical or even impossible. Thus, many-body theoretical physics most often relies on a set of approximations [making it] among the most computationally intensive fields of science.").

60. *See* Hessel, *supra* note 52.

61. IVAN AMATO, STUFF: THE MATERIALS THE WORLD IS MADE OF 8 (1997) ("The hard-won insight that the vast menagerie of materials in the world is a result of a small pantry of elements, that the personality of each material is the result of an inner hierarchy of chemical and physical structures, has become the principle of a new alchemy practiced by those people known as material scientists.").

62. *See, e.g.*, Roderic Lakes, *Materials with Structural Hierarchy,* 361 NATURE 511, 511 (1993); AMATO, *supra* note 61, at 166.

63. *See* Lakes, *supra* note 62, at 512.

organization they combine to form small molecules; for example, a pharmaceutical compound or the repeating cell of a crystal. Small compounds can also include monomers—molecules that can be chained to form a polymer—sometimes thousands or hundreds of thousands of units long.[64] Biological monomers include the four base pairs that make up DNA and the twenty amino acids that comprise proteins.[65]

Macromolecules are a level higher and polymers are an important member of the class—familiar man-made polymers include nylon and Kevlar.[66] Natural polymers include strands DNA and RNA, protein structures, such as wool, and polysaccharides like chitin of an insects' carapace.[67] Biological polymers may have additional structure, such as the uniform double helix, the hydrogen bonding interactions that bind strands of spider silk together, or the complex fold of an enzymatic protein.[68] Nanotechnology is a broad category of highly engineered molecules, for example, carbon nanotubes, which can also be included at this scale.[69]

A number of intermediate levels follow, sometimes stacking until visible to the unaided eye. What appears to be smooth metal may actually be a cascade of microscopic grains with chaotic arrangement at one level and periodic arrangement at another.[70] Some polymers, on the other hand, may be randomly arranged from the molecular level all the way to becoming a familiar shape like a plastic filament.

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64. *Id.*

65. *See* Meyers et al., *Biological Materials: Structure and Mechanical Properties*, 53 PROGRESS MATERIALS SCI. 1, 1 (2008).

66. *See* J. Preston, *Man-Made Fibre*, ENCYCLOPAEDIA BRITANNICA, http://www.britannica.com/EBchecked/topic/361113/man-made-fibre (last visited Mar. 6, 2015).

67. *See* Meyers et al., *supra* note 65.

68. Leslie K. L. Cheng & Peter J. Unrau, *Closing the Circle: Replicating RNA with RNA*, COLD SPRINGS HARBOR PERSP. BIOLOGY 1, 5 (2010).

69. Some structures associated with nanotechnology form part of the hierarchy of matter. For example, self-assembling RNA and carbon nanotubes. However, this article does not include within its description of the new era self-assembling nanorobots or similar technologies. *See* Jason Wejnert, *Regulatory Mechanisms for Molecular Nanotechnology*, 44 JURIMETRICS J. 323, 323–29 (2004) (discussing fears surrounding advanced nanotechnology).

70. *See* Kay Geels, *The True Microstructure of Materials*, STRUERS, *available at* http://www.struers.com/resources/elements/12/2474/35art2.pdf; *see also,* AMATO, *supra* note 61, at 242–43.

At some point, an object appears "complete," that is, having compartmentalized utility or meaning. The complete object may stand alone. Or it might be incorporated into an assembly with even more organization like the Eifel Tower or a multicellular organism. Even purification of a substance can be considered a level of organization. Purification may be critical for that substance to act as a basis for subsequent levels of structure. No matter how an organization is effected or at what level, that collection of matter is potentially a "raw" material for a higher level and yet a "finished" object in its own right.

The organization on each level has the potential to impart new properties to any of the levels above.[71] The evolutionary deletion of a single oxygen-hydrogen pair turned tangled RNA into regimented, efficient DNA magnitudes more effective at managing the use, retention, and replication of genetic information.[72] An alloy's harness and brittleness is determined not only by its atomic composition, but also by microstructure established by factors such as the rate at which the metal is cooled.[73] In the modern era, we are discovering that strategic impurities, sometimes introduced into a material in mere parts per million, can cause dramatic results (and utility) in the object made with that material.[74] Things in a higher level of organization sometimes appear startlingly different because of emergent properties of its constituents.[75]

CAM, until recently, has only affected the organization of matter to a limited degree. The first generation of CAM acted upon a single, lifeless, uniform material.[76] Exhilarating

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71. *See* Roderic Lakes, *Materials with Structural Hierarchy*, 361 NATURE 511, 511 (1993).

72. Michael P. Robertson & Gerald F. Joyce, *The Origins of the RNA World*, COLD SPRINGS HARBOR PERSPECTIVES BIOLOGY, May 2012.

73. *See* Martin Tarr, *Metal Basics*, U. BOLTON, http://www.ami.ac.uk/courses/topics/0131_mb (last visited Mar. 17, 2015).

74. *See* Michal Meyer, *Industrial Vitamins*, CHEM. HERITAGE FOUND. (2012), http://www.chemheritage.org/discover/media/magazine/articles/30-1-industrial-vitamins.aspx.

75. P. W. Anderson, *More Is Different*, 177 SCIENCE 393, 393 (1972) ("The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear . . . .").

76. *See* William Harris, *How 3-D Bioprinting Works*, HOWSTUFFWORKS, http://health.howstuffworks.com/medicine/modern-technology/3-d-bioprinting1.htm

geometries—one additional level of structure—were made of materials deplete with indented structure on lower levels.[77] Contemporary CAM works with raw materials that have more interesting atomic composition and microstructure, for example, carbon fiber.[78] But even these materials are an incremental advance.

CAM's future is much more ambitious. In the abstract, organization is CAD and CAM's forte—first, leveraging a computer to model an organization of matter, and second, reorganizing raw material to conform to the model. An object is modeled based on a combination of the information related to the smaller pieces of matter that the object is composed of along with the information that describes the relationships among those smaller objects. Growing digital storage capacity, especially demonstrated by distributed computing, is able to retain massive amounts of this information. This new capability allows us to move beyond descriptions of matter that are understandable by the human memory, or simple extension of human memory, such as blueprints. While some eagerly await long-standing materials to be adapted to 3D printing, CAM is preparing a fundamental departure from twenty-first century material science and engineering. The first indication of the technology's shift is its burgeoning capability to work with several materials simultaneously.

Additive manufacturing is building in heterogeneous substances, for example, by incorporating electrical leads into plastic.[79] Complete circuits do not appear far off.[80] Of even greater importance, materials are beginning to mix during the building process, changing their microstructure. It has been long known that nanoscale arrangement of atoms in a material matters to its macroscale properties, but now we are able to control these

(last visited Mar. 6, 2015) (explaining that materials were fairly weak through the 90s, that the first use of cells on a 3D printed scaffold occurred in 1999).

77. *Id.* For example, many of the materials used were anything that could be turned into a paste for direct deposition or could be powdered and "sintered" with a laser.

78. *NovaCopy to Sell Mark One, the World's First & Only Composite 3D Printer*, MARKET WIRED (Feb. 10, 2015, 2:00 PM), http://www.marketwired.com/press-release/novacopy-to-sell-mark-one-the-worlds-first-only-composite-3d-printer-1990553.htm.

79. *See* LIPSON & KURMAN, *supra* note 3, at 23.

80. Hermans, *supra* note 58.

properties directly.[81] For example, some machines can blend two polymers to create material of varying consistencies,[82] and NASA is experimenting with printing gradient alloys.[83] The result is infinite shades of materials—an "unexplored palette."[84]

At the same time, CAM devices are collectively spanning the entire hierarchy. CAD can already model molecules and skyscrapers. CAM is catching up with some CAM devices transforming matter at the root of the hierarchy and others at the tip. Biological CAM is already there. The power to synthesize DNA almost covers all levels of biological organization because, equipped with the right blueprints, life assembles itself. As one researcher puts it, DNA is a type of software that makes its own hardware.[85]

As CAM becomes more powerful, instances of CAM will be able to use a wider range of materials on several organizational levels. The pinnacle of power, perhaps, would be a ubiquitous machine able to arrange individual atoms at any scale. It is unlikely such a device will ever exist. But it might be emulated by coordinating machines. For example, in a level of indirection, DNA fabricators may be able to make single-cell organisms that produce many unusual chemical compounds for polymerization.[86] Together, CAM devices of differing scope may form an assembly line from the bottom of the hierarchy to the top, an entire ecology or economy of production and consumption.

In the slow progression toward CAM taking complete control over organizing matter, there will be "holdout materials." Holdout materials are those materials that are useful in forming higher levels of organization but which cannot be made using accessible CAM. For example, extreme pressure may be required

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81. NAT'L SCI. & TECH. COUNCIL, MANUFACTURING AT THE NANOSCALE: REPORT OF THE NAT'L NANOTECHNOLOGY INITIATIVE WORKSHOPS 2002–2004 1–2 (2007) *available at* http://www.whitehouse.gov/files/documents/ostp/NSTC%20Reports/NNI_Manufacturing_at_the_Nanoscale%202004.pdf.

82. Terry Wohlers, *Additive Manufacturing 101: Part III,* WOHLERS ASSOCIATES (May/June 2010), http://www.wohlersassociates.com/MayJun10TC.htm.

83. David Sher, *NASA Is 3D Printing Multiple Metals Simultaneously with New Radiant Deposition Technique*, 3D PRINTING INDUSTRY (Aug. 7, 2014), http://3dprintingindustry.com/2014/08/07/nasa-3d-printing-multiple-metals-simultaneously-new-radiant-deposition-technique.

84. *See* LIPSON & KURMAN, *supra* note 3, at 23.

85. *See* Hessel, *supra* note 52.

86. *Id.*

to shift a lattice from one crystal state to another, or exceptional heat to coax a compound into a strained atomic configuration. Despite their importance to democratized manufacturing they will continue to be produced in centralized factories and laboratories. They will remain in the "old-world" where creation is more easily regulated.

Building in the entire structural domain, with multiple blended materials, startling properties will move up the organizational chain to emerge in the finished product. It is even more difficult to predict how the new bit-to-atom interfaces will change our economy or society, especially as these devices become smaller, cheaper, more powerful, and begin to work together. Focus remains on the novel shapes additive manufacturing can produce and the way it can make physical things act more like information. These basic abilities are showing their first economic impact.

IV. REVOLUTION

A third industrial revolution[87] may emerge from bit-atom symmetry and convergence. Objects will increase in customization and utility. Prototyping and development will accelerate. Business, and by extension the economy, may become more flexible and efficient. Individuals and small groups will have tools to inflate novel markets with unprecedented innovations.

Things will materialize faster. Additive manufacturing's original use case, for example, was to quickly build mockup industrial designs and architectural models.[88] Designers can manifest ideas quickly and at low cost, exploring a wider range of alternatives and speeding products to market.[89] However, despite its usefulness in prototyping, CAM's ability to make mature products will be what defines the revolution.

Put simply, it will all just fit better. CAM devices are general-purpose machines that can build distinct objects back-to-

87. For usage of this term, see Chris Anderson, *In the Next Industrial Revolution, Atoms Are the New Bits*, WIRED (Jan. 10, 2010, 12:00 PM), http://www.wired.com/2010/01/ff_newrevolution; *A Third Industrial Revolution*, THE ECONOMIST (Apr. 21, 2012), http://www.economist.com/node/21552901.

88. Banning Garrett, *3D Printing: New Economic Paradigms and Strategic Shifts*, 5 GLOBAL POLICY 70, 71 (2014).

89. *See* LIPSON & KURMAN, *supra* note 3, at 30–33.

back without retooling.[90] Shrinking economies of scale lead to costless customization;[91] this means economic, small-run production for idiosyncratic communities or individuals.[92] Working with 3D scanning, anything that interacts with the body, such as prosthetics,[93] will mate perfectly.[94]

Customized medicine will expand from prosthetics. Exact joint replacements can be printed from MRI scans[95] and printed organs are in development.[96] Surgeons can practice a procedure on a rubbery printout of a patient's body.[97] Food printing may enable personalized nutrition.[98] There are proposals for individualized cancer treatment using special viruses made by DNA fabricators.[99] Somewhat more speculative, chemical printers may be able to formulate and compound medications.[100]

It might all work better, too. Of course, custom things will be adapted to their circumstance. But computer optimizations can be directly built,[101] as can "biomimicking" objects that imitate efficient natural structure.[102] New designs may be more modular[103] and composed of fewer pieces when complex shapes simplify

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90. Ashlee Vance, *3-D Printing Spurs a Manufacturing Revolution*, N.Y. TIMES (Sept. 13, 2010), http://www.nytimes.com/2010/09/14/technology/14print.html?_r=2&ref=printers.

91. Bill Conerly, *The Economics of 3-D Printing: Opportunities*, FORBES (Nov. 3, 2014, 10:50 AM), http://www.forbes.com/sites/billconerly/2014/11/03/the-economics-of-3-d-printing-opportunities.

92. ANDERSON, *supra* note 37, at 61 (discussing the ability within the "Sims" videogame to create a virtual home with endless customization possibilities).

93. *See* LIPSON & KURMAN, *supra* note 3, at 33.

94. Duann, *Revealing Dita Von Teese in a Fully Articulated 3D Printed Gown*, THE SHAPEWAYS BLOG (Mar. 5, 2013), http://www.shapeways.com/blog/archives/1952-Revealing-Dita-Von-Teese-in-a-Fully-Articulated-3D-Printed-Gown.html.

95. Avi Reichental, *What's Next in 3D Printing*, TED (Mar. 2014), http://www.ted.com/talks/avi_reichental_what_s_next_in_3d_printing?language=en#t-226184.

96. Anthony Atala, *Printing a Human Kidney*, TED (Mar. 2011), https://www.ted.com/talks/anthony_atala_printing_a_human_kidney.

97. Rachael King, *Printing in 3D Gets Practical*, BLOOMBERG BUS. (Oct. 6, 2008), http://www.businessweek.com/stories/2008-10-06/printing-in-3d-gets-practicalbusinessweek-business-news-stock-market-and-financial-advice.

98. *See* Reichental, *supra* note 95.

99. Andrew Hessel, *Synthetic Virology*, TEDXDANUBIA (May 2014), http://www.tedxdanubia.com/videos/synthetic-virology:andrew-hessel-at-tedxdanubia-2014.

100. *See* Cronin, *supra* note 53.

101. *The Printed World*, ECONOMIST (Feb. 10, 2011), http://www.economist.com/node/18114221.

102. *See* LIPSON & KURMAN, *supra* note 3, at 186–87.

103. *Id.* at 184.

overall design. Some assemblies will even be consolidated into a single piece that is stronger and lighter.[104] CAM could extend product life by giving replacement parts an eternal existence in CAD files,[105] now a common technique for maintaining vintage automobiles.[106]

Despite widespread customization, the revolution may mean less waste.[107] Additive manufacturing, with the exception of discarded structural scaffolding, only uses the material needed for the final product.[108] In some cases, the amount used is 90 percent less than subtractive manufacturing where ground-away material is thrown away.[109] Vehicles can be made lighter, saving fuel,[110] and recyclable materials can take on new functions prompting wider use.[111] For many of the reasons that CAM could be an important environmental technology, it will also help enterprise.

Without re-tooling costs, products can be made-to-order, yielding low overhead despite vast digital inventory.[112] CAM generally presents predictable and linear manufacturing costs,[113] making it easy for businesses to evaluate cost and risk.[114] Similarly, the technology makes it easier to estimate material usage and production speed.[115] Distribution is instant when CAD files move as impulses "on the wire."[116] This might encourage local

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104. *Id.* at 33; Lisa Harouni, *A Primer on 3D Printing*, TED (Nov. 2011), https://www.ted.com/talks/lisa_harouni_a_primer_on_3d_printing.

105. *Id.*

106. Kyle Maxey, *Jay Leno and 3D Printing*, ENGINEERING.COM (Oct. 11, 2012), http://www.engineering.com/3DPrinting/3DPrintingArticles/ArticleID/4861/Jay-Leno-and-3D-Printing.aspx.

107. *But see* LIPSON & KURMAN, *supra* note 3, at 212–13 (citing fears about a new mindset where people rapidly build and discard objects or create a "debugging mentality" to the prototyping process).

108. *Id.* at 22.

109. *Id.*

110. *Id.* at 204.

111. *Id.* at 209.

112. *Id.* at 204.

113. ANDERSON, *supra* note 37, at 87–88.

114. *Id.*

115. Peter Zelinski, *Why Is Additive Manufacturing Important?*, MOD. MACH. SHOP (Sept. 10, 2012), http://www.mmsonline.com/articles/why-is-additive-manufacturing-important.

116. LIPSON & KURMAN, *supra* note 3, at 205.

manufacturing, which could shorten supply chains.[117] And these advantages to enterprise will translate into the larger economy.

Supply and demand may speed to equilibrium,[118] which may result in a more efficient economy.[119] CAM efficiently distributes technical knowledge.[120] Specifically, a 3D printer allows for greater specialization of the workforce.[121] Users can focus on design from within the familiar GUI without understanding the more complex CAM interface. This is especially important for biological exploration, where genetic engineering can be appreciated at a gene level without a need to know the complex chemistry that assembles macromolecules.[122]

Overall, this revolution could have a profound effect on the United States and the world. Some have predicted that CAM can repatriate the United States' lost manufacturing base.[123] Conversely, developing countries may be able to "leap-frog" industrial development,[124] not unlike rapid expansion of wireless communications in nations otherwise lacking infrastructure.[125] An economy equipped with CAM could advance much faster,[126] and could be a key technology in space exploration by enabling efficient manufacturing on Mars.[127] In total, the Third Industrial Revolution will be a return to cottage industry while retaining the industrial advances of the twenty-first century. It will be

117. *Id.* at 21.

118. An economy comprised of CAM general-purpose devices will be able to respond to rising demand or shift to other purposes in response to rising supply.

119. CORY DOCTOROW, MAKERS (2009) (describing a dystopian maker society where physical things are so rapidly copied that the worldwide economy collapses).

120. Todd Grimm, *The Real Benefits of Additive Manufacturing*, TCT (Nov. 23, 2012), http://www.tctmagazine.com/blogs/grimmblog/the-real-benefits-of–additive-manufacturing.

121. *See* LIPSON & KURMAN, *supra* note 3, at 22 (describing 3D printing as "zero skill manufacturing").

122. *See* Hessel, *supra* note 52 ("If you can type, you can be a genetic engineer today.").

123. *See* Garrett, *supra* note 88, at 71.

124. *Id.*

125. *See* Matthew Wall, *Africa's Mobile Boom Powers Innovation Economy*, BBC NEWS (June 30, 2014, 7:02 PM), http://www.bbc.com/news/business-28061813.

126. Garrett, *supra* note 88, at 71.

127. *See* Dina Spector, *In the Future, Astronauts Could Print out Their Moon Bases*, BUSINESS INSIDER (Feb. 4, 2013, 2:05 PM), http://www.businessinsider.com/3d-printed-moon-base-2013-2.

"somewhere between mass production and a local farmer's market."[128]

As economies of scale fall, there will also be another fundamental economic change. The means of production will pass to the individual. Labor—computers, abstracted by the GUI, amplify individual efforts. Software and global collaboration augments design and engineering skill. Capital—crowd funding, microloans, and cryptographic currency provide new channels of funding. And now, equipment—accessible bit-to-atom interfaces are the catalyst that transforms raw material.[129] As one author explains: "The great opportunity is . . . to be both small and global. Both artisanal and innovative. Both high-tech and low cost."[130]

It is too early to tell whether CAM will become a staple of the home. But the comparison to botched expert analysis of personal computers is tempting. When asked to find a use for computers in the home, IBM's and AT&T's brightest minds came up with a recipe card manager.[131] Chris Anderson, author of leading books on the revolution, characterizes the movement's hesitant beginning: "[l]ike [personal computers], the first users are a little lost."[132] But the number of self-identifying "makers" is growing rapidly.[133] As people return to their roots of making things, they are first finding CAM as a medium for expression.

V. RENAISSANCE

CAM can make anything art. Every surface is a potential canvas subject to industrial design or sculpture. With limitless geometry, style has been liberated and fashion is changed forever.[134] Models clad in wild shapes[135] strut runways in baroque

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128. LIPSON & KURMAN, *supra* note 3, at 27.

129. *Cf.* ANDERSON, *supra* note 37, at 26 ("If Karl Marx were here today, his jaw would be on the floor. Talk of 'controlling the tools of production': you (you!) can now set factories into motion with a mouse click.").

130. *Id.* at 16.

131. *Id.* at 56.

132. *Id.* at 58.

133. *See* LIPSON & KURMAN, *supra* note 3, at 48.

134. *See* Duann, *supra* note 94.

135. Erica Fink, *Models Hit Runway in 3D Printed Clothing*, CNN MONEY (Feb. 20, 2014), http://money.cnn.com/video/technology/2014/02/20/t-3d-printing-fashion-show.cnnmoney.

printed heels.[136] An entire subculture of 3D printed cuisine is emerging.[137] Architects are experimenting with biomimicry and jewelers with fractals.[138] While nature is increasingly reflected in inanimate objects, we have yet to see how people will find expression through biological and genomic CAM. One of the first biological applications may be cosmetic alternation.[139]

If not yet adjusting our personality, CAM is already projecting it into things. Children design and customize toys,[140] for example, by placing their face on superhero figurines.[141] We may reduce "Barbie syndrome"[142] when dolls can take on any facial structure and skin tone.[143] Similarly, prosthetic legs are not only ergonomic, but sexy.[144] Imbuing things with self can even be literal. For example, an artist in Japan 3D scanned her vagina and incorporated it into cell phone cases and a kayak.[145]

Several scholars argue the First Amendment applies to CAD files and possibly the act of making itself.[146] It is tempting to analogize 1st Amendment freedom of the "press" with freedom of

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136. LIPSON & KURMAN, *supra* note 3, at 184.

137. *Id.* at 129–51.

138. *Id.* at 178–79.

139. *See* Ryan Jaslow, *Man's Face Reconstructed with 3D Printer After Motorcycle Accident*, CBS NEWS (Mar. 13, 2014, 5:33 PM), http://www.cbsnews.com/news/mans-face-reconstructed-with-3d-printer-after-motorcycle-accident; Hanna Rose Mendoza, *Cosmetic Surgeon 3D Prints Incredible Before and After Masks for a Rhinoplasty Patient*, 3DPRINT.COM (Sept. 5, 2014), http://3dprint.com/14054/rhinoplasty-3d-print.

140. *See* Borison, *supra* note 6.

141. Michael Molitch-Hou, *3D Printing Invites You to Join the Avengers*, 3D PRINTING INDUS. (Sept. 19, 2014), http://3dprintingindustry.com/2014/09/19/3d-printing-invites-join-avengers.

142. *See, e.g.*, Valerie Comer, *The Barbie Syndrome*, VALERIECOMER.COM (Jan. 24, 2014), http://valeriecomer.com/barbie-syndrome.

143. *See* Borison, *supra* note 6.

144. LIPSON & KURMAN, *supra* note 3, at 108.

145. Brittney Sevenson, *3D Printing Your Vagina Is Not Legal in Japan – Artist Megumi Igarashi Is Finally Indicted*, 3DPRINT.COM (Dec. 24, 2014), http://3dprint.com/33239/megumi-igarashi-3d-printed-vagina.

146. *See* Josh Blackman, *The 1st Amendment, 2nd Amendment, and 3D Printed Guns*, 81 TENN. L. REV. 479, 501–02 (2014) (advocating that CAD files are information, the regulation of which is subject to strict scrutiny); Barton Lee, *Where Gutenberg Meets Guns: The Liberator, 3D-Printed Weapons, and the First Amendment*, 92 N.C. L. REV. 1393 (2014); Anthony M. Masero, Note, *I Came, ITAR, I Conquered: The International Traffic in Arms Regulations, 3D-Printed Firearms, and the First Amendment*, 55 B.C. L. REV. 1291 (2014); Jean-Yves Meyer, Comment, *The Basin of the Danaides: How 3-D Printing Will Push the Limits of International Gun Control and Digital Freedom of Speech in the Twenty-First Century*, 41 DENV. J. INT'L L. & POL'Y 555 (2013).

expression through 3D printers.[147] People everywhere are starting to experiment with 3D printers. That experimentation may soon shift from speech to valuable scientific discovery.

VI. RESEARCH

Bit-to-atom interfaces could begin a new era of individual contribution to science. In an auxiliary role, CAM is building inexpensive laboratory equipment for use by small groups and developing nations.[148] But CAM also drives direct research, especially working closely with simulation software and distributed computing.

Science was relatively accessible a hundred years ago. Once the right information could be found, it took moderate catching up before one could contribute. Prominent scientists dabbled in several subfields. Like Benjamin Franklin's kite experiment,[149] apparatuses to test new theories were relatively easy to design and build. Materials like steel and rubber were invented largely through trial and error.[150] In 1919, Milton Humason was promoted from janitor to astronomer—he would help discover the universe was expanding—closing the era.[151] Specialization proliferated, theses narrowed, and knowledge collected in segregated circles. Apparatuses grew complex, and science came to rely on expensive computational power. At the end of the twentieth century, science was powerful and sophisticated but had left its humble roots.

In 1998, a group of scientists known as the Search for Extraterrestrial Intelligence ("SETI") identified an electromagnetic wavelength they believed to be ideal for

147. *See* Lee, *supra* note 146, at 1393. The author acknowledges that "press" recited in the First Amendment is generally understood to mean the media, rather than a physical printing press.

148. *PrintMyLab Results*, TEKLA LABS, http://www.teklalabs.org/print-my-lab-results (last visited Mar. 6, 2015) (A number of projects within Tekla Labs including a group from U.C. Berkley provides open source DIY instructions to build high-quality laboratory equipment, some made by 3D printers).

149. INDEPENDENCE HALL ASS'N, *Franklin and His Electric Kite*, USHISTORY.ORG, http://www.ushistory.org/franklin/info/kite.htm (last visited Feb. 10, 2015).

150. AMATO, *supra* note 61, at 45–46, 49–51.

151. Brian Ventrudo, *The Mule Driver Who Measured the Universe*, ONE-MINUTE ASTRONOMER (May 17, 2010), http://oneminuteastronomer.com/1562/mule-driver-measure-universe.

interstellar transmission.[152] The organization installed a receiver at Arecibo Observatory in Puerto Rico, co-opting the massive radio telescope into a cosmic listening post.[153] But the voluminous data generated by the receiver, expensive to analyze with supercomputers, represented an intractable problem.[154] They founded the revolutionary SETI@home project where anyone's personal computer could help crunch data.[155] By 2012, over six million people had participated.[156] Folding@home out of Stanford followed, using donated computation to run molecular simulations for Alzheimer's research.[157] A substantial minority of the public wanted to participate, even if all they could make was a passive little push to get groundbreaking research rolling.

In 2006, parallel processing opened up when Amazon launched its Elastic Compute service known as EC2.[158] Amazon's "cloud computer" allowed individuals to rent idle servers from the company's global network.[159] Researchers could now run fluid dynamic and genomic simulations in hours rather than weeks and at a fraction of the cost of owning infrastructure.[160] One University of Illinois researcher using EC2 for a personal experiment explained the advantage: "Not every researcher receives millions of dollars in grants and access to the speediest supercomputers. . . . [EC2] deliver[s] such good performance to anyone with a few dollars at the click of a button."[161] Cloud computing—representing virtually unlimited processing power and storage—

152. *SETI@Home: Millions Together, Searching for a Signal from the Stars*, PLANETARY SOC'Y, http://www.planetary.org/explore/projects/seti/seti-at-home.html (last visited Mar. 6, 2015).

153. *Id.*

154. *Id.*

155. *Id.*

156. *Id.*

157. *See What If Even While You Sleep You Could Help Find a Cure,* STAN. U., http://folding.stanford.edu (last visited Mar. 6, 2015).

158. Arif Mohamed, *A History of Cloud Computing*, COMPUTERWEEKLY.COM (Mar. 27, 2009), http://www.computerweekly.com/ feature/A-history-of-cloud-computing.

159. *Id.*

160. Cade Metz, *Amazon Builds World's Fastest Nonexistent Supercomputer*, WIRED (Dec. 23, 2011), http://www.wired.com/2011/12/nonexistent-supercomputer/all/; *see also The MegaRun*, CYCLE COMPUTING, http://www.cyclecomputing.com/discovery-invention/use-cases/ (last visited Mar. 6, 2015).

161. Ryan McGreevy, *Personal Supercomputing in the Cloud*, RYANMCGREEVY.COM (Sept. 21, 2011), http://rmcgreevy.com/2011/09/21/personal-supercomputing-cloud.html.

empowers anyone to build and run computationally taxing models and simulations.

Computation and CAM are inextricably bound. The quality of the models that bit-to-atom interfaces can materialize is a direct result of computation and storage capacity. For example, simulation can create a solid body with maximized fluid dynamic or heat transfer properties. In this way, CAM not only represents a tool of discovery, it has created an entirely new universe of inquiry. Additive manufacturing, able to make shapes according to a model generated by affordable computation, may shift engineering, simplified by assumptions for computational reasons, back toward raw physics and mathematics. That allows for a fresh look at everything. As CAM reaches farther down the structural hierarchy to rearrange individual atoms, redefining material science, its close relationship with processing power and storage capacity will become evident.

While raw computation is technically available to anyone now, it will soon be practical and easy to use as well. High grade CAD software is already being adapted for widespread use: "Industrial giants such as Autodesk, PTC and 3D Systems have released free design software . . . They are pivoting from professionals to everyone."[162] Powerful simulation will soon be integrated into these tools. Parametric modeling, for example, allows designs to be automatically generated based on input parameters such as weight, height, and tensile strength.[163] Similarly, artificial "natural selection" simulations can be run to evolve a model that will thrive in a specific environment.[164] These tools bypass proficiency in engineering generally and require only that someone can specify the problem they face.

Another area especially ripe for computational modeling and participation is biology. While not an entirely new universe of inquiry, CAM is making genetic engineering widely accessible. The cost of DNA sequencing has fallen dramatically.[165] For example,

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162. ANDERSON, *supra* note 37, at 20.

163. ROBERT PLOTKIN, THE GENIE IN THE MACHINE 51–55 (2009).

164. *Id.* at 55–61; *see also* Daniel Davis, *A History of Parametric*, DANIELDAVIS.COM (Aug. 6, 2013), http://www.danieldavis.com/a-history-of-parametric.

165. The cost of sequencing base pairs fell from about one dollar per base pair in 2003 to three million base pairs per dollar in 2013. Solve for X, *Solve for X: Austen Heinz on Democratizing Creation*, YOUTUBE (Feb. 11, 2013), https://www.youtube.com/watch?v=7yscphwaWNs#t=180.

the cost of sequencing the human genome dropped from $300,000,000 in 1998[166] to $1000 by 2014.[167] When it comes to building new strands of DNA, one fabricator has lowered the cost 10,000 fold.[168] One researcher describes the falling cost as unprecedented: "In the history of the world, perhaps no other technology has dropped in price and increased in performance so dramatically."[169]

The ability for small groups to contribute to life sciences cannot be understated. Radically new things, otherwise dismissed, will be created such as yeast that produces caffeinated beer,[170] or trees that glow in the dark to obsolete street lamps.[171] People may even be able to research the disease of a family member. CAM will directly permit the results of a digital experiment, like those generated by Folding@home, to be brought into reality and tested. Life, like materials, are emergent systems, or, in the language of patent law, "unpredictable arts." This is a way of saying that small changes can yield unexpected results. Although some fear the collateral damage, more cooks in the biological kitchen will certainly lead to new discoveries. A club for home laboratories called DIY Bio is spreading worldwide.[172]

Some might question whether demi-professional scientists are valuable as direct contributors. Leads are probably stacking up faster than formal institutions can follow up. Conversely, an army of hobbyists may observe new phenomena that flag promising opportunities for professionals. On a more fundamental level, interdisciplinary, outsider, or even amateur researchers push science and engineering forward. Thomas Kuhn, author of *Structure of Scientific Revolutions*, describes the importance of fresh and diverse insight: "Almost always the men who achieve . . .

166. Andrew Hessel et al., *Hacking the President's DNA*, ATLANTIC (Oct. 24, 2012, 10:42 PM), http://www.theatlantic.com/magazine/archive/2012/11/hacking-the-presidents-dna/309147/#.

167. Erika Check Hayden, *Is the $1,000 Genome for Real?* NATURE INT'L WKLY. J. SCI. (Jan. 15, 2014), http://www.nature.com/news/is-the-1-000-genome-for-real-1.14530.

168. Bloomberg Business, *DNA Consumer Products: Not as Far Out as You Think*, YOUTUBE (Jun. 5, 2013), https://www.youtube.com/watch?v=HCKpl_T5r_I#t=306 ("It means that anyone in the world is going to be able to be a genetic designer. . . . I think synthetic DNA will become a consumer product.").

169. Hessel et al., *supra* note 166.

170. Hessel, *supra* note 52.

171. *Id.*

172. *Id.*

fundamental inventions of a new [scientific] paradigm have been either very young or very new to the field whose paradigm they change."[173] People with careers to defend tend toward safe, incremental steps. Others chase long shot theories or eccentric research, almost certain to fail but having the small possibility to push science in a new direction.

We may never see personal electron microscopes or particle accelerator gym memberships. But some of the personalized and cottage-industrial flavor of the next revolution and renaissance will visit science as well. Certain disciplines will accelerate not as a function of government grants or corporate coffers, but of how many people are asking questions. Science may become better balanced when individuals or small groups propose projects outside of the influence of government and academia. But revolution, research, and renaissance, away from government influence, are exactly what many fear.

VII. FEAR

Legal systems assume that things are difficult to make. At the very least, creation of controlled objects must occur in factories and laboratories where raw materials and conduct can be observed. Monitoring may occur directly through inspection or indirectly through licensing, auditing, and reporting. The bit-to-atom interfaces, increasingly compact and accessible, irreversibly challenge these assumptions.

Early anxiety (and elation) centers on the weakening of intellectual property. Primarily, CAM makes it easier to infringe.[174]

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173. THOMAS S. KUHN, THE STRUCTURE OF SCIENTIFIC REVOLUTIONS 90 (2d ed. 1970).

174. *See generally* Daniel Harris Brean, *Asserting Patents to Combat Infringement via 3D Printing: It's No "Use,"* 23 FORDHAM INTELL. PROP. MEDIA & ENT. L.J. 771 (2013); Ben Depoorter, *Intellectual Property Infringements & 3D Printing: Decentralized Piracy*, 65 HASTINGS L.J. 1483 (2014); Desai & Magliocca, *supra* note 13; Darrell G. Mottley, *Intellectual Property Issues in the Network Cloud: Virtual Models and Digital Three-Dimensional Printers*, 9 J. BUS. & TECH. L. 151 (2014); Brian Rideout, *Printing the Impossible Triangle: The Copyright Implications of Three-Dimensional Printing*, 5 J. BUS. ENTREPRENEURSHIP & L. 161 (2011); Davis Doherty, Note, *Downloading Infringement: Patent Law as a Roadblock to the 3D Printing Revolution*, 26 HARV. J.L. & TECH. 353 (2012); Charles W. Finocchiaro, Note, *Personal Factory or Catalyst for Piracy? The Hype, Hysteria, and Hard Realities of Consumer 3-D Printing*, 31 CARDOZO ARTS & ENT. L.J. 473 (2013); Skyler R. Peacock, Note, *Why Manufacturing Matters: 3D Printing, Computer-Aided Designs, and the Rise of End-User Patent Infringement*, 55 WM. & MARY L. REV. 1933 (2014); Michael Weinberg, *It Will Be Awesome If They Don't Screw It Up: 3D Printing, Intellectual Property, and the Fight over the Next Great Disruptive Technology*, PUBLIC KNOWLEDGE (Nov. 2010), *available at* https://www.publickn

CAD files, trivial to distribute with current information technology, may include patented elements once they are translated to atoms.[175] Similarly, trade dress like the Coca-Cola bottle or a copyrighted sculpture can be scanned and printed.[176] Rights are also more difficult to enforce. Intellectual property requires significant infringing activity to justify the expense of legal action.[177] Distributed small-batch creation may be hard to deter, if it can even be spotted. CAD files cross boarders as bits and then pop into reality sight-unseen.[178] Tension is building between CAM's unprecedented ability to create and intellectual property's carefully balanced policy to reward creation.

CAM will not just challenge the right to copy things, but also the regulatory value of physical objects in general. For example, the *New York Post* published a photograph of high-security keys to sensitive areas of the New York subway.[179] Within weeks the photos were 3D printed by a group at MIT.[180] In 2011, the digital blueprints for a firearm component known as a receiver were uploaded to the free online service Thingiverse.[181] Being the only regulated piece, acquisition of the receiver allows assembly of a complete gun from over-the-counter parts without submission to a background check.[182] In 2013, the first plastic handgun was printed,[183] followed shortly after by a metal pistol on a professional 3D printer.[184]

Chemical and biological CAM will have its own dangers. Chemical fabricators with the power to make pharmaceuticals, still

owledge.org/news-blog/blogs/it-will-be-awesome-if-they-dont-screw-it-up-3d-printing.

175. *See* Rideout, *supra* note 174, at 166–68.

176. Desai & Magliocca, *supra* note 13, at 1709–10.

177. Doherty, *supra* note 174, at 362.

178. Desai & Magliocca, *supra* note 13, at 1705–09.

179. Andy Greenberg, *MIT Students Release Program to 3D-Print High Security Keys*, FORBES (Aug. 3, 2014, 12:36 PM), http://www.forbes.com/sites/andygreenberg/2013/08/03/mit-students-release-program-to-3d-print-high-security-keys.

180. *Id.*

181. Peter Jensen-Haxel, *3D Printers, Obsolete Firearm Supply Controls, and the Right To Build Self-Defense Weapons Under Heller*, 42 GOLDEN GATE U. L. REV. 447, 454 (2012).

182. *Id.* at 458.

183. *See* Greenberg, *supra* note 12.

184. Dara Kerr, *Uh-oh, This 3D-printed Metal Handgun Actually Works*, CNET (Nov. 7, 2013, 6:12 PM), http://www.cnet.com/news/uh-oh-this-3d-printed-metal-handgun-actually-works.

theoretical, may produce illicit drugs.[185] However, democratized genomics may present a greater challenge. For example, engineered yeast, as easy for people to cultivate and distribute as bakers yeast, may produce cocaine.[186] While many DNA synthesis services already scan for virulent sequences,[187] no such checks are available for owned CAM devices.[188] Personal DNA makers could, in theory, build pandemic-scale pathogens.[189] While the danger of the next plague originating in a garage is ripe for sensation, there are subtler surprises that arise from accessible DNA manipulation. Andrew Hessel, Distinguished Research Scientist at Autodesk, presents a scenario in which viruses could be engineered as "personalized bioweapons" that would innocuously spread through a population before finding and eliminating its intended target.[190]

As physical things become harder to regulate, they will also become harder to trust. The Bulgarian mob was caught using 3D printers to make fake debit-card-filching ATM covers.[191] Along these lines, CAM may be a powerful tool for counterfeiting and forgery. One 3D printer, for example, can emulate a Van Gough down to the brush-stroke.[192] Novel issues of product liability arise when faulty designs are downloaded and made at home.[193]

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185. *See* J.D. Tuccille, *3-D Printing the New War on Drugs*, DAILY RECKONING (Dec. 13, 2013), http://dailyreckoning.com/3-d-printing-the-new-war-on-drugs.

186. *Cf.* Gelphman, *supra* note 7 ("[P]eople are already hacking yeast for biofuels, for specialty chemicals, for all sorts of flavorings . . . . [Y]ou can bet more than one intoxicant is going to be added.").

187. Jonathan B. Tucker, *Double-Edged DNA: Preventing the Misuse of Gene Synthesis*, ISSUES SCI. & TECH., http://issues.org/26-3/tucker-2 (last visited Mar. 6, 2015).

188. For example, the DNA fabricator by Cambrian Genomics is a stand-alone device that synthesizes a sequence that its operator inputs. *See* Bloomberg Business, *supra* note 169. It does not appear to require Internet connectivity, except in the sense that a long input sequence is most easily downloaded from a database that may be online. *Id.*

189. *Id.*

190. Hessel et al., *supra* note 166.

191. John Newman, *3D Printers Among Equipment Seized from Bulgarian Organized Crime Network*, RAPIDREADY (Oct. 9, 2014), http://www.rapidreadytech.com/2014/10/3d-printers-among-equipment-seized-from-bulgarian-organized-crime-network.

192. *See* Liszewski, *supra* note 11.

193. *See, e.g.*, Nora Freeman Engstrom, *3-D Printing and Products Liability: Identifying the Obstacles*, 162 U. PA. L. REV. ONLINE 36 (2013).

Weapons might take on innocent shapes[194] and consist of materials that bypass security.[195]

Finally, many of the ways in which information technology challenges authorities could spread to the physical world. The Internet, for some a bastion of obscenity, was at least out of sight when the screen was off. With the 3D printing of sex toys[196] and intimate body parts, that is no longer the case. The cheery Japanese vagina-kayak artist, giving birth to herself through her own labia as she protruded through the hull, could not paddle fast enough: expression or not, she was arrested for violating Japanese obscenity law.[197]

Many of these concerns have been sensationalized, especially the production of 3D printed firearms. It may be decades before CAM can become a worrisome source compared to the 300 million guns circulating the United States.[198] Still, a number of lawmakers called for legislation to ban 3D printed weapons.[199] Although no legislation was passed, these attempts show that CAM is subject to attack in moments of fervor. Some scholars have called 3D printed firearms a red herring.[200] In fact, all of these examples may be.

These examples may fundamentally mischaracterize the long-term disruption of bit-to-atom interfaces. Serious discussions of regulation may not arise because of the old things that CAM can imitate, but because of the new objects it enables. Perhaps the runaway example of personalized bioweapons comes closest. Whatever the object, it will not derive from some prestidigitation of shape on a single level of organization. It will be something else, deriving from the infinite possibility of arranging materials at

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194. *See* Julian J. Johnson, Note, *Print, Lock and Load: 3-D Printers, Creation of Guns, and the Potential Threat to Fourth Amendment Rights*, 2013 U. ILL. J.L. TECH. & POL'Y 337, 343 (2013).

195. *See* Dara Kerr, *Congress: Undetectable 3D-printed Guns Are Still Illegal*, CNET (Dec. 9, 2013, 5:56 PM), http://www.cnet.com/news/congress-undetectable-3d-printed-guns-are-still-illegal.

196. *See* Sevenson, *supra* note 145.

197. The author does not know whether she was arrested in the act of kayaking. *Id.*

198. Jensen-Haxel, *supra* note 181, at 460, 492.

199. Chris Eger, *California 'Ghost Gun Bill' Creeps onto Governor's Desk*, GUNS.COM (Sept. 2, 2014), http://www.guns.com/2014/09/02/california-ghost-gun-bill-creeps-onto-governors-desk; Cyrus Farivar, *New NYC Bill Would Require 3D Printed Guns to be Registered with Police*, ARS TECHNICA (June 13, 2013), http://arstechnica.com/tech-policy/2013/06/new-nyc-bill-would-require-3d-printed-guns-to-be-registered-with-police.

200. Desai & Magliocca, *supra* note 13, at 1700.

several levels of the structural hierarchy. It will not be "grey goo," the tiny self-replicating robots that could consume the world, according to last decade's nanotechnology speculation.[201] Rather, it will be comparable to the union of brittle tin and soft copper into strong bronze, an alloy that shifted the balance of empires.[202] Alongside all of the wonders, something that regulators find startling and deeply troubling will inevitably spawn.

Scholars have proposed a number of regulation points for CAM[203] that, like "angels-at-the-gate," attempt to block the portals that allow bits to materialize as atoms. Data regulation methods include: monitoring CAD files at internet service providers ("ISPs"); requiring CAD files to be submitted to electronic clearing houses; and digital rights management ("DRM") systems installed locally on CAM devices (that could presumably monitor and enforce other prerogatives).[204] There are two primary physical regulations. First, restricting CAM devices, essentially the underlying technology.[205] Second, regulators can focus on the raw material of CAM devices.[206]

Short of regulating CAM machines, materials may be the only viable point of regulation. Susceptible raw materials will include any holdouts that accessible CAM cannot produce. Whether chasing red herrings or facing something else, a new understanding of matter and transformation is required to ensure minimal impact on the movement.

VIII. THING THEORY

Flooded with custom objects made of unique materials, it will be harder to classify those objects or distinguish a raw material from a finished product. Policymakers will have to dabble in the philosophical realm of object theory.[207] Applied in section IX, this section sets forth a consistent, general model for what objects are,

201. *See, e.g.*, Wejnert, *supra* note 69, at 328.

202. AMATO, *supra* note 61, at 26.

203. *See* Desai & Magliocca, *supra* note 13, at 1714–16.

204. *Id.*

205. *See id.*; *see also* Blackman, *supra* note 146, at 512.

206. *See* Desai & Magliocca, *supra* note 13, at 1702; *see also* Blackman, *supra* note 146, at 512.

207. For history on object theory and its competing approaches, *see Substance*, STANFORD ENCYCLOPEDIA OF PHILOSOPHY (Oct. 3, 2004), http://plato.stanford.edu/entries/substance/#UndIde.

how they interact with and effect their environment, and how they transform into new objects.[208]

An object is a collection of organized matter. Specifically, the object is composed of smaller pieces of matter along with the information that represents the relationships between and among those smaller pieces of matter. Its structure is comprised of not only its highest recognizable level of organization, but every underlying level as well. An object has inherent properties, can give rise to emergent properties in other structures or large systems, and can be transformed into other objects.

First, an object has "inherent properties." Inherent properties include physical properties, which can be measured or quantified, along with an object's immediate effects on small systems. An object can also give rise to emergent properties in other systems with which that object interacts.[209] There are two types of emergent properties[210] associated with other systems that interact with the object: "internal emergent properties" and "external emergent properties." Internal emergent properties arise in a higher level of organization as a result of an object's incorporation into lower levels of structure. That incorporation must be intimate and physical.[211] External emergent properties, in contrast, arise from a larger context into which the object is placed; for example, what arises out of a community or an economy once the object is inserted. The object is not intimately connected to the system that manifests the external emergence.

An object can be assembled or rearranged into a new object. The former is referred to as a raw material and the latter a product.[212] Transformation from one object to another occurs at a cost for rearranging the matter of the raw material into the

208. The model presented here borrows from both substance theory and bundle theory, but has been formulated as a practical framework for the specific purpose of analyzing the merits of raw material regulation. They are adapted from the comprehensive philosophy of Dhryl Anton, to which the author is grateful. *See* Dhryl Anton, *Quantumism: a Tao of Thought*, ITUNES (Jan. 4, 2014) (downloaded using iTunes).

209. For a history of emergence, *see* Jeffrey Goldstein, *Emergence as a Construct: History and Issues*, 1 EMERGENCE 49 (1999), *available at* http://www.liacs.nl/~haring/bigscience/Emergence%20as%20a%20construct.pdf.

210. JAMES A. VAN SLYKE, THE COGNITIVE SCIENCE OF RELIGION 31 (2011).

211. For example, direct interaction could be electrostatic, dispersion forces, ferromagnetic, or force arising from friction.

212. Raw materials may also be referred to as reagents or reactants in chemistry and as substrates in biology.

product. From the perspective of an actor effecting this transformation the cost includes, for example, energy, computation, chemical catalysts, knowledge, skill, and equipment.[213] In theory, any collection of matter can be turned into any other matter of equivalent mass or energy.[214] But the cost of assembly or rearrangement practically determines, for a particular person, group, or organization, what a collection of matter may become. One object possesses the "transformative potential" to become a new object when the transition is within that rearrangement or assembly cost to create the necessary relationships among the pieces of matter that are the raw material.

For example, a spool of plastic filament is an object. Its inherent properties include physical traits like melting point and color. Because additive manufacturing can shift its filamentous form into any shape (redefining the relationships among the strands of polymer making up the filament), the spool has the transformative potential to become an object of any geometry within the printable volume and resolution of an accessible 3D printer. For those that can afford a 3D printer and download the appropriate CAD file, now a good portion of the public, that includes a firearm receiver.

Morphine's transformation into heroin is more complicated. The morphine molecule's inherent properties include its absorption spectra and perhaps its cozy association with mammalian opioid receptors.[215] Its inherent properties also include its effect on a small biological system: analgesic efficacy in the human body.[216] After a simple acetylation reaction recited in many accessible sources,[217] a moderately available reagent, acidic anhydride, can be combined with morphine in basic glassware.[218]

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213. Risk of civil or criminal liability is not included as a cost within this formulation.

214. *See* A. Einstein, *Does the Inertia of a Body Depend Upon Its Energy-Content?*, 18 ANNALEN DER PHYSIK 639 (1905) (proposing mass-energy equivalence).

215. *See generally* Andrew P. Feinberg et al., *The Opiate Receptor: A Model Explaining Structure-activity Relationships of Opiate Agonists and Antagonists*, 73 PROC. NAT'L. ACAD. SCI. 4215 (1976) *available at* http://www.pnas.org/content/73/11/4215.full.pdf.

216. It may sometimes be difficult to distinguish between effects on a small system (an inherent property) and effects arising out of a large system (an external emergent property). As with many theories, the boundaries are difficult to define.

217. *See* K. R. Bedford et al., *The Illicit Preparation of Morphine and Heroin from Pharmaceutical Products Containing Codeine: 'Homebake' Laboratories in New Zealand*, 35 SIEGERS FORENSIC SCI. INT'L 197 (1987).

218. *Id.*

The result is a new object—heroin. Thus, morphine can be said to have the transformative potential to become heroin. Due to heroin's nature, regulators have decided its inherent properties (e.g., likely addiction related to its efficient penetration of the blood-brain barrier) and external emergent properties (e.g., societal effects when available to a population) require that heroin, and molecules that have the transformative potential to become heroin, are regulated.[219]

Internal emergent properties are not likely exhibited by morphine or heroin. They do not polymerize to form into chains,[220] and neither is likely to become intimately incorporated into some higher assembly.[221] Acidic anhydride, on the other hand, reacts with many molecules to increase their hydrophobicity—that is, their solubility in oils and fatty tissues.[222] For example, acidic anhydride was originally used to improve the medicinal value of willow bark extract, converting it to Aspirin. The acetic anhydride molecule has a variety of laudable uses, including engineering corncobs to sop up oil spills.[223] Still, because of its notorious contribution to heroin, acetic anhydride is regulated, albeit as a "listed chemical" with less stringent controls than heroin.[224]

Transformative potential is a dynamic concept, like ore, that changes with factors external to the object itself. Costs of both the raw materials and the transformation process determine, from the perspective of a particular person, group, or organization, whether that raw material has the transformative potential to become the product. Each object has a set of transformative potentials. Morphine can be said to have a limited set being that without significant alternation it is a raw material ("precursor")

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219. 21 U.S.C.A. §§ 812(I)(b)(4), 812(I)(b)(10).

220. Ramon Novoa-Carballal et al,, *Chitosan Hydrophobic Domains Are Favored at Low Degree of Acetylation and Molecular Weight*, 54 POLYMER 2081 (2013).

221. Their inclusion in the human body does not constitute an assembly within this framework. Some small molecules, however, may actually become integrated into biological systems in such a way that it contributes to a biological structure. For example, prolonged exposure to deuterated nutrients may cause bacteria to be comprised of structures where hydrogen has been replaced with deuterium, causing a cell to function differently. *See* D. J. Kushner et al, *Pharmacological Uses and Perspectives of Heavy Water and Deuterated Compounds*, 77 CAN. J. PHYSIOLOGY PHARM. 79 (1999).

222. Novoa-Carballal et al., *supra* note 220, at 2081.

223. *Id.*

224. 21 C.F.R. 1310.02 (b)(1).

for only a few other molecules. In contrast, the ABS spool has a wide transformative potential, able to take on many shapes or even build intermediate levels of structure having different properties than the spool itself.

Governments commonly illegalize conduct related to creation of a particular object or its possession. However, where a government decides that an object should never come into existence at the hands (or tools) of a particular actor, that government must keep the costs of transformation high. In other words, it must try to prevent circulating raw materials from acquiring the transformative potential to become the object of regulatory scrutiny. Some regulatory schemes are even designed around the principle of designating and withholding a critical component to regulate higher order of structure. For example, rather than worry about regulating every piece of a gun, the United States arbitrarily designated a single piece from a subset of critical pieces.[225] That component, the receiver, was assumed to have a structure—specifically, a particular shape defined within a single level of organization—that was difficult to produce.[226]

Evaluated through this model, a number of phenomena—technological, economic, and social—have drastically reduced the costs of rearranging and assembling objects, part of the overall shift of the means of production to individuals. Bit-to-atom interfaces are the cornerstone of this change. CAM dramatically increased the transformative potential of currently available material, including expanding their potential to make unprecedented objects and entirely new raw materials.

However, many of the objects that can be made with CAM technologies will be dependent on the "holdout" raw materials. While these materials will be feedstock for revolution, renaissance, and research, they will be products of the old world and subject to regulation.

IX. THING POLICY

CAM is building an ever increasing repertoire from the universe of known objects, indifferent to legal status. Based on CAM's trajectory, unfamiliar things may soon pop from bit-to-atom

225. *See* Jensen-Haxel, *supra* note 181, at 457–58.
226. *Id.*

portals. Some of these will be more problematic for policymakers than any our society has encountered, both due to the capability of these new objects and their decentralized genesis. A number of regulatory strategies may be entertained including several on the digital side of the bit-atom divide. But CAM is also fundamentally a technology that reorganizes matter, and every transformation begins with something to transform. A raw material that cannot be produced by a democratized device represents a regulatory pressure point.

Determining whether to regulate a raw material, how to regulate it, and even what to regulate presents new considerations. If this era of revolution, renaissance, and research is to flourish, policymakers will be confronted with three challenges. Regulatory analysis will have to be adjusted to respect individuals as prime industrial contributors. It will also require appreciating the risk of regulating a material that could contribute to higher levels of structure. Finally, struggling to classify and specify things in the face of the yawning universe of organization, policymakers must be wary of vague and broad functional descriptions of matter.

A. The New Economic Engine: Everyone

A policy toward the raw materials of CAM cannot be merely "balance interests" and "regulate with caution." The regulatory culture of the United States displays awareness for the dangers of hamstringing technology.[227] But when it comes to manufacturing—the word invokes images of corrugated aluminum and smokestacks—we are used to analyzing from an industrial perspective. Regulation of democratized CAM and its raw materials, whether by legislative codification, agency rulemaking, or judicial opinion (e.g., civil liability), must account for a new class of economic actors, everyone.

Indifferent to economies of scale and other traditional barriers to entry, CAM has already become the central tool of individuals and small groups. It is the seed of agile business, profound art, and exciting research—a great equalizer. Materials will become increasingly important for these stakeholders, not just to experience the new era of revolution, renaissance, and

227. *See, e.g.*, Nathan Cortez, *Regulating Disruptive Innovations*, 29 BERKELEY TECH. L.J. 175, 189–91 (2014) (describing regulatory restraint through agencies using threats to regulate rather than promulgating regulations).

research, but to initiate it. However, the routine of analyzing from an industrial viewpoint may gloss over disparities between costs of small groups and large corporations. We might assume that economies of scale are somehow inherent to the way the economy is organized and that smaller firms unavoidably bare disproportionate cost.

For example, the cost of licensing and compliance, especially in manufacturing, is formulated for medium- to large-sized corporations. Similarly calibrated are the timetables of licensing, reporting requirements, and administrative adjudication. Tiny groups move fast. For CAM-centric startups, regulation may become the limiting factor in innovation. At the same time, rules that are relatively costly to comply with shield incumbents. No company could survive today without ready access to electricity or computation. As a growing portion of products are made by CAM, raw materials could become necessary for businesses to compete. Raw materials may rise to the level of a public resource and maybe even a public utility.

The United States has just placed its big toe on the dime on which it will make an economic, cultural, and scientific pivot. While our nation is generally comfortable with recognizing individuals as potent generators of culture apart from institutional backing, we must ensure that respect is extended. Ordinary people, once mere consumers, must be taken seriously as economic engines and springs of research in any analysis of raw material regulation.

B. Forced into Philosophy

The risk of regulating raw materials used by CAM has a special severity. We are accustomed to hearing that regulation of nascent innovation leads to unintended consequences.[228] But raw materials are a foundation on which innovation is built, the substrate for creativity itself. A missing material at one level within the hierarchy of organization cascades upward into higher levels.

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228. *See, e.g.*, Daniel Gervais, *The Regulation of Inchoate Technologies*, 47 HOUS. L. REV. 665, 685 (2010) ("The law of unintended consequences, when applied to an inchoate technology, supports the claim that because of the high degree of unpredictability of the evolution of the technology, the impact of future chains of events is almost impossible to predict, and whether more harm than good will be prevented by even well-intended regulation is educated guesswork at best.").

From an economic perspective, every other level of structure to which that material could contribute is eliminated, along with every object that could be created with those levels as well.

In the new world, custom objects will proliferate.[229] Like software code, things will be easily copied, modified, and modularized.[230] And like programming languages that abstract computer instructions at various levels, CAM will build at different layers in the structural hierarchy. As a result, it will become increasingly difficult to distinguish raw material from finished object.

A first effect, as discussed below, will be to strain anyone who is in the business of specifying and classifying things, including regulators. However, this change will also force policymakers into the philosophical realm of analyzing the potential of each organization of matter (each object) to contribute to higher levels of organization. This section, along with section VIII, provides a framework for that analysis, including best practices for protecting the new era. Under this framework, an organization of matter that is an object that has four primary considerations: inherent properties, external emergent properties, internal emergent properties, and transformative potential.

We begin with inherent properties and external emergent properties, the bread and butter of regulatory debate. As a general principle, an object can be regulated based upon either of these properties without direct impact on creation of other objects.[231] For example, dynamite has an inherent property of chemical instability.[232] Similarly, Beryllium metal interacts with a small system, the body, to cause cancer.[233] In addition to inherent properties, it is traditional to regulate an object based on what emerges from its interaction with a larger system to which it is not physically or intimately connected. For example, heroin is determined to have negative societal consequences for public

229. *See supra* Part IV.

230. *See* Anderson, *supra* note 87.

231. This assumes that this object plays no role in increasing the transformative potential of other objects. For example, regulating additive manufacturing technology directly because it is associated with the emergent property of massively increasing transformative potential of raw materials would have an obvious effect on transformation.

232. Alfred Nobel, *On Modern Blasting Agents*, 23 J. SOC'Y ARTS 611, 621 (1875).

233. *Toxicology*, BERYLLIUM SCI. & TECH. ASS'N, http://beryllium.eu/health-environment-legislation/health-safety/toxicology/ (last visited Jan. 2015).

health or safety, and the insecticide DDT is shown to damage ecosystems by inhibiting reproduction of birds.[234] Lawmakers may argue whether a particular inherent property should be regulated. Or, they may debate whether an external emergent property is causally linked to an accused object. But they do not question that these are permissible attributes in which to ground or justify regulation.

But the new era requires analysis of internal emergence and transformative potential. In contrast to the first two properties, an object generally should not be regulated based solely on its transformative potential. The object is removed from the structural hierarchy for no harm of its own, and with its excision comes every higher order of structure that could be built on top of it. For example, a new crystal lattice may be so light and strong that it can be made into thin knives invisible to x-rays. Not only is that material likely to be useful for a wide variety of applications at the hand-held scale, it may provide an important foundation for many additional levels of structure.

There is an exception. It is permissible to regulate based on transformative potential when an object has a limited number of alternatives to become. Specifically, an object has limited transformative potential where it is unlikely to be incorporated into higher levels of organization or it is tailored to a specialized assembly. Firearms components and drug "precursors" are primary examples. A firearm receiver is a highly specialized shape that has null use other than incorporation into a firearm, itself an object extensively regulated for its internal and external emergent properties.[235] Similarly, it is permissible to control a drug precursor where that precursor's chemical structure is so specialized that only small modification will convert it to the regulated drug. Unlikely to polymerize or contribute to a lattice, the only chance the precursor has to contribute to a higher structure is to undergo regression into more fundamental components.

234. J. J. Hickey & D. W. Anderson, *Chlorinated Hydrocarbons and Eggshell Changes in Raptorial and Fish-Eating Birds*, 162 SCIENCE 271 (1968).

235. For example, the Department of Justice's Bureau of Alcohol, Tobacco, Firearms, and Explosives ("ATF") defines "receiver" as "[t]hat part of a firearm which provides housing for the hammer, bolt or breechblock, and firing mechanism, and which is usually threaded at its forward portion to receive the barrel." 27 C.F.R. § 478.11.

However, general-purpose structures that are incorporated into an object should not be considered the primary structure or the primary regulatory target. In the chemical context, generally useful reagents are not the main "precursors" of a product.[236] This admittedly runs counter to current approaches. There are, for example, an array of "listed chemicals"[237] under the Controlled Substances Act that are regulated due to the general way they help transform a boring molecule into a scheduled substance. For example, acetic anhydride involved in the conversion of morphine to heroin has a plethora of uses that has nothing to do with drugs.[238] We may need to reconsider availability of these basic reagents of creation, for example, oxidizing and reducing reagents, if they are required for widespread creation of legitimate things.[239]

The last major principle is that the more internal emergence a material exhibits, the more protection it should receive. When one level of structure is known to cause higher levels to exhibit very different properties, that material demonstrates an uncanny synergism with other matter and should remain free for use and exploration.

In analyzing transformative potential and internal emergence two challenges arise. First, there will be raw materials whose existence seems solely useful for creation of a deleterious object. But how can we be sure the transformative potential is so narrow? Similarly, where no other applications of the material exist, how do we recognize its promise for internal emergence? The notion of predicting emergence is in tension with the very idea of emergence.[240] At the risk of resorting to reductionism,

236. "Precursor" can be used to describe any reactant molecule that contributes structure to a product. *See, e.g.*, J. K. Cunningham et al., *Essential ("Precursor") Chemical Control for Heroin: Impact of Acetic Anhydride Regulation on US Heroin Availability*, 133 DRUG & ALCOHOL DEPENDENCE 520 (2013). Acetic anhydride is a four-carbon molecule and only contributes a relatively small amount of structure to morphine. Morphine, having seventeen carbons, already exhibits the physiological properties that affect the body and can be seen as the primary precursor in these regards. *See id.*

237. 21 C.F.R. § 1310.02.

238. *See, e.g.*, Cunningham et al., *supra* note 236, at 2081.

239. Studies have shown that control of general chemical reagents has a measurable affect on narcotics production. *See id.* However, these benefits may eventually need to be weighed against the hindrance of democratic manufacturing if there are no suitable replacement reagents for the movement's needs.

240. *See* Goldstein, *supra* note 209, at 60 (discussing theories that emergence implies unpredictability).

emergence's longstanding nemesis,[241] there are indicators of meritorious transformative potential and internal emergence.

Perhaps an obvious indicator is the fundamentality of a material. The more basic the level of organization, the more likely it is to effect change on higher levels. In an extreme example, removal of a single atom, such as carbon, from the root of the hierarchy precludes every organic molecule and with it all of known life. But other small units above atoms, for example, self-assembling structures,[242] also hold promise as primary building blocks of useful objects.

A second indicator is a material's capacity for physical interaction with other materials. For example, "hydrogen bonding" capability, as occurs between strands of both silk and Kevlar, tend to form strong macrostructure.[243] Similarly, there are "functional groups" known for reactivity in chemistry and structural "domains" and "motifs" in proteins.[244] Even the ability of an object to interact with other aspects of itself can be important for emergence such as occurs in self-assembly.[245] In this way, structure by analogy provides clues even when an application has yet to be identified.

A third indicator is unusual inherent properties, which often correlate with strong internal emergence. For example, the "rare earth elements" exhibit an array of odd behaviors compared with other elements.[246] Over the last century, mining operations that generated rare earth elements as a byproduct of other ore wisely stockpiled them, even before their use was appreciated.[247]

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241. Anderson, *supra* note 75, at 393 (discussing the belief that any system or science can be completely understood by examining its most fundamental components, namely atoms).

242. For an example of self-assembling molecules, see Arkadiusz Chworos, et al., *Building Programmable Jigsaw Puzzles with RNA*, 306 SCIENCE 2068 (2004).

243. Lin Römer & Thomas Scheibel, *The Elaborate Structure of Spider Silk*, 2 PRION 154, 158 (2008).

244. Khan Academy Organic Chemistry, *Functional Groups I*, YOUTUBE (Mar. 14, 2012), *https://www.youtube.com/watch?v=KqjENf-ym-I&feature=youtu.be*; Tracy Kovach, *Four Levels of Protein Structure*, KHAN ACADEMY (Sep. 17, 2013), https://www.khanacademy.org/test-prep/mcat/chemical-processes/proteins/v/four-levels-of-protein-structure.

245. RNA, for example, has a high capacity for interaction with other RNA. *See* Chworos et al., *supra* note 242.

246. *Rare Earth Elements*, MIT.EDU, http://web.mit.edu/12.000/www/m2016/finalwebsite/index.html ("REEs have many important applications in modern technology for which there is no equal substitute.") (last visited Mar. 17, 2015).

247. *See id.*

Yet in the past twenty years, rare earth elements have become an essential part of modern technology. Like material seasoning, they are added in small amounts to vastly change the properties of alloys and composites.[248] Similarly, unusual quantum mechanical phenomenon is evidence of strong internal emergence. Such materials sit on the shelf for decades before acting as the key to a vexing puzzle or the spark for a new technology.

The materials of biological CAM warrant their own examination within this framework. DNA fabricators organize at the most fundamental level of life, base pairs.[249] DNA is the quintessential example of strong internal emergence and broad transformative potential. Two strands of DNA, appearing a monotonous and random repetition of base pairs up close, represent the difference between celery and a turtle. For example, changing even a single base pair can result in increased resistance to a neurotoxin.[250]

DNA as a discrete organization of matter has no harmful inherent properties or negative external emergent properties. In a sense, DNA fabricators do not translate bits to atoms, they translate electronic bits to molecular bits.[251] Life, it turns out, has its own general-purpose CAM devices, like RNA polymerase and ribosomes that allow proteins to arise out of that information. In other words, proteins and the products of those proteins are primarily what affect other systems.[252] Perhaps the distinction strains the framework. After all, it seems trivial for those proteins to spawn once DNA is placed into the right environment. Regardless, it seems clear that regulating the raw materials of life

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248. Maggie Koerth-Baker, *4 Rare Earth Elements That Will Only Get More Important*, POPULAR MECHANICS, http://www.popularmechanics.com/technology/engineering/news/important-rare-earth-elements#slide-1 (last visited Mar. 17, 2015).

249. *See* YOUNG SUN & CHING-HWA KIANG, DNA-BASED ARTIFICIAL NANOSTRUCTURES: FABRICATION, PROPERTIES, AND APPLICATIONS 3 (2005), *available at* http://cds.cern.ch/record/827525/files/0503114.pdf.

250. *See, e.g.*, Manda C. Jost et al., *Toxin-Resistant Sodium Channels: Parallel Adaptive Evolution Across a Complete Gene Family*, 25 MOLECULAR BIOLOGY & EVOLUTION 1016 (2008).

251. Gelphman, *supra* note 7.

252. DNA is sequestered in the nucleolus of the cell, not unlike a database. Occasionally RNA plays a direct role within the cell distinct from its well-known place in the central dogma of biology as a communicator of genetic information to the cytosol for subsequent translation into protein. For example, some RNA is catalytic, including the active site of the Ribosome.

would drastically reduce the capability of people to participate in biological research.

But it may be impossible to regulate the materials of life, anyway. Biological raw materials are *everywhere*. Andrew Hessel explains that the raw materials of life are just too ubiquitous to regulate.[253] Regulating purified chemicals used in genetic engineering, such as dNTPs and laboratory-grade enzymes, might conceivably work for a while. However, it seems a matter of time before there is a simple way to sort and purify these materials from nature. Bioengineering will probably never have holdout materials.

Biology appears to be a specialized application of the framework. But as CAM commands control over DNA and inanimate structure, there will be hybrids to address. The approach presented here is general enough to analyze chimeric systems of electronics, biology, and inanimate matter that CAM can produce moving forward.

C. Classifying the Infinite

Since the second industrial revolution, objects have been designed and built by centralized organizations. Economies of scale mandated that things enter economic circulation in batches. A batch had a clear origin, each component traceable to a manufacturer that had an address. This parentage classified things by default: make, model, and year. Marketing materials and instruction manuals documented. But we are entering a new time. As economies of scale are eliminated and matter is organized in novel ways, CAM wipes away our notions of objects and their constituent parts. Lawmakers are slowly sinking into taxonomic quicksand.

It will become increasingly difficult to specify or classify what is subject to regulation when everything—every thing—can be customized. Again, firearms provide a perfect example. California attempted to regulate several firearms it designated as "assault weapons," including a model called the AR15.[254] One strategy was to define the weapons structurally, that is, in terms of

253. Interview with Andrew Hessel, Distinguished Research Scientist of Bio/Nano Programmable Matter Group, AutoDesk Inc., in S.F., Cal. (Nov. 21, 2014).

254. CAL. PENAL CODE § 12276(a) (Deering 2003), *repealed by* 2010 Cal. SB 1080.

features.[255] However, rather mundane changes to the cosmetics of the AR15 made it compliant, and the gun was otherwise functionally indistinguishable from legal hunting rifles.[256] A second strategy was to list every known AR15 model designated using the "lower receiver."[257] Over the following decade hundreds of new lower-receiver companies popped up and California gave up on maintaining the list.[258] Now, imagine these receivers appearing not over ten years, but over mere hours or minutes. That is the capability of CAD and CAM. One responsibility of the ATF is to designate which piece of a new firearm model is the critical part for regulation.[259] Faced with a deluge of design, the manual process of specification by exhaustion becomes untenable.

It will be tempting in such an amorphous environment to increasingly rely on functional descriptions of matter. That is, describing what a thing does rather than its structure. Here, policymakers should take a lesson from patent law. Functional descriptions often lead to overly broad restrictions.[260] This is especially true in technologies where things can be described at various levels of abstraction like software.[261] The problem is, in the new era, "hardware is becoming a lot more like software."[262] We must be careful not to end up with regulations that read like patents—a short list of offending "embodiments" followed by "claims" struggling to describe a thing with more-than-statutory doses of strategic vagueness. Defining various states of microstructure in materials might be even more difficult. This

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255. CAL. PENAL CODE § 12276.1(a) (Deering 2003), *repealed by* 2010 Cal. SB 1080.

256. *See* Paul Markel, *California Compliant Firearms: Enabling Bad Behavior*, AMMOLAND SHOOTING SPORTS NEWS (Aug. 5, 2013), http://www.ammoland.com/2013/08/california-compliant-firearms-enabling-bad-behavior/#axzz3VYxj7a2J; *see also AR-15's in California*, Wikipedia, http://en.wikipedia.org/wiki/AR-15s_in_California (describing two methods for compliance: fixing features listed in Cal. Penal Code 12276.1(a)) (last modified Oct. 25, 2014).

257. *Id.*; CAL. PENAL CODE § 12276(a).

258. OFFICE OF THE ATTORNEY GEN. OF CAL., ASSAULT WEAPONS IDENTIFICATION GUIDE, 3D ED. at 70–84 (2001), *available at* https://oag.ca.gov/firearms/awguide. The "blacklist" models have not been updated since 2000.

259. S*ee* STEPHEN P. HALBROOK, FIREARMS LAW DESKBOOK § 2:4 (2014) (discussing ATF designation of regulated components).

260. For a history of functional claiming in patent law and examples of overly broad claims, see Mark A. Lemley, *Software Patents and the Return of Functional Claiming*, 2013 WIS. L. REV. 905, 910–28 (2013).

261. *See id.* at 919–36.

262. Anderson, *supra* note 87, at 58, 64.

challenge comes as a time when, due to the democratizing nature of CAM, a wider demographic will need to understand the law.

Technology could provide part of the answer, at least in specifying what is regulated so that the public can attempt compliance. Digitized models of regulated objects, for example, files that are considered firearm components or problematic DNA sequences, could be digitized and placed in a database open to public query. Such verification is already used by DNA synthesis services to flag DNA coding for virulent organisms.[263] Similarly, just as things can be invented through parametric design they could be specified through parametric regulation. Defining objects within ranges provides some risk for over breadth but also creates definite boarders. The ranges could be adjusted when evidence or simulation suggested that a particular attribute was not linked to a negative externality. In a similar way, the cloud computing power available to the public can be used to run simulations on various CAD files that were voluntarily submitted for analysis.

With the limited vision available at the beginning of revolutions, these three challenges have been presented. Of course, an object raising ire and its raw material will need a tailored discussion. It is a hope that the above considerations of perspective, object and transformation theory, and classification help guide that discussion.

X. CONCLUSION

The 3D printer, just one of many CAM devices, captivates the public. So far, two qualities are the focus of innovation and disruption. First, the technology's bit-to-atom translation makes physical things a lot more like digital things. They can be stored, sent, and modified as bits, resulting in new efficiencies and new problems. Second, a large proportion of the fear and excitement centers on the novel shapes that additive manufacturing can produce, from elegant fractals to firearm receivers.

These are only two facets of the technology's future. CAM's ability to transition matter within a widening domain of levels of organization is less appreciated, especially when amplified by the virtually unlimited computational power and storage of distributed

263. Tucker, *supra* note 187, at 25–27.

computing. Here, the increasing symmetry and convergence of worlds goes far past recreating the objects we are familiar with and generates fundamentally different organizations of atoms. When regulatory challenges to materials arise, it is the author's hope that this paper explains the importance of the technology, provides a lens to understand CAM's novel relationship to matter, and provides a model to evaluate raw materials regulation.

To demonstrate its stereo lithography products, 3D System, owner of the first additive manufacturing patent, designed a chess piece that could not have been made through injection molding.[264] The rook is now widely used to test and compare 3D printer capability. On close inspection, a delicate double helix runs through the interior of the tower.[265] The seemingly mismatched combination is foreshadowing. Finally, now that we can print the ivory tower, we can see from the ramparts.[266] Matter and information *are* synonymous.

264. The model was created by a subsidiary of 3D Systems, Cubify. *See* Seechless, *Rook*, THINGIVERSE (June 5, 2013), http://www.thingiverse.com/thing:99028 (digital CAD file of rook chess piece).

265. *Id.*

266. *Id.*