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INTRODUCTION

Imagine that you purchase the next generation sports car—it is not just autonomous, but entirely 3D-printed. The chassis bio-mimics mammalian bone structure to achieve revolutionary strength-to-weight ratio.[1] The body borrows aerodynamic design from winged insects.[2] Uniquely built for your body, the seats fit perfectly.[3] But the printed engine dwarfs the car's other technological marvels. Oddly shaped

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1. *Cf.* Randall Desmond, *Researchers Inspired by Human Bones, 3D Print Extremely Light, Strong Structures*, 3DPRINT.COM (Feb. 3, 2014), http://3dprint.com/635/researchers-inspired-by-human-bones-3d-print-extremely-light-strong-structures/.

2. *Cf.* Olivia Solon, *Tiny 3-D-Printed Insect Robots Take Flight*, WIRED (Mar. 23, 2011), http://www.wired.com/2011/03/flying-robot-insects/.

3. *See* Tyler Koslow, *Toyota & Materialise Team to 3D Print Lightweight Car Seat*, 3D PRINTING INDUS. (Sept. 17, 2015), http://3dprintingindustry.com/2015/09/17/toyota-materialise-team-to-3d-print-lightweight-car-seat/.

compared to last century's blocks and cylinders, the engine delivers stunning torque with a fraction of the fuel.[4]

A three-dimensional printer constructed the engine according to a digital blueprint called a computer-aided design (CAD) file. But as computing took the lead role in development, the "aid" in the acronym became an understatement. Powerful thermodynamic, fluid-dynamic, and heat transfer simulations approximated the unique physical context in which the engine would operate.[5] Iteration after iteration of the simulation looped until the system defined and thoroughly tested the design. The resulting CAD file specified the engine's bizarre geometry that, once brought into reality through a 3D printer, seems to cheat physics.

The amount of computing power required for this innovation would have been unavailable to such a tiny firm decades earlier. But the small company has no need to spend millions of dollars on warehouse space and computer hardware. Instead, the manufacturer rented a remote cloud computing cluster.[6] The computing resources of many individual servers were pooled into a temporary supercomputer that expended millions of "processor hours" in only a few days.

The engine came out of the printer in a single, pre-assembled piece,[7] all of its moving parts entombed in a casing devoid of fasteners making the engine impossible to disassemble or, for that matter, repair. But the engine will not need repair. Additional government-mandated safety simulations yield negligible chance of even a stress fracture before 800,000 miles.

On your first road trip, while coasting a silent and smooth eighty-five miles an hour, the engine explodes. You wake up in the hospital, lucky to be alive. Media outlets report hundreds,

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4. *See* HOD LIPSON & MELBA KURMAN, FABRICATED: THE NEW WORLD OF 3D PRINTING 204–05 (2013) (discussing fuel efficiency gains possible in 3D-printed engines).

5. *See id.* at 85–102 (discussing design software and modeling used in 3D printing); *see also* discussion *infra* Part III.

6. *See, e.g.*, *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 Jan. 11, 2016) (detailing the initial use of cloud computing clusters as a supercomputer).

7. 3D printers can produce completed mechanical assemblies. *See* Duncan Graham-Rowe, *3-D Printing for the Masses*, MIT TECH. REV. (July 31, 2008), http://www.technologyreview.com/Infotech/21152/.

then thousands of similar victims. Within weeks, the automobile is recalled. The engineering team sinks into bafflement and guilt. The engine had undergone rigorous testing, both "in silico"[8] and in real life. It had performed perfectly.

Then security analysts find a breach in the automotive manufacturer's network. You have, of course, heard about viruses infecting the software that controls mechanical systems.[9] But the analysts are puzzled when they find no trace of malware in the car's computers. Finally, after months of investigation, researchers discover the problem: after infiltrating the manufacturer's digital warehouse, the hackers maliciously modified the engine's digital blueprints.[10] This was not a mere "bit-flip" in which some of the ones and zeros of the file were scrambled. Rather, the hackers used the same level of high powered simulation to reverse-engineer the engine, determining the exact modifications that would lead to a catastrophic buildup of resonance. In other words, they industrially sabotaged the CAD file with "counter-simulation." The altered file was placed back in its original location. Weeks later, as the 3D printer read the file to produce your engine layer-by-layer, the virus left the digital world and infected your car's engine, a physical *thing*.[11] The hackers, too, have unprecedented access to cloud computers.

This paper focuses on an underappreciated aspect of the 3D printing: computation. Right now, we are fixated on the manufacturing device. We are excited for a new industrial

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8. "In silico" refers to computer simulation experiments. The term is most often applied in respect to pharmacological simulations. *See* Eric Winsberg, *Computer Simulations in Science*, STAN. ENCYCLOPEDIA PHIL. (Apr. 23, 2015), http://plato.stanford.edu/entries/simulations-science/.

9. *See* discussion *infra* Part IV.

10. *See* discussion *infra* Part IV. While not yet observed, fears are already mounting that 3D printers are vulnerable to attack by hackers. *See* KELLEY DEMPSEY & CELIA PAULSEN, NAT'L INST. STANDARDS & TECH., RISK MANAGEMENT FOR REPLICATION DEVICES (2014), http://csrc.nist.gov/publications/drafts/nistir-8023/nistir_8023_draft.pdf.

11. The virus has moved from a state processor such as a computer, to the state processor of reality (i.e., the physical laws of the universe). Unlike computer viruses, the infected physical "host" will in general not continue to incubate and perpetuate the virus. *See* Beat Schwendimann, *What Is the Difference Between a Simulation and a Model?*, PROTO-KNOWLEDGE (Dec. 7, 2010), http://proto-knowledge.blogspot.com/2010/12/what-is-difference-between-simulation.html.

revolution in which computer aided manufacturing (CAM) permeates society, empowering people like you to build the things that fit your body, lifestyle, or any other unique need or context. But the printing press, copy machine, and desktop printer also fascinated us at their introduction. Long after those familiar devices fell into our tech repertoire, the words they copy or print continue to carry magic. 3D printers and other CAM technologies are no different. The information contained in the design files, and the process by which it comes into existence, is the long-term story.

That story leads one place: consumption of computation in unprecedented quantities. CAM allows direct translation of information, in the form of a CAD file, into reality.[12] In other words, the power of the manifested object is in many cases proportional to the computation expended to build its blueprints. Such a manufacturing technology could not have risen at a better time. Cloud computers make high-powered computation[13] available to anyone for a minor cost, perhaps even as easy to tap and consume as electricity.[14] Cloud computing and CAM are extraordinary tools, and their coordination enables ordinary people make extraordinary things. Or, if one chooses, to manipulate and destroy in unforeseen ways.

The futuristic scenario above demonstrates the destructive potential of powerful computation in combination with CAM. Objects that are surprising, dangerous, and deceptive already spring from 3D printers,[15] and commentators anticipate regulation of CAM technology.[16] Scholars identify several possible regulatory choke points, including the CAM devices themselves, the CAD files they read, or the raw materials they

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12. *See generally* discussion *infra* Part III.

13. This article uses the term “high powered computing” to describe a relatively large number of parallelized processors, a definition coextensive with some formulations of High Performance Computing (HPC). For example, “[HPC] generally refers to the practice of aggregating computing power in a way that delivers much higher performance than one could get out of a typical desktop computer or workstation in order to solve large problems in science, engineering, or business.” *What Is High Performance Computing?*, INSIDEHPC, http://insidehpc.com/hpc-basic-training/what-is-hpc/ (last visited Feb. 8, 2016).

14. *See* discussion *infra* Part II.

15. *See, e.g.*, discussion and examples *infra* Part IV.

16. *See infra* Parts III, IV.

transform.[17] As CAM propagates through the economy and percolates down to consumers, the process by which the most ingenious, destructive CAD files are created—high powered computation—may reach the top of the list.[18] CAM leveraging supercomputing will yield dangerous objects unlike anything we have seen, and represent a novel cyber security threat.

This Article describes the emerging bond between CAM and powerful computation, explains the coming accessibility of both, identifies simulation software and raw computing resources as regulatory targets, and presents high powered cloud computation as an essential tool that should be regulated with the utmost tact. Part I describes a shift in computing tools that historically solved simple formal systems, and now resolve complex models and simulations leading to a fundamental change in the design process. Part II describes the development of cloud supercomputers that small organizations and individuals can now access as an on-demand, pay-per-use commodity. Part III describes CAM's dependence on computation to reach its full potential and identifies CAM as a key driver that will encourage lay use of high powered computing. Part IV describes the danger when CAM, as enhanced by supercomputers, develops contextually dangerous objects such as physical viruses. Part V describes high powered computation as a regulatory target and argues that cloud regulations cut off a nascent tool critical to realize the full potential of a new industrial revolution.

I. MODEL AND SIMULATION

Traditionally, when architects or engineers designed something, they applied their imagination to the elements of their profession and output the results on paper as blueprints. The context for the operation of the design might be hinted by design constraints written in the blueprints, but the full context primarily existed within the head of the designer. To test behavior or performance required physically building the design. If one was lucky, a scaled down version could be used to prove an aspect.

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

18. *See id.*; *see also* discussion *infra* Part III, V.

The first CAD software merely recreated the design workflow in digital form. But the speed and storage capacity of computing soon began to steer the design process. Today, we are transitioning to a new model of design in which processes, rather than people, define the information to be manufactured. This new approach generates a context in which to simulate behavior and performance. The transition to this new method is critical to understanding the long-term promise, danger and potential of CAM.

The digital computer did not just change how we computed, it changed what we computed. Until the mid-twentieth century, computing tools performed basic mathematical operations stitched together with human brainpower.[19] The times called for nothing more. Formal systems such as Newtonian physics and pre-quantum chemistry modeled reality in the most idyllic, linear way.[20] Scientists gave short shrift to complexity, believing that small changes in initial conditions equated to small changes in results.[21]

Then mathematics started hitting limits. Equations lacking analytical solutions have historically plagued mathematicians. But these problems started showing up in pressing science—for example, the differential equations describing "n-bodies" that interact through gravitational or quantum forces.[22] Some researchers proposed new methods but

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19. *See Birth of the Computer*, COMPUTER HIST. MUSEUM, http://www.computerhistory.org/revolution/birth-of-the-computer/4/intro (last visited Feb. 28, 2016).

20. *See generally* JAMES GLEICK, CHAOS: MAKING A NEW SCIENCE 14 (1987) (portraying the efforts of various scientists whose work contributed to the development of chaos theory).

21. *See id.* at 14–18.

22. *See* N.H. MARCH 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*, WIKIPEDIA, http://en.wikipedia.org/wiki/Many-body_problem (last modified May 8, 2014) [https://web.archive.org/web/20160120071234/https://en.wikipedia.org/wiki/Many-body_problem] ("[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.").

lacked the toolsets to implement them[23]—for example, proposals that involved stochastic systems where the outcome derives from probabilities at each of a series of interdependent steps.[24] In other words, the "[s]cientific work and discoveries of Archimedes, Isaac Newton or Galileo, based on a few manual computations [became] . . . legacy science."[25] Numerical methods—the inelegant way to solve problems with lots of manual calculations—offered a way out. Such methods have been with us since Babylon,[26] but the modern scope in many cases called for too many of such calculations.[27]

In the 1950s information theorists recognized that with enough yes/no questions any aspect of reality could be imitated. The new digital computer had just enough memory to hold, and logic to resolve, these approximated realities.[28] The theorists created our modern notion of a computer model: a set of algorithms, equations, constants, and other predefined behaviors that represent a particular system.[29] A simulation is

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23. Researchers were trying hard to find tools to solve their problem. For example, Vannevar Bush developed a mechanical device called the differential analyzer in 1931 in order solve up to sixth-order differential equations implicated in circuitry, physics, seismology, and ballistics. *See Bush's Analog Solution*, Exhibit to *Analog Computers*, COMPUTER HIST. MUSEUM, http://www.computerhistory.org/revolution/analog-computers/3/143 (last visited Jan. 11, 2016).

24. *Cf.* Harold J. Kushner, *A Partial History of the Early Development of Continuous-Time Nonlinear Stochastic Systems Theory*, 50 AUTOMATICA 303, 303–04 (2014) (noting initial attempts to develop stochastic control theory as early as the 1920s and 30s, but where theoretical clarity could not progress until the 1950s and 1960s as dynamic programming advanced); Peter Lynch, *The Origins of Computer Weather Prediction and Climate Modeling*, 227 J. COMPUTATIONAL PHYSICS 3431, 3432–36 (2008) (describing early attempts to model atmospheric conditions, which could not progress until computing power improved).

25. Levente Hajdu et al., *Grids, Clouds, and Massive Simulations*, *in* HANDBOOK OF RESEARCH ON HIGH PERFORMANCE AND CLOUD COMPUTING IN SCIENTIFIC RESEARCH AND EDUCATION 308, 308 (Marijana Despotović-Zrakić et al. eds., 2014).

26. *See generally* David Fowler & Eleanor Robson, *Square Root Approximations in Old Babylonian Mathematics: YBC 7289 in Context*, 25 HISTORIA MATHEMATICA 366, 366–76 (1998).

27. Lewis Richardson created the first weather simulation, not run on computers. Richardson saw the need for higher computing power, and dreamed of a massive room with 64,000 people to gather weather data and compute predictions. *See* Lynch, *supra* note 24, at 3435.

28. *See* GLEICK, *supra* note 20, at 18–21.

29. *See* Schwendimann, *supra* note 11 ("A model is a product (physical or digital) that represents a system of interest. A model is similar to but simpler

the running of that model, the system's behavior over time.[30] The first computer simulation solved a problem for which no analytical solution existed: the average distance a neutron travels through a material before colliding with an atomic nucleus.[31] Instances of n-body problems could be solved by computing the state of the bodies at every relevant point in time.[32] It was solution not through elegant chalkboard derivation but electrical brute force; truth not universal but contextual.

While researchers struggled to predict global weather with their new tools, factories offered simple systems that could be meaningfully modeled.[33] In the 1960's several companies attempting to shift from batch production to continuous assembly deployed simulation to optimize their facilities.[34] The buggy but successful trials ignited multidisciplinary interest.[35] The meeting of the 1968 Application of Simulation conference applied the new science not just to manufacturing but to transportation, urban planning, communications, marketing, human behavior, and ecology.[36] By the end of the decade simulation had its own computer languages and a professional

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than the system it represents, while approximating most of the same salient features of the real system as close as possible . . . . A simulation is the process of using a model to study the behavior and performance of an actual or theoretical system."); *see also* Catherine M. Banks, *Introduction to Modeling and Simulation*, *in* MODELING AND SIMULATION FUNDAMENTALS 1, 1 (John A. Sokolowski & Catherine M. Banks eds., 2010) ("[M]odels are approximations of the real world . . . . [A] model can then be modified in which simulation allows for the repeated observation of the model." (emphasis omitted)); *Computer Simulation*, WIKIPEDIA, https://en.wikipedia.org/wiki/Computer_simulation [https://web.archive.org/web/20160206233511/https://en.wikipedia.org/wiki/Computer_simulation] (last modified Dec. 10, 2015) ("A computer model is the algorithms and equations used to capture the behavior of the system being modeled. By contrast, a computer simulation is the actual running of the program that contains these equations or algorithms.").

30. *See* Schwendimann, *supra* note 11.

31. *See* Hajdu et al., *supra* note 25, at 309.

32. *See* ANDRZEJ MARCINIAK, NUMERICAL SOLUTIONS OF THE N-BODY PROBLEM 1, 49 (1985).

33. *See generally* Sagar Shinde, *Introduction to Modeling and Simulation Systems*, UNIV. HOUS., http://www.uh.edu/~lcr3600/simulation/historical.html (last visited Jan. 11, 2016) (discussing the development history of the advanced versions of simulation software today).

34. *Id.*

35. *See id.*

36. *Id.*

society.[37] In the 1970s simulation informed product development, for example predicting engine emissions and, in response to the Arab oil embargo, reducing energy loss from structures.[38] Still, it took the rest of the century for the learning curve to flatten.[39]

By century's end, many researchers tucked simulation in their standard toolbox. Computational electromagnetics shaped the sensory organs of the information age: antenna, radar, and satellite.[40] Biologists applied metabolic computer models to inform organism engineering.[41] Material scientists tested environmentally friendly replacements for previously indispensable toxic compounds.[42] Simulation led projects that could not afford to fail in real life, such as nuclear reactor design.[43] Each study enhanced our confidence in emulating reality. For example, in 2003, rival teams set out to improve a

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37. *See id.*

38. *See id.*

39. *See id.* ("Two common fears of simulation in early 80s were: []Simulation is extremely complicated, so only experts can use it [and s]imulation takes forever because of programming and debugging.").

40. *See Computational Electrodynamics*, WIKIPEDIA, https://en.wikipedia.org/wiki/Computational_electromagnetics [https://web.archive.org/web/20160125030521/https://en.wikipedia.org/wiki/Computational_electromagnetics] (last modified June 9, 2015) ("Several real-world electromagnetic problems like electromagnetic scattering, electromagnetic radiation, modeling of waveguides etc., are not analytically calculable . . . . Computational numerical techniques can overcome [this deficiency] . . . . [Making them] important to the design, and modeling of antenna, radar, satellite and other communication systems . . . .").

41. *See* Christopher S. Henry et al., *Application of High-Performance Computing to the Reconstruction, Analysis, and Optimization of Genome-Scale Metabolic Models*, 180 J. PHYSICS, 2009, at 1, http://iopscience.iop.org/article/10.1088/1742-6596/180/1/012025/pdf ("[Computer simulation has] been used to identify essential genes, determine growth conditions, predict phenotypes, predict response to mutation, and study the impact of transcriptional regulation on organism phenotypes. This growing field of applications, combined with the rapidly growing number of available genome scale models, is producing a significant demand for computation to analyze these models.").

42. *See* Tomio Iwasaki & Shin Takahashi, *Material Property Simulations for Efficient Design of Environmentally Conscious Functional Materials*, 61 HITACHI REV. 239, 243 (2012).

43. *See Computer Simulations Help Design New Nuclear Reactors*, ARGONNE NAT'L LABORATORY, http://www.ne.anl.gov/About/headlines/new_nuclear_age.shtml (last visited Jan. 11, 2016).

potentially medicinal compound.[44] One group applied traditional high-overhead trial-and-error techniques, the other group applied "in-silico" computer simulation.[45] Remarkably, they proposed identical modifications.[46]

Researchers are now merging discrete models into "multi-physics" simulations.[47] For example, material scientists stimulate a stress facture snaking through steel at multiple scales, quantum mechanics controlling near a tear's tip and classical forces governing a distant "quasi-continuum."[48] A bacterial cell was simulated in 2012, the first organism to be completely modeled.[49] The Illustris simulation recreated, at several distinct scales, thirteen billion years of cosmic evolution in a 350 million cubic light-year volume.[50] But multi-physics techniques provide more practical insights, as well. In 2015, the U.S. Army combined "ridged body" models with fluid dynamics to simulate helicopter rotor designs proposed by several competing defense contractors.[51]

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44. Gregory Sliwoski et al., *Computational Methods in Drug Discovery*, 66 PHARMACOLOGICAL REVIEWS 334, 337 (2014) (citing Juswinder Singh et al., *Successful Shape-Based Virtual Screening: The Discovery of a Potent Inhibitor of the Type I TGFbeta Receptor Kinase (TbetaRI)*, 13 BIOORGANIC & MEDICINAL CHEMISTRY LETTERS 4355 (2003)).

45. *Id.*

46. *Id.*

47. *See generally* DAVID KEYES ET AL., MULTIPHYSICS SIMULATIONS: CHALLENGES AND OPPORTUNITIES 71 (2011), http://www.mcs.anl.gov/uploads/cels/papers/ANL_MCS-TM-321.pdf ("[A] vast variety of approaches to high-performance multiphysics . . . contributed from the applications, mathematics, and computer science communities in developing the science, the methods, and the computational infrastructure necessary for bringing together complex simulations of multiple physics processes in parallel computing environments.").

48. *Id.* at 14, 13 fig.4; *see, e.g.*, ELLAD B. TADMOR & RONALD E. MILLER, MODELING MATERIALS: CONTINUUM, ATOMISTIC AND MULTISCALE TECHNIQUES 1 (2011).

49. *See* Jamie Rigg, *Scientists Create First Computer Simulation of a Complete Organism*, ENGADGET (July 24, 2012), http://www.engadget.com/2012/07/24/first-simulated-organism/ (reporting that *Mycoplasma genitalium* is the first organism to be entirely recreated in binary).

50. *See Astronomers Create First Realistic Virtual Universe*, HARV.-SMITHSONIAN CTR. FOR ASTROPHYSICS (May 7, 2014), https://www.cfa.harvard.edu/news/2014-10; ILLUSTRIS, http://www.illustris-project.org/ (last visited Jan. 11, 2016).

51. *See* John Russel, *First Use of HPC to Pick Vendors in Army Procurement Program*, HPCWIRE (Apr. 29, 2015), www.hpcwire.com/2015/04/29/first-use-of-hpc-to-pick-vendors-in-army-

This is part of a broader trend already underway with simulation playing a key role in "artificial invention technology."[52] This is simulation software with streamlined interfaces that accept simple parameters based on a particular problem.[53] For example, parametric design allows you to specify the weight, height, and tensile strength of an object.[54] A design solution is then calculated that fits within the parameters.[55] These tools are increasingly commonplace. Autodesk CAD software offers plugins for heat transfer and fluid dynamic simulation.[56] A related approach to product development is rapid natural selection. The Oral-B CrossAction toothbrush emerged out of a grueling, Darwinian simulation in which species of randomly evolved toothbrushes died off when a fitter version scrubbed virtual teeth better.[57] The number and type of input parameters, the accuracy of the results, and the usability of the software improves weekly.

Computer modeling and simulation have become indispensable tools of science and engineering. As one journalist explains, the scope may be widening into a "simulation economy" with profound effects for innovation: "While failing 10,000 times in the age of Edison required superhuman fortitude, today . . . we have the opportunity to fail in the virtual world as many times as we like at minimal cost in blood and treasure."[58] Within the design process, simulation's analysis of context both lowers risk and increases

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procurement-program/. As the Department of Defense explains, the goal is to have any powerful simulation directly guide the creation process rather than ex-post-facto analysis. Right now, many simulations analyze what is already proposed but the ambition is for inverse solutions. KEYES ET AL., *supra* note 47, at 2 ("Success in simulating forward models leads to ambitions for inverse problems, sensitivity analysis, uncertainty quantification, model-constrained optimization, and reduced-order modeling, which tend to require many forward simulations. In these advances, the physical model is augmented by variables other than the primitive quantities in which the governing equations are defined.").

52. *See* ROBERT PLOTKIN, THE GENIE IN THE MACHINE 1 (2009).

53. *Id.* at 51 (stating that a set of parameters are used to describing features of toothbrushes for the simulation software).

54. *See, e.g.*, *id.*

55. *Id.* at 51–52.

56. *See* *Computational Fluid Dynamics Software*, AUTODESK, http://www.autodesk.com/products/cfd/overview (last visited Jan. 11, 2016).

57. *See* PLOTKIN, *supra* note 52, at 51–52.

58. Greg Satell, *The Simulation Economy*, DIGITAL TONTO (Jan. 6, 2013), http://www.digitaltonto.com/2013/the-simulation-economy/.

certainty as to risk.[59] The simulation economy places powerful computation in the center of the design process.

Surprisingly, the massive computing resources required to run these simulations may soon be available to anyone at a much lower cost.[60]

II. YOUR ACCESSIBLE, ELASTIC, SUPERCOMPUTER

At their debut, computing technologies that far outstrip current computational needs are often unappreciated for their widespread application, especially among "lay" users, such as consumers. For example, Charles Babbage designed a massive "difference engine" in the nineteenth century to churn out polynomial values.[61] His contemporaries found it inconceivable that ordinary people would ever need that level of computing power.[62] As Gottfried Wilhelm Leibniz, one of the co-inventors of the calculus asserted: "[A calculating engine] is not made for those who sell vegetables or little fishes, but for observatories, or the private rooms of calculators, or for others who can easily bear the expense, and need a good deal of calculation."[63] Pocket calculators have more power, speed, and flexibility than Babbage's five-ton single-purpose contraption.[64] Today, an

59. *See, e.g.*, MSC SOFTWARE CORP., MSC SOLUTIONS MEDICAL DEVICE INDUSTRY: SIMULATION METHODS FOR REDUCING RISK AND ACCELERATING INNOVATION (2013), http://www.mscsoftware.com/sites/default/files/br_industry-medical_ltr_w_0.pdf (marketing software solutions that help medical device manufacturers conduct massive simulations within complex biological and environmental conditions to identify risks in design and to communicate risks to regulators).

60. *See* Satell, *supra* note 58.

61. *See The Engines*, COMPUTER HIST. MUSEUM, http://www.computerhistory.org/babbage/engines/ (last visited Jan. 11, 2016).

62. *See* JAMES GLEICK, THE INFORMATION: A HISTORY, A THEORY, A FLOOD 119–20 (2011).

63. H.P. Babbage, *The Analytical Engine*, PROCEEDINGS OF THE BRITISH ASS'N, Sept. 12, 1888, *reprinted in* CHARLES BABBAGE AND HIS CALCULATING ENGINES: SELECTED WRITINGS BY CHARLES BABBAGE AND OTHERS 331, 333 (Philip Morrison & Emily Morrison eds., 1961), [https://www.fourmilab.ch/babbage/Ohpb.html] (paraphrasing Leibniz in a report given by Babbage's son to the British Association).

64. *A Brief History*, COMPUTER HIST. MUSEUM, http://www.computerhistory.org/babbage/history/ (last visited Feb. 19, 2016); *see The Engines*, *supra* note 61 ("[Difference engines] crunch numbers the only way they know how - by repeated addition according to the method of finite differences. They cannot be used for general arithmetical calculation. [Yet t]he Analytical Engine is much more than a calculator and marks the progression

iPhone computes thousands of times faster than the Apollo 11 guidance computer.[65]

We are about to experience the largest leap in accessible computation in history, a time when anyone can have a supercomputer and therefore become direct participants in the simulation economy. What may be surprising is that this capability echoes gains made one generation prior in an IT architecture from the 1960s. That seemingly stale model, a centralized mainframe with peripheral terminals, is re-emerging half a century later to deliver supercomputing to the masses.

Like most new computing tools, the mainframe computer was expensive, difficult to use, and reserved for "worthwhile" projects.[66] Time-sharing systems made it economical, within a single organization and physical location, to share this resource with ordinary employees.[67] "Dumb" terminals at workstations communicated inputs over simple cables to the centralized processor.[68] Some time would pass while the computer queued the request and played "electronic round-robin" with users' workloads.[69] Finally, the output returned along the same path to be displayed at the terminal.[70] Time-sharing mainframes brought computation to people who had never interacted with computers before.[71]

The mainframe fell out of service and gave birth to two apparently distinct family lines, one maximizing toward the supercomputer, and the other miniaturizing toward the PC.[72] The Cray-1 initialized a perpetual, global race for the fastest

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from the mechanized arithmetic of calculation to fully-fledged general-purpose computation.").

65. *See* Rhuaridh Marr, *To the Moon and Back on 4KB of Memory*, METRO WKLY. (July 24, 2014), http://www.metroweekly.com/2014/07/to-the-moon-and-back-on-4kb-of-memory/.

66. *See* PAUL E. CERUZZI, A HISTORY OF MODERN COMPUTING 154–58 (2d ed. 2003).

67. *Id.* at 154–55 ("[E]ach user had the illusion that a complete machine and its software was at his or her disposal . . . . The few seconds that a person might pause to ponder the next command to type in was time enough for a computer to let another user's creation emerge, grow, and die . . . .").

68. *Id.* at 154–58.

69. GLEICK, *supra* note 20, at 179.

70. CERUZZI, *supra* note 66.

71. *Id.*

72. This is, of course, a simplified model of the development of computers.

supercomputer. Supercomputers increased in power "vertically" as the processing of each CPU,[73] or physically proximate groups of CPUs, improved according to Moore's law.[74] But supercomputers also began to advance "horizontally" by coordinating many, less-tightly associated CPUs, for example cohabitating in the same warehouse a few yards from one another.[75] A horizontally scaled hardware "cluster," that is, a collection of similarly configured processors, labored as a team to solve one problem or a set of related problems.[76] By the mid-2000s supercomputers had made huge gains. For example, IBM's Blue Gene processed 10,000,000-fold faster than Cray-1, and, despite more tightly packed transistors, took up many times the physical footprint.[77]

The second progeny of the mainframe tended in the opposite direction, starting with the refrigerator-sized "minicomputer."[78] A brief intermediate, the minicomputer split into the personal computer (PC) and the more powerful server that became the hub of small local area networks.[79] Linking

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73. *See Scalability*, WIKIPEDIA, https://en.wikipedia.org/wiki/Scalability [https://web.archive.org/web/20160219065102/https://en.wikipedia.org/wiki/Scalability] (last modified Feb. 16, 2016) ("To scale vertically (or scale up) means to add resources to a single node in a system, typically involving the addition of CPUs or memory to a single computer.").

74. *See 50 Years of Moore's Law*, INTEL, http://www.intel.com/content/www/us/en/silicon-innovations/moores-law-technology.html (last visited Jan. 11, 2016) ("From careful observation of an emerging trend, Moore extrapolated that computing would dramatically increase in power, and decrease in relative cost, at an exponential pace.").

75. *See Scalability*, *supra* note 73 ("To scale horizontally (or scale out) means to add more nodes to a system, such as adding a new computer to a distributed software application. An example might involve scaling out from one Web server system to three.").

76. *See An Introduction to High Performance Computing on AWS*, AMAZON WEB SERVICES 7 (Aug. 2015), https://d0.awsstatic.com/whitepapers/Intro_to_HPC_on_AWS.pdf ("[A cluster occurs where] two or more computers are connected and used together to support a single application, or a workflow consisting of related applications . . . . Clusters are most commonly assembled using the same type of computers and CPUs . . . .").

77. *See Computer Simulations Help Design New Nuclear Reactors*, *supra* note 43.

78. *See Smaller Is Better*, Exhibit to *Minicomputers*, COMPUTER HIST. MUSEUM, http://www.computerhistory.org/revolution/minicomputers/11/332 (last visited Feb. 20, 2016).

79. This is an oversimplified development history that involved many shapes, sizes, and powers of computer. The PC, while by some standards

those small networks into the Internet enhanced how we exchanged information—but it did not immediately change where the user's primary computation took place. Computation set into motion by ordinary users cycled in their desktop chassis. The organization's primary computation occurred in their information technology (IT) department's on-site server room. The nascent Internet only had enough information transport capacity, known as bandwidth, to allow rudimentary messaging such as email and web page retrieval.[80]

In the late 1990s, connectivity and bandwidth strengthened enough to support remote access to software.[81] The resulting software-as-a-service (SaaS) ran on a server at a distant site, with users interfacing with it through a "light" PC application.[82] For example, Salesforce, one of the first major companies to succeed at the business model, allowed for complete customer relations management through a web browser.[83] SaaS created economies of scale by sharing a server between multiple users, described as "multi-tenant" like an apartment complex.[84] Users who could not previously afford IT departments gained access to new business software,[85] a slight resemblance to the timesharing model.

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originating as its own line, can be seen as within the same family line of "miniaturization" as the minicomputer. In general during this time period, personal computers and business server computers were considered "commodity hardware" and more similar to one another than either was to supercomputers. For example, PCs could be used as web servers, and some minicomputers continued to power internet nodes well into the 1990s.

80. *See* Steven J. Vaughan-Nichols, *The Pre-History of Software as a Service*, SMARTBEAR (Jan. 7, 2014), http://blog.smartbear.com/cloud-computing/the-pre-history-of-software-as-a-service/.

81. *See id.*

82. *See id.*

83. *See id.*

84. *See id.*

85. *Cf.* Patrick Lo, *Cloud Computing Is About to Get Personal*, NETWORK WORLD (June 6, 2013), http://www.networkworld.com/article/2166996/tech-primers/cloud-computing-is-about-to-get-personal.html ("[T]he personal cloud will create opportunity. Opportunity for users who have not been able to afford services historically tethered to an expensive device; opportunity for manufacturers to design lower-cost hardware to reach a new demographic in developing countries; and huge opportunity for businesses to bring a new wave of services to this previously untapped audience."); Scott Sehlhorst, *The Economics of Software as a Service (SaaS) vs. Software as a Product*, PRAGMATIC MARKETING, http://pragmaticmarketing.com/resources/the-economics-of-software-as-a-service-saas-vs-software-as-a-product (last visited Jan. 11, 2016).

Years after its founding analysts would describe Salesforce as one of the first "cloud computing" companies.[86] This Article attaches specific meaning to the context-dependent term "cloud" in three iterations: cloud service, cloud computing, and cloud computer. Economist Joe Weinman provided one of the first useful definitions.[87] According to Weinman a *cloud service* (not necessarily related to computing) possesses five properties: (1) infrastructure is shared;[88] (2) resources are accessible over networks;[89] (3) the resources are location independent, accessible from almost anywhere;[90] (4) pricing occurs on a utility basis;[91] and (5) resources are on-demand.[92] Within the context of *cloud computing*, the infrastructure is physical hardware like cabling and servers (i.e., processors, RAM, hard disks).[93] The resources may take several forms. They may be software, such as that offered by Salesforce, or even a simple data backup service.[94] They may also be a platform to design or build software.[95] However, on a lower level, the resource may simply be the raw processing power, memory, storage, or bandwidth that can be put to any purpose.[96] Utility pricing is based on, for example, the number of users accessing software, bytes of storage or bandwidth, and sometimes even the amount of expended computing cycles.[97]

For decades the world of supercomputing and commodity computing seemed far apart, with the capital expenditure required for supercomputing a prohibitive barrier to many. But in 1998, those watching closely received a brief glimpse into a future where the two might converge. A group of scientists called the Search for Extra Terrestrial Intelligence (SETI)

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86. *See, e.g.*, Arif Mohamed, *A History of Cloud Computing*, COMPUTER WKLY. (Mar. 2009), http://www.computerweekly.com/feature/A-history-of-cloud-computing.

87. *See* JOE WEINMAN, CLOUDONOMICS: THE BUSINESS VALUE OF CLOUD COMPUTING 63–70 (2012).

88. *Id.* at 68–69.

89. *Id.* at 70.

90. *Id.* at 69–70.

91. *Id.* at 67–68.

92. *Id.* at 66–67.

93. *Id.* at 68–69.

94. *Id.* at 63.

95. *Id.* at 277.

96. *Id.* at 279.

97. *Id.* at 68.

attempted to parse massive quantities of interstellar radio signals.[98] But the sky poured too much data onto their telescope.[99] Universities allocated only so much supercomputing time (searching for aliens had to get in line with other research), and buying additional time was costly.[100] The group appealed to their fans to donate idle computing time of their PCs.[101] In contrast to a cluster made from uniform hardware, the SETI network defined a "grid" of dissimilar computing hardware.[102] SETI's grid, yet to find alien signals, succeeded as an organizational effort. Over six million people have participated in the project.[103]

Then, the segregated families reunited. E-commerce giant Amazon built a sprawling network of computers to serve their global user base.[104] Yet, because Amazon's network was designed to handle any conceivable demand spike much of it sat unused at any given time.[105] Amazon struck on an idea: why not rent the idle computing resources? The company launched its Elastic Compute Cloud (EC2) in 2006, allowing anyone with a credit card to "stand up" a virtual server.[106] Distinct from a mere cloud software service, Amazon gave birth to the first general purpose cloud computer. Within this Article, a *cloud computer* is a collection of pooled computing resources, such as processing, memory, and storage, that act together as a single computer.[107] In other words, it is a cloud computing

98. *SETI@Home: Millions Together, Searching for a Signal from the Stars*, *supra* note 6.

99. *Id.*

100. *Id.*

101. *Id.*

102. *See An Introduction to High Performance Computing on AWS*, *supra* note 76 ("[A grid occurs where] locality is not a primary requirement, and the size of the cluster can grow and shrink dynamically in response to the cost and availability of resources. Grids can be assembled over a wide area, perhaps using a heterogeneous collection of server and CPU types, or by 'borrowing' spare computing cycles from otherwise idle machines in an office environment, or across the Internet.").

103. *SETI@Home: Millions Together, Searching for a Signal from the Stars*, *supra* note 6.

104. *See* Mohamed, *supra* note 86.

105. *Id.*

106. *Id.*

107. *See* PETER MELL & TIMOTHY GRANCE, NAT'L INST. OF STANDARDS & TECH., THE NIST DEFINITION OF CLOUD COMPUTING 2 (2011), http://nvlpubs.nist.gov/nistpubs/Legacy/SP/nistspecialpublication800-145.pdf ("Cloud computing is a model for enabling ubiquitous, convenient, on-demand

service that offers up not application specific software like Salesforce but raw computing stuffs—it is infrastructure-as-a-service (IaaS).[108]

EC2 resurrected the mainframe-terminal timesharing model, familiar but amplified in its scope and consequence.[109] The mainframe reappeared as the hundreds or thousands of consorting servers in one or more data centers; the dumb terminal evolved into a "thin client," like our PC or smartphone; and the connection between the centralized hub and the interface changed from a simple bus wire to the tangled Internet. But there are also stark differences between the mainframe and the cloud. Every mainframe had factory-defined specs, at best extensible in modular but finite blocks. The cloud computer, on the other hand, shape-shifts to arbitrary size at a whim. Like the name of a later cloud provider, it is a "digital ocean" of resource.[110]

Originally intended for use to power large-scale enterprise applications, scientists immediately recognized EC2 as the supercomputer they always wanted. With the cloud, the project-killing capital expenditure and result-capping time allocation dropped to a small, buy-anytime operational expense.[111] High performance computing workloads have begun a steady migration to the cloud.[112] But this new tool is not just

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network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction.").

108. *See Infrastructure as a Service (IaaS)*, GARTNER, http://www.gartner.com/it-glossary/infrastructure-as-a-service-iaas/ (last visited Jan. 11, 2016) ("Infrastructure as a service (IaaS) is a standardized, highly automated offering, where compute resources, complemented by storage and networking capabilities are owned and hosted by a service provider and offered to customers on-demand.").

109. *See* Michael Otey, *Is the Cloud Really Just the Return of Mainframe Computing?*, SQL SERVER PRO (Mar. 22, 2011), http://sqlmag.com/cloud/cloud-really-just-return-mainframe-computing.

110. DIGITAL OCEAN, https://www.digitalocean.com/ (last visited Jan. 11, 2016).

111. *See* Cliff Saran, *Cloud-Based Simulation Cuts Engineers' Design Costs*, COMPUTER WKLY. (July 2009), http://www.computerweekly.com/feature/Cloud-based-simulation-cuts-engineers-design-costs.

112. *See* Tiffany Trader, *Amazon Web Services Spotlights HPC Options*, HPCWIRE (Aug. 11, 2015), http://www.hpcwire.com/2015/08/11/amazon-web-services-spotlights-hpc-options/ ("In summary, [International Data Corporation] foresees public clouds, and especially custom public clouds,

for powerful commercial use or sophisticated users like researchers. Like the mainframe timesharing it also allows distribution of previously scarce computing resources to less sophisticated users. For example, a New York newspaper needed to convert 11 million scanned documents to PDF format, a process that normally would take months.[113] EC2 allowed them to provision 100 servers to complete the project in 24 hours for just $250.[114]

The cloud is not just decreasing in cost, it is becoming more usable. Fundamentally, each cloud provider defines a basic API to manipulate computing resources.[115] Configuration management software automates large-scale cloud use and enables sharing of deployment blueprints.[116] Newer systems have incorporated these functions into code-less graphical user interfaces.[117] Application "containers," such as Docker easily "ship" applications to the cloud for launch, control, and termination.[118] Finally, software running on a local machine, for example, Autodesk 360 CAD software, calls directly for the cloud to process difficult jobs such as rendering or fluid dynamics.[119] New artificial intelligence tools that interpret natural language, such as IBM's Watson, may widen the

supporting an increasing proportion of the aggregate [high performance computing] workload as these cloud facilities grow more capable and mature.").

113. *See* Yasir Ahmed Hamza & Marwan Dahar Omar, *Cloud Computing Security: Abuse and Nefarious Use of Cloud Computing*, INT'L J. COMPUTATIONAL ENGINEERING RES., June 2013, at 22, http://www.ijceronline.com/papers/Vol3_issue6/part%204/D0364022027.pdf.

114. *Id.*

115. *See AWS Documentation*, AMAZON WEB SERVICES, http://docs.aws.amazon.com/AWSEC2/latest/CommandLineReference/Welcome.html (last visited Jan. 20, 2016).

116. *See Software Configuration Management*, WIKIPEDIA, https://en.wikipedia.org/wiki/Software_configuration_management [https://web.archive.org/web/20151217180912/https://en.wikipedia.org/wiki/Software_configuration_management] (last modified Dec. 9, 2015).

117. *E.g.*, VIXTERA, http://www.vixtera.com/index/unity-platform (last visited Jan. 20, 2016).

118. *See* DOCKER, https://www.docker.com/ (last visited Jan. 20, 2016).

119. *See* Josh Mings, *Autodesk Simulation 360 Reveals the Cost of the Cloud*, SOLIDSMACK (Sept. 19, 2012), http://www.solidsmack.com/cad/autodesk-simulation-360-reveals-the-cost-of-the-cloud/ ("[T]he time has come where you can release your mesh from the bondage of itty-bitty-gigabitties of processing power and ship it off to the cloud for unlimited mesh mashing.").

audience for solving such problems.[120] We are a step away from consumer-oriented applications entering "orders" for high-powered simulation jobs.[121] Like all previous expansions of computing to which ordinary users aspired, today's high performance computing inevitably becomes tomorrow's lay reckoning tool.[122]

While adoption will follow that inevitable cycle, the cloud knows no precedent in a new computing tool's leap in computing power and accessibility. A decade ago we acquired and consumed computation through a historical procedure: one saved money and bought a computing tool. Slowly, sequentially, you fed the device jobs until the hardware broke or passed into obsolescence. A cloud computer is nothing like this. You now can command forty thousand processors, working tirelessly in parallel, rented anywhere on demand for as long as your calculation takes. Thousands of years of processing power[123] flash by in hours, minutes, or seconds.[124] At the flick of a switch, for a relative pittance, the hardware and all its associated encumbrances dissolve and you simply get what you came for: an answer.

Cloud computers may become more personal than the PC, with the added power removing the conceptual barrier between man and machine. In reference to the *Iron Man* superhero

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120. *See* *Natural Language Classifier*, IBM, http://www.ibm.com/smarterplanet/us/en/ibmwatson/developercloud/nl-classifier.html (last visited Jan. 11, 2016).

121. *Cf.* Autodesk Inventor, *Computational Fluid Dynamics (CFD) Simulation Overview - Autodesk Simulation*, YOUTUBE (May 5, 2011), https://www.youtube.com/watch?v=oL_DOxFagvI (emphasis on 1:30) ("[Product that streamlines] terminology, workflow guidance, and user-friendly tools and wizards that automate the transfer of simulation results between multiple analysis—letting you focus on product performance, not advanced numerical or simulation methods.").

122. *See supra* Part I.

123. *Cf.* Ben Butler, *Intro to High Performance Computing in the AWS Cloud*, AMAZON WEB SERVICES (July 25, 2014), http://www.slideshare.net/AmazonWebServices/intro-to-high-performance-computing-in-the-aws-cloud (emphasis on slide 23) (explaining a quantum mechanics simulation run on AWS with an estimated single-processor computing time of 264 years).

124. *See* Mehul Patel, *The Future of Engineering Simulation Is in Cloud*, PRODUCT DESIGN & DEV. (July 24, 2015, 9:51 AM), http://www.pddnet.com/article/2015/07/future-engineering-simulation-cloud ("Since there is no limitation on the computational power, it is possible to obtain results in hours or minutes compared to on-premise deployment . . . .").

movies, one supercomputing researcher describes the future "Tony Stark interface," where a person interactively designs physical objects through an automated, high-fidelity simulation.[125] The fictional Stark uses that cognitive extension to enhance his physical form with the body-fitted Iron Man suit.[126] Weinman's description of the significance of virtually unlimited computing for the common person lays groundwork for this imagined future:

> Computing used to be restricted to a few disciples granted admission to the inner sanctum . . . . Now the cloud has unleashed creativity, innovation, and experimentation . . . . This is not just the democratization of the *use* of IT enabled by the PC and desktop software but the democratization of the *creation* of IT . . . .[127]

For a moment, adopt Weinman's analysis and entertain the premise that CAM transcribes information into reality. Then cloud computers democratize the creation of reality itself.

III. CAM AND COMPUTATION: THE INEXTRICABLE LINK

The ability to simulate context and generate CAD files does little good if one cannot build the proposed design economically or technically. For example, simulation may show that a specific design that may be an ideal solution for a particular heat transfer problem. But the design's shape, or intricate combines materials, may be impossible to make with traditional manufacturing techniques. CAM, led by 3D printers, empowered information to translate directly to reality with almost complete fidelity between the physical and digital objects.

Five years ago, 3D printers crept into the consumer marketplace in the opening whitespace of several expiring patents.[128] Articles on the technology painstakingly detailed their "layer-by-layer" construction technique as if apologizing

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125. *See* HPCwire, *Roger Strawn, HPC User Forum, Norfolk, VA*, YOUTUBE (Apr. 21, 2015), https://www.youtube.com/watch?v=1pcsNIRKoEg (emphasis on 24:50) (depicting a presentation on High Performance Computing Applications and Future Requirements for Army Rotocraft).

126. *Id.*

127. WEINMAN, *supra* note 87, at 31.

128. *See* Pieter Van Lancker, *Technology Mapping: The Influence of IP on the 3D Printing Evolution*, CREAX (Aug. 12, 2015), https://www.creax.com/en/our-work/the-3d-printing-evolution-insights-on-the-influence-of-ip-on-technology-dev.

for miraculous functionality.[129] Since then, venture capital has poured in and developments outpace analysts: UCLA researchers print nano-structures finer than a hair;[130] Dutch-based Boskalis prints artificial coral reefs for deployment in Monaco;[131] the U.S. Air Force integrates 3D printing into every aspect of aircraft design, construction, and maintenance;[132] engineers at Cornell print bio-actuators that mimic octopus tentacles.[133] These developments headlined in the same two-week period.

The new industrial revolution[134]—as people are getting comfortable calling it—is your revolution.[135] These tools will be

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129. *See, e.g.*, Ashlee Vance, *3-D Printing Spurs a Manufacturing Revolution*, N.Y. TIMES (Sept. 14, 2010), www.nytimes.com/2010/09/14/technology/14print.html ("A 3-D printer, which has nothing to do with paper printers, creates an object by stacking one layer of material — typically plastic or metal — on top of another, much the same way a pastry chef makes baklava with sheets of phyllo dough.").

130. *See* Kira Charron, *New 3D Printing Technique Creates Complex Micro-Objects Smaller than a Human Hair*, 3DERS.ORG (Nov. 3, 2015), http://www.3ders.org/articles/20151103-new-3d-printing-technique-creates-complex-micro-objects-smaller-than-a-human-hair.html.

131. *See* Kira Charron, *3D Printed Reefs in Monaco Help Preserve and Save Marine Biodiversity*, 3DERS.ORG (Oct. 22, 2015), http://www.3ders.org/articles/20151021-3d-printed-coral-reefs-in-monaco-help-preserve-and-save-marine-biodiversity.html ("While the concept of artificial reef ecosystems already exists, they are traditionally made from concrete poured into a mould, and lack the complexity of caves . . . in natural reefs, prohibiting wildlife from safely settling in. What makes these reefs stand apart is that rather than concrete, they were 3D printed with actual sand, allowing them to better mimic natural formations.").

132. *See* Kira Charron, *US Air Force to Integrate 3D Printing into Almost All Aspects of Aircraft Design and Maintenance*, 3DERS.ORG (Oct. 21, 2015), http://www.3ders.org/articles/20151021-us-air-force-to-integrate-3d-printing-into-aircraft-design-and-maintenance.html.

133. *See* Alec Buren, *Cornell University Engineers 3D Print Soft Actuator that Mimics the Muscles of Octopus Tentacles*, 3DERS.ORG (Oct. 15, 2015), http://www.3ders.org/articles/20151015-cornell-university-engineers-successfully-3d-print-soft-actuator-that-mimics-the-muscles-of-octopus-tentacles.html.

134. For early works declaring the revolution, see CHRIS ANDERSON, MAKERS: THE NEW INDUSTRIAL REVOLUTION 16–20 (2012) [hereinafter ANDERSON, MAKERS]; Chris Anderson, *In the Next Industrial Revolution, Atoms Are the New Bits*, WIRED, Feb. 2010, at 58, http://www.wired.com/2010/01/ff_newrevolution/ [hereinafter Anderson, *Atoms Are the New Bits*]; *A Third Industrial Revolution*, ECONOMIST, Apr. 21, 2012, at 4, http://www.economist.com/node/21552901.

135. *See* Anderson, *Atoms Are the New Bits*, *supra* note 134 ("Transformative change happens when industries democratize, when they're

widespread and our familiarity with them intimate.[136] By 2016, some plastic-based consumer 3D printers sold for as little as $100.[137] Big box stores such as Lowe's have on-site 3D printers for customers to print repair parts.[138] For high-end printing, one can submit CAD files over the Internet to services that mail back parts in ceramics and metals.[139] Three-dimensional printers are standard fare at "maker spaces,"[140] and are the hottest addition to the classroom.[141] And the revolution is not just industrial. It means a new era of artistic expression and

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ripped from the sole domain of companies, governments, and other institutions and handed over to regular folks. The Internet democratized publishing, broadcasting, and communications . . . the long tail of bits. Now the same is happening to manufacturing — the long tail of things.").

136. Some believe 3D printing will become a home staple. *Compare* Steve Heller, *A 3D Printer in Every Home? MakerBot's CEO Thinks So*, MOTLEY FOOL (May 15, 2015, 10:04 AM), http://www.fool.com/investing/general/2015/05/15/a-3d-printer-in-every-home-makerbots-ceo-thinks-so.aspx (suggesting that 3D printers in the home will soon become a reality), *with* Filemon Schoffer, *Down the Hype Cycle: A 3D Printer in Every Home?*, TECHCRUNCH (Jan. 26, 2016), http://techcrunch.com/2016/01/26/whats-next-for-3d-printing-hype-cycle/ (suggesting that 3D printers will not be needed in every home and that their implementation is further way than some realize). Whether 3D printers arise to or surpass the prevalence of desktop printers, consumers are likely to have a close interaction with the technology through local distribution facilities, "micro factories," communal 3D printers available for hire in copy shops, or via mail order services.

137. *See, e.g.*, PEACHYPRINTER, http://www.peachyprinter.com/ (last visited Jan. 11, 2016) (showing a Kickstarter crowdfunding campaign for a combination 3D printer and 3D scanner at a one hundred dollar retail price).

138. Krystina Gustafson, *Lowe's Brings 3-D Printing to Home Improvement*, CNBC (Apr. 29, 2015, 9:00 AM), http://www.cnbc.com/2015/04/28/lowes-brings-3-d-printing-to-home-improvement.html; *see 3D Scanning & Printing*, LOWE'S INNOVATION LABS, http://www.lowesinnovationlabs.com/3dprintscan/ (last visited Mar. 11, 2016).

139. *See, e.g.*, *About Us*, SHAPEWAYS, http://www.shapeways.com/about (last visited Jan. 11, 2016) (explaining how clients can send their ideas to Shapeways which will produce and mail the completed object back to clients); I.MATERIALISE, http://i.materialise.com (last visited Jan. 11, 2016) (explaining that i.materialise turns ideas into 3D printed reality).

140. *See* ANDERSON, MAKERS, *supra* note 134, at 18 (describing the number of shared production facilities around 1000); HACKER DOJO, http://www.hackerdojo.com (last visited Jan. 11, 2016); NOISEBRIDGE, https://www.noisebridge.net (last visited Jan. 11, 2016); TECHSHOP, http://techshop.ws (last visited Jan. 11, 2016).

141. *See* Shanie Phillips, *3 Educational Initiatives Bringing 3D Printing to the Classroom*, INSIDE3DP (Aug. 4, 2014, 6:18 PM), http://www.inside3dp.com/3-educational-initiatives-bringing-3d-printing-classroom/.

fresh scientific research driven by individuals and small groups.[142]

With all this excitement it's easy to miss the forest for the trees. First, the underlying technological shift is broader than the 3D printer. More generally, CAM uses self-contained devices to build objects according to CAD files.[143] For example, CAM devices include DNA fabricators that have made heroic gains in the last decade and chemical synthesizers are currently under development.[144] Behind in awareness, these tools are just as important to the revolution in the long term.

CAM has three idealized properties. First, the self-contained little factories produce substantially complete products.[145] Second, making entirely different objects doesn't require retooling the device.[146] In other words, economies of scale break down.[147] You can customize any design or create idiosyncratic one-offs without extra cost.[148] Finally, 3D printers exactly translate a digital design into a physical object. The translation is tempered by the inherent limits of the CAM device, for example, the materials the device can use and the resolution with which it can deposit that material. But this property of accurate translation is the most significant. If powerful computer simulations mimic reality, CAM now effects

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142. *See* Peter Jensen-Haxel, *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*, 5 WAKE FOREST J.L. & PUB. POL'Y 231, 248–54 (2015).

143. One DNA fabrication device has lowered the cost of DNA creation by 10,000 fold. *See* Bloomberg Business, *DNA Consumer Products: Not as Far Out as You Think*, YOUTUBE (June 5, 2013), https://www.youtube.com/watch?v=HCKpl_T5r_I#t=306; TEDx Talks, *The Dark Side of the Double Helix: Andrew Hessel at TEDx Marin 2012,* YOUTUBE (Nov. 2, 2012), https://www.youtube.com/watch?v=pZpHdlORAGw (describing DNA fabricator accessibility).

144. *See* William Herkewitz, *This Chemistry 3D Printer Can Synthesize Molecules from Scratch*, POPULAR MECHANICS (Mar. 12, 2015), http://www.popularmechanics.com/science/health/a14528/the-chemistry-3d-printer-can-craft-rare-medicinal-molecules-from-scratch/ (explaining that a chemical printer is in development with aspirations to 'print' such molecules as "obscure medicinal compound[s] found only in . . . jungle plant[s]").

145. In practice, some post-processing or assembly may be required.

146. *See* Vance, *supra* note 129.

147. *See* 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/.

148. *Id.*

the inverse. 3D printers materialize intricate shapes that, even if describable, could not be built.[149] Similarly, where past generations could only assemble small chains of DNA or stitch together preexisting strands, fabricators can "print" arbitrary sequences typed out in a text file.[150]

CAM has an ambitious trajectory. In the first phase of its development, 3D printers matured from building prototypes to completed products.[151] Each CAM device generally worked with one material at a time and within a single scale.[152] As this phase ends, the number of materials available is vast and CAM devices of one kind or another build things tiny and gigantic.[153] In the second phase, now ongoing, a single CAM device simultaneously builds with several materials and at multiple scales.[154] In phase three, soon to begin, CAM will create entirely novel raw materials.[155] Almost every product or technology we know could improve drastically. Finally, CAM will span the entire structural hierarchy of matter within one

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149. *See, e.g.*, Liz Stinson, *15 Amazing Designs that Were Impossible to Make 15 Years Ago*, WIRED (Nov. 5, 2013), http://www.wired.com/2013/11/digital-fabrication-created-these-tk-crazy-works-of-art/.

150. *See* TEDx Talks, *supra* note 143.

151. *See* Jensen-Haxel, *supra* note 142 ("The first generation of CAM acted upon a single, lifeless, uniform material."); Victoria Turk, *Finally, 3D Printers Are Making Things that Are Actually Useful*, VICE: MOTHERBOARD (Sept. 4, 2014, 8:45 AM), http://motherboard.vice.com/read/finally-3d-printers-are-making-things-that-are-actually-useful.

152. *See generally* LIPSON & KURMAN, *supra* note 4, at 23 (providing a history of 3D printers); Mary-Ann Ruson, *MIT Invents 'Breakthrough' 3D Printer that Can Print 10 Different Materials Simultaneously*, INT'L BUS. TIMES (Aug. 26, 2015, 2:43 PM), http://www.ibtimes.co.uk/mit-invents-breakthrough-3d-printer-that-can-print-10-different-materials-simultaneously-1517149.

153. *See* Roland Hutchinson, *3D Printer Creates the World's Smallest 3D Printed Objects*, GEEKY GADGETS (Mar. 13, 2016, 7:29 AM), http://www.geeky-gadgets.com/3d-printer-creates-the-worlds-smallest-3d-printed-objects-video-13-03-2012/ (explaining that 3D printers can print nanoscale objects the size of a grain of sand).

154. *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/.

155. For example, materials can be formed with "gradient metal alloys." *See* David Sher, *NASA Is 3D Printing Multiple Metals Simultaneously with New Radiant Deposition Technique*, 3D PRINTING INDUS. (Aug. 7, 2014), http://3dprintingindustry.com/2014/08/07/nasa-3d-printing-multiple-metals-simultaneously-new-radiant-deposition-technique/.

or a few ubiquitous devices.[156] It may even be possible to seamlessly mix inorganic structure, biology, and electronics.[157] In other words, the machines are advancing toward materializing any design that can be specified and stored as information.

CAM's bond to powerful computation surfaced early but remains mostly submerged. In some of the first 3D printer projects, mathematically minded artists demonstrated the technology's novelty through algorithm-based art.[158] Similarly, fun projects include ridiculous shapes that a machinist would never allow into his or her twentieth century manufacturing vocabulary, for example, concentric spheres.[159] In other cases, algorithms warp CAD models to imbue them with new utility. For example, one program adjusts a CAD file so that, while still completely recognizable, it is bestowed with a perfect moment of inertia when spun as a top.[160]

Yet many of the objects that CAM produces derive from, or are strongly influenced by, pre-CAM design. People print replacement parts for vintage automobiles.[161] New companies offer anthropomorphic fantasy figurines wearing armor and wielding weapons dictated by the limitations of Middle Ages hand tools.[162] We are trying hard to escape the gravity of 5000

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156. *See* Jensen-Haxel, *supra* note 142 ("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.").

157. *See id.* (describing theoretical "chimeric systems of electronics, biology, and inanimate matter").

158. *See, e.g.*, Michael Molitch-Hou, *Paul Nylander's World of 3D Printed Math Art*, 3D PRINTING INDUS. (Feb. 5, 2014), http://3dprintingindustry.com/2014/02/05/paul-nylanders-world-3d-printed-math-art/.

159. *See* Chris Waldo, *10 3D printed Objects that Defy Traditional Manufacturing*, 3D PRINTER (July 16, 2012), http://www.3dprinter.net/10-3d-prints-that-defy-traditional-manufacturing.

160. Andrew Liszewski, *Disney Can Turn Any 3D-Printed Object into a Perfectly Spinning Top*, GIZMODO (Aug. 8, 2014, 5:11 PM), http://gizmodo.com/disney-can-turn-any-3d-printed-object-into-a-perfectly-1618384694.

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

162. *See* IMAGINE 3D MINIATURES, http://www.imagine3dminiatures.com/ (last visited Jan. 11, 2016).

years of collective manufacturing experience. Nature is the first place we turn for fresh inspiration.[163] But for now, our creativity is imperceptibly hobbled by every man-made object we've ever encountered.

That is, until we recognize our new computing capacity and extend our design capability to the digital ocean. Because of CAM's unique properties, the technology only blossoms in cooperation with powerful computation.[164] First, the elimination of economies of scale means objects can be created for their unique context. In its simplest form, "[w]hat is to prevent you from [printing] a toaster that squeezes into that oddly shaped nook in your kitchen?"[165] Here the solution is intuitive: measure the nook in your kitchen. Perhaps an algorithm only slightly more complex than the spinning top optimizer will ensure that the heating elements don't pose a fire hazard in their custom configuration.

Let us re-examine the custom toaster approach: what is to prevent you from printing an automobile engine based on your average daily commute, favorite off-road trails, unique towing requirements, and personal environmental stance. An algorithm developed for the purpose, possibly requiring supercomputing time, may parse this context and generate a CAD file for the engine. Alternatively, or in addition, one or many simulations may run to determine the shape the engine should take. This highlights the second unique property that ties CAM to computation: physical faithfulness to the digital design. Almost any output CAD file can be built, no matter the result's shape, molecular conformation, or DNA sequence. The more computer cycles expended, the closer the context can be simulated, the crisper the resulting CAD model, the better the physical result.

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163. *See* LIPSON & KURMAN, *supra* note 4, at 186–87.

164. *See* Jensen-Haxel, *supra* note 142, at 252 (arguing that CAM and powerful computation are "inextricably bound" because the quality of producing computer bit to physical atom design is directly related to quantity of computation and storage capacity).

165. 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*, PUB. KNOWLEDGE (Nov. 10, 2010), https://www.publicknowledge.org/files/docs/3DPrintingPaperPublicKnowledge.pdf.

We have never grasped such utility. Within the year, sneakers with unique flourishes will adjust to your gait;[166] within a decade personalized viruses dispensed from inexpensive DNA fabricators may cure cancer.[167] Sophisticated researchers will be the first to work with these tools. But lay users will adapt and adopt current modeling and simulation in the service of a new killer app, the 3D printer and other CAM devices. In this new age of limitless design, high-powered modeling and simulation may spawn not only marvels but terrors.

IV. DARK SHAPES IN THE CLOUDS

Edward Lorenz, a pioneer of simulation and initiator of chaos theory was described by author James Gleick as "the god of [his] machine universe, free to choose the laws of nature as he pleased."[168] In this way, a tract of idle supercomputing resources waits to amplify personality. Lorenz simulated hurricanes and tornadoes, but they never entered our world. However, the time when trouble can cross the threshold is coming. Regulators anxiously watch as the list of problematic objects producible by CAM grows, from 3D-printed painting forgeries[169] to home-brewed Ebola.[170] But the deceptive and dangerous things created to date cling to past design. When CAM marries supercomputing to reach its full potential the danger could fundamentally change.

High-powered computing first consolidates the threat of existing problematic designs. 3D-printed plastic firearms are a

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166. *See* Claire Maldarelli, *New Balance Plans to Sell a 3D Printed Sneaker in Early 2016*, POPULAR SCI. (Nov. 20, 2015), http://www.popsci.com/new-balance-plans-to-sell-3d-printer-sneaker-in-early-2016.

167. *See* Andrew Hessel, *Synthetic Virology*, TED[X] DANUBIA (May 2014), http://www.tedxdanubia.com/videos/synthetic-virology:andrew-hessel-at-tedxdanubia-2014.

168. GLEICK, *supra* note 20, at 12.

169. *See* 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.

170. *See* Caroline Winter, *Andrew Hessel's Autodesk Team Seeks Crowdsourced Cancer Cure*, BLOOMBERG: BUSINESSWEEK (Mar. 20, 2014), http://www.bloomberg.com/bw/articles/2014-03-20/andrew-hessels-autodesk-team-seeks-crowdsourced-cancer-cure.

well established challenge.[171] But for the individuals and communities developing such weapons, adapting plastic to survive strenuous firing conditions has been trial-and-error.[172] Powerful computing simulation could, on the other hand, accomplish much of the testing "in silico."[173] It will require someone "smart" to build the model and skin it with a usable interface, perhaps a plugin to approachable CAD software. Someone will inevitably take on this feat. Next, molecular simulations may propose new microstructure that teaches cheap plastic to withstand acute pressures. Each generation of model will bring printed firearms closer to the reliability of current industrially produced models.

Parameterized design has the potential to outflank regulators. Man-made rules are just another constraint for supercomputers to take into account and design around. In some cases this may encourage compliance. In other cases, design will tease the shortfalls of written language, allowing a nefarious designer to conform to black letter law while grossly violating legislative intent. Regulatory processes or workflows that occur in physical space are similarly in danger. A criminal or terrorist, for instance, may experiment to find an innocuous object that consistently passes a security checkpoint. They could then parameterize a firearm or explosive to conform to the object's dimensions, weight, and balance profile, and simulate the device's operation for functionality. In a final touch, they may even solicit a dark online community for an airport x-ray simulation to vet the disguise. A dangerous object keyed to a particular circumstance is characteristically different, and has a higher probability for succeeding than may be anticipated by those who define security standards.

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171. *See* Andy Greenberg, *How 3-D Printed Guns Evolved into Serious Weapons in Just One Year*, WIRED (May 15, 2014, 6:30 AM), http://www.wired.com/2014/05/3d-printed-guns/ (noting the first 3D-printed gun was printed and shot in May 2013 garnering significant attention and replication).

172. *See generally id.* (detailing a cascade of incremental improvements to 3D-printed guns as individuals modify, print, and test each other's designs).

173. *See* Greg Satell, *Why the Future of Innovation Is Simulation*, FORBES (July 15, 2013, 7:39 AM), http://www.forbes.com/sites/gregsatell/2013/07/15/why-the-future-of-innovation-is-simulation ("[A] new breed of innovators are outsourcing failure to computer simulations . . . . Whereas before, design prototypes were almost exclusively physical objects, we now develop them in CAD software, and produce a replica in minutes using a 3D printer or a [Computer Numeric Control] router.").

In a more complex example, CAM's control over microstructure guided by high-powered simulation redefines the destructive potential of everyday materials.[174] We see a puddle of gasoline as a fire hazard, but not an unlit candle. Yet the two compounds are first cousins at the molecular level.[175] Our ordinary experience tell us that wax only burns when its surface area expands relative to air, for example, as it liquefies and disperses through a wick. CAM may have the ability to weave commonly available fuel and oxidizers, like paraffin and pool bleach, into military-grade explosives. Such a magic microstructure is only likely to be found by high-powered molecular simulation. This example may represent a conservative prediction in the shadow of the blending of inorganic materials, electronics, and biology.[176]

While these examples are destructive in almost any setting, a more subtle challenge will emerge, this time in cyber security. The first generation of hackers generally confined their activity to software, stealing data, and seizing computer networks.[177] Contemporary hackers pushed a step farther, manipulating systems that directly interact with reality. For example, they have attacked energy grids,[178] sabotaged

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174. While this paper focuses on the contribution of supercomputing, the utility and danger posed by CAM-made objects will also amplify due to unprecedented control over CAM to manipulate the entire hierarchy of matter. For a more in-depth discussion of this point, see Jensen-Haxel, *supra* note 142 *passim*.

175. *See Alkane Types and Structures*, PETROLEUM.CO.UK, http://www.petroleum.co.uk/alkane-chemistry (last visited Jan. 11, 2016).

176. *See* Jensen-Haxel, *supra* note 142, at 270–72 (discussing "chimeric hybrids" of electronics, biology and inorganic matter); Klint Finley, *The Internet of Anything: The 3-D Printer that Can Spit Out Custom Anything*, WIRED (Jan. 1, 2015, 6:30 AM), http://www.wired.com/2015/01/internet-anything-3-d-printer-can-spit-quadcopter-parts/; John Sullivan, *3D Printed Ear Binds Biology with Electronics*, FUTURITY (May 10, 2013), http://www.futurity.org/3d-printed-ear-binds-biology-with-electronics/.

177. *See generally* Mudawi Mukhtar, *Computer Crime: The New Threat*, COMPUTER CRIME RES. CTR., http://www.crime-research.org/library/Mudavi1.htm (last visited Mar. 11, 2016) (providing an overview of activities hackers engaged in during the 1990s and early 2000s).

178. *See Industrial Infection: Hackers Put Chokehold on Energy Firms with Stuxnet-Like Viruses*, RT (July 1, 2014), https://www.rt.com/news/169532-russian-hackers-energy-industry/; *see also* Dan Goodin, *First Known Hacker-Caused Power Outage Signals Troubling Escalation*, ARS TECHNICA (Jan. 4, 2016, 2:46 PM), http://arstechnica.com/security/2016/01/first-known-hacker-caused-power-outage-signals-troubling-escalation/.

mechanical controllers at a smelting factory,[179] and, of course, deployed the Stuxnet virus to destroy uranium centrifuges.[180] The next generation of hacker, however, will target CAD files and the process by which they are created. They will manipulate the deterministic systems of matter itself, utilizing model and simulation as their rootkit.

Specifically, just as supercomputers empower CAM to manifest objects that excel in a given context, they can also create objects that excel at failing within that context or even destroy higher assemblies into which they are incorporated. Deliberately engineering CAD files to build a flawed physical object can be likened to injection of malicious code in software. We can therefore think of the resulting objects as physically infected by a digital virus.

Burgeoning data sources offer not only CAD files but the information required to assemble that object's context and engineer its failure. In biology, as in IT, viruses are contextual, infecting specific organisms or software versions.[181] It would be almost impossible for hackers to write malicious code to manipulate a program they had never seen.[182] As a matter of course, they test their hacks on software systems identical or similar to their target. Likewise, the new breed of reality hackers will analyze a target object and its real world environment. Primarily, they will gain access to the CAD files themselves, which are increasingly prevalent in every form. The race to "wireframe the world" is on. For example the e-commerce service McMaster-Carr includes solid models of

179. *See* Kim Zetter, *A Cyberattack Has Caused Confirmed Physical Damage for the Second Time Ever*, WIRED (Jan. 8, 2015, 5:30 AM), http://www.wired.com/2015/01/german-steel-mill-hack-destruction/.

180. *See* Kim Zetter, *An Unprecedented Look at Stuxnet, The World's First Digital Weapon*, WIRED (Nov. 3, 2014, 6:30 AM), http://www.wired.com/2014/11/countdown-to-zero-day-stuxnet/.

181. *Cf.* Stephen Pincock, *Biology Fights Computer Viruses*, SCIENTIST, July 2006, at 20 (using insights from biologic immune response to viruses to argue that IT security needs to develop more autonomous adaptability and self-repair because viruses adapt to the responses and systems designed to kill them).

182. *Cf.* Goodin, *supra* note 178 (reporting that a virus that caused an unprecedented electricity blackout in Ukraine was a virus package originally detected in 2007 that had been updated and adapted numerous times in order to function as effectively as it did).

every mundane screw, pipe, and fitting they sell.[183] This trend accelerates as CAM objects gain market share because such objects were originally conceived as bits. And the data is getting richer, no longer mere solid models. For example, 3D printing standards organizations hammer out new file types that don't just specify shape but also the production material, density gradient, and microstructure.[184] The environment data is next. Objects hooked up to the "internet of things" tirelessly sense and transmit information about their surroundings.[185]

Attacks will occur on one of three weak links within the automated design process: the CAD file itself, the simulation that designed it, or the original data fed into the simulation. When hackers can use simulation to accurately determine what will cause an object to fail, they can modify or replace the CAD file, as described in the introduction. However, they could also modify the simulation that would otherwise output legitimate CAD files. For example, they can alter a model's parameters by introducing improper or unrealistic assumptions about the physical world. More pronounced, they may realign the underlying model to comport with some fictional universe inconsistent with our own. Finally, they could modify initial data going into a simulation, such that it is highly unlikely the resulting CAD file will operate properly. In any of these cases, malicious structure (or lack of structure) will end up in the resulting physical object.

A physical infection will also take one of two forms: objects that catch viruses and objects that are viruses.[186] Objects that catch viruses are simply engineered to fail. In contrast, objects that are viruses pose no danger on their own but cause a larger assembly to fail when the virus is associated or incorporated. For example, high powered simulation could engineer a

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183. *See* MCMASTER-CARR, http://www.mcmaster.com/ (last visited Jan. 11, 2016).

184. *See* Brian Krassenstein, *Microsoft Unleashes the 3MF File Format for 3D Printing, Launches 3MF Consortium*, 3DPRINT.COM (Apr. 30, 2015), http://3dprint.com/62032/3mf-file-format/.

185. *See* Bill Wasik, *In the Programmable World, All Our Objects Will Act as One*, WIRED (May 14, 2013, 6:30 AM), http://www.wired.com/2013/05/internet-of-things-2/.

186. Once in physical form the infected object is "sick" but will not likely spawn new viruses. Therefore, a more accurate description may be objects that catch infections and objects that infect other objects into which they are incorporated or come into contact with.

fastener to critically deteriorate when shaken at specific frequencies. The fastener could therefore cause a satellite, into which it was incorporated, to fall apart as it enters orbit. Hackers may even be able to define a monkey-wrench chemical compound that crystalizes inside one and only one type of engine. Highly contextual physical viruses could even emerge literally. Researchers propose a biological virus, created with low-cost DNA synthesizers, that is keyed to a specific person.[187] The virus would spread rapidly through an entire population with no effect until it reached the intended target, killing them.[188] In such an environment lawmakers may recognize new regulation points.[189]

V. SUPERCOMPUTING AND SIMULATION AS REGULATORY TARGETS

Regulators will start to see the dangerous objects of CAM not just as the product of 3D printers, CAD files, and raw materials. Long after our fascination with additive manufacturing or rapid DNA synthesis subsides, the information contained in CAD files, and the process of its genesis, will emerge as the predominant storyline. Regulators will link the problematic objects and the cyber security threat of physical viruses directly to simulation software and raw computing power.

Governments worldwide already label cloud computing as disruptive, but so far not for any of the reasons in this Article. In one breath they laud its adoption,[190] with the recent Trans-Pacific Partnership implementing several pro-cloud provisions.[191] But in the next breath they worry. Urs Gasser of

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187. *See, e.g.*, Andrew Hessel et al., *Hacking the President's DNA*, ATLANTIC (Nov. 2012), http://www.theatlantic.com/magazine/archive/2012/11/hacking-the-presidents-dna/309147/.

188. *See id.*

189. *See* Desai & Magliocca, *supra* note 17, at 1714–16 (describing possible regulation points).

190. *See Unleashing the Potential of Cloud Computing in Europe,* at 2–16, COM (2012) 529 final (Sept. 27, 2012) http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2012:0529:FIN:EN:PDF ("The Commission therefore aims at enabling and facilitating faster adoption of cloud computing throughout all sectors of the economy . . . . The Commission calls upon Member States to embrace the potential of cloud computing.").

191. Bill Curry, *The ABCs of TPP*, GLOBE & MAIL (Jan. 25, 2016, 11:23 AM), http://www.theglobeandmail.com/report-on-business/international-

the Berkman Center for Internet and Society at Harvard recently compiled the cloud computing anxieties of the United States, European Union, and Japan.[192] The study dismissed most of the policy talking points as applying to information technology generally, with only four "risk vectors" uniquely applying to cloud computing: outsourcing, centralization of computing resources, internationalization of data storage and transit, and opacity of the complex network topology.[193] With the tacit assumption that vanilla work loads will merely run under a new business model, the long list nowhere concerns itself with *what* cloud computers will process—or, for that matter, how they may amplify the effects of other technologies.[194]

Computation is unlikely to be singled out while its influence remains confined to the digital world. Rather, regulators will perk up when an object with seemingly incredible utility like a physical virus accessorizes a sinister act. However, once identified as a key enabler supercomputing would be easy to restrict for four reasons. First, to those unversed in the new industrial revolution, supercomputing seems unnecessary for most users. Second, cloud computers are centralized resources with feasible control points. Third, supercomputing hardware has been a historical item of export controls. Finally, cloud computing can already be used for malicious acts independent of CAM.

Cloud supercomputing may be relatively easy to restrict at a time before widespread use because it appears to be a tool only for sophisticated researchers. Few ninteenth-century

business/what-is-tpp-understanding-the-new-pacific-tradedeal /article26648948/ ("There are rules in the deal to protect the digital economy, and practices likes cloud computing. It would prevent national governments from cutting off data flows, by limiting laws that require local storage of data.").

192. *See* Urs Gasser, *Cloud Innovation and the Law: Issues, Approaches and Interplay* 14–15 (Berkman Ctr. for Internet & Soc'y, Research Publication No. 2014-7, 2014), https://cyber.law.harvard.edu/node/92450 (surveying government cloud policy concerns that include: data protection, data security, data retention, contract law as it relates to cloud services and consumer protection, intellectual property concerns associated with easy copyright violation, trade restrictions, jurisdictional issues, regulatory compliance (e.g., regarding rules relating to a particular industry such as health or education), and corporate and user responsibility).

193. *Id.* at 14.

194. *See id.* at 12–16.

Britons would have objected to Parliament policing Babbage's engine, as it was government-funded and apparently useless for the common man.[195] Similarly, the U.S. military could have squirreled away digital computing with little notice immediately after the Second World War.[196] Scholars argue 3D printer technology could be directly restricted,[197] but the window on comprehensive regulation shuts as the technology's innovative aura expands.[198] On the other hand, even in an age where new computing tools are widely appreciated, every new computing tool has its on-ramp.

The cloud computer is a viable target due to its grounding in regulated industry. Cloud computers are, in general, centralized resources located in data warehouses with a physical address, even if multiple of these "data farms" flexibly contribute to a given cloud computer.[199] Similarly, like the roads and hubs used to distribute factory-made goods, data traveling to and from data centers courses through the fiber optics controlled by highly-regulated parties, from mom-and-pop internet service providers to deep-sea cable-owning multinationals.[200] It is not necessarily easy to track nefarious use of a cloud supercomputer through tangled global

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195. *See* GLEICK, *supra* note 62, at 104–05, 119–20.

196. *Cf.* GLENN J. MCLOUGHLIN & IAN F. FERGUSSON, CONG. RESEARCH SERV., RL31175, HIGH PERFORMANCE COMPUTERS AND EXPORT CONTROL POLICY: ISSUES FOR CONGRESS 6–7 (2005) (explaining different export control strategies used to restrict access to supercomputing in the Soviet Union following World War II).

197. *See, e.g.*, Desai & Magliocca, *supra* note 17, at 1713–19 (proposing actions Congress should take to smooth the entry of 3D printing on various IP and products liability issues); *cf.* Jessica McLaughlin, *Regulating the Innovative World of 3D Printing*, L. STREET (May 30, 2015), http://lawstreetmedia.com/issues/technology/3d-printing-innovations-regulations/ (reporting on different reactions from federal regulators and legislators to regulation of 3D printing and 3D-printed items).

198. *See* McLaughlin, *supra* note 197 ("We have only just seen the beginning of 3D printing. It could enter our everyday lives in force within the next couple of years.").

199. *See An Introduction to High Performance Computing on AWS*, *supra* note 76.

200. *Cf.* *Open Internet*, FED. COMM. COMMISSION, https://www.fcc.gov/general/open-internet (last visited Mar. 11, 2016) (describing the overall regulatory scheme for broadband internet service providers).

networks.[201] But where cloud providers or governments enforce strict authentication protocols, or closely monitor networks, turning off the spigot of floating point operations shouldn't be hard. In contrast, a primary regulatory challenge of the CAM movement is that it is a decentralized phenomenon, making oversight and regulation challenging, for example, easing patent infringement or illegal drug manufacture.[202] Ironically then, manufacturing and computing will swap in the coming industrial revolution—PCs replaced by distributed CAM devices and factories replaced by centralized data centers. In short, powerful computation is relatively easy to restrict, whether regulators choose to license large-scale use of flops and bytes or cap it to cubical-sized cloudlets.

The United States has long taken the stance that supercomputing hardware should be withheld from the nation's adversaries, starting with the Soviet Union in the late 1940s.[203] Just before the cloud era, Congress implemented export controls for high performance computer components, potential importing nations tiered according to how much computing speed legislators thought they deserved.[204] Most recently,

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201. *See* Hamza & Omar, *supra* note 113, at 24 ("[The c]loud computing model by its very nature involves multiple data centers . . . this in turn makes investigating and detecting unauthorized or inappropriate activity . . . difficult in a cloud environment.").

202. *See generally* Ben Depoorter, *Intellectual Property Infringements & 3D Printing: Decentralized Piracy*, 65 HASTINGS L.J. 1483, 1493–97 (2014) (arguing that 3D printing's decentralized nature will impede enforcement of intellectual property rights and bring on "the next wave" of non-commercial intellectual property infringement); Darrell G. Mottley, *Intellectual Property Issues in the Network Cloud: Virtual Models and Digital Three-Dimensional Printers*, 9 J. BUS. & TECH. L. 151 (2014) (describing the issues 3D printing creates for intellectual property rights holders); 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) (stating that 3D printing may lead to a new wave of digital piracy).

203. *See* MCLOUGHLIN & FERGUSSON, *supra* note 196.

204. *See id.* at 1 ("[High Performance Computers (HPCs)] can be used for various military applications from design and testing of weapons of mass destruction to battlefield management. In response to concerns about proliferation, Congress legislated licensing, post-shipment verification and Congressional notification of exports and changes in licensing thresholds for HPCs in 1997."); *Supercomputer Export Controls Strengthened*, ARMS CONTROL ASS'N (Nov. 1, 1997), https://www.armscontrol.org/node/3147 ("Prompted by reports that Moscow and Beijing had circumvented U.S. export controls and acquired U.S. supercomputers for use in military research

jealous of China's top worldwide supercomputing ranking, the United States denied export of Intel's new Phi processors to the Middle Kingdom, citing "a significant risk of [the processors] being or becoming involved in activities that are contrary to the national security or foreign policy interests of the United States."[205] While export controls are generally loosening, the next leap in power such as quantum computing might revitalize the practice.[206]

While traditional "big iron" hardware continues to concern regulators, their gaze could shift to the destructive potential of the cloud independent of CAM. Hackers launch denial-of-service (DoS) attacks that take down Internet services with floods of fake communication requests from "bot nets" of hijacked PCs (not unlike a zombified SETI grid).[207] But such assaults have also been launched from EC2,[208] and use of the cloud theoretically allows the attack to scale infinitely. Amazon's network has become a useful tool for data theft.[209] Cloud computing resources, a commodity with burgeoning

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facilities, including nuclear weapons labs, legislators forced three key changes to U.S. export policy.").

205. Iain Thompson, *US Govt Bans Intel from Selling Chips to China's Supercomputer Boffins*, REGISTER (Apr. 10, 2015, 6:08 PM), http://www.theregister.co.uk/2015/04/10/us_intel_china_ban/.

206. For example, quantum computers under development could crack the encryption algorithms the current IT is built on. Steven Rich & Barton Gellman, *NSA Seeks to Build Quantum Computer that Could Crack Most Types of Encryption*, WASH. POST (Jan. 2, 2014), https://www.washingtonpost.com/world/national-security/nsa-seeks-to-build-quantum-computer-that-could-crack-most-types-of-encryption/2014/01/02/8fff297e-7195-11e3-8def-a33011492df2_story.html. Would inexpensive quantum computers mean the re-decentralization of computing power? Maybe briefly. Economies of scale and new bandwidth will, just like cloud's echo of timesharing, return us to the centralized model unless bandwidth cannot keep pace.

207. *See What Is a DDoS Attack?*, DIGITAL ATTACK MAP, http://www.digitalattackmap.com/understanding-ddos/ (last visited Jan. 11, 2016).

208. *DDoS-ers Launch Attacks from Amazon EC2*, INFOSECURITY (July 30, 2014), http://www.infosecurity-magazine.com/news/ddos-ers-launch-attacks-from-amazon-ec2/.

209. Hamza & Omar, *supra* note 113, at 24–25 ("They showed that investing a few dollars to buy an instance of a VM with Amazon EC2 service can have a % 40 [sic] chance of successfully placing a malicious VM on the same physical machine as the target customer. Moreover; cyber hackers can masquerade themselves as legitimate cloud users and abuse this feature to launch spam campaigns, run botnets, and brute force attacks.").

exchanges and derivatives, may be ripe for securities regulation.[210] Or they could be harnessed to steal from, and ultimately destroy, digital currencies like Bitcoin that rely on computational proof-of-work security mechanisms.[211] As governments increasingly see cyberspace as a theatre of warfare, they may label any large, flexible pool of computing resources as a risk, even where the threat is not clearly definable.

Once cloud supercomputing becomes applicable to the masses via CAM and the simulation economy, the policy of limiting or hoarding computation has to be reconsidered. On-demand supercomputing may become a fundamental tool for twenty-first century survival. As Amazon explains, the cloud computer allows individuals to compete: "a common man with just a credit card can afford to think about massive distributed computing and compete with the rest and emerge to the top."[212] As more of the world's objects are built by CAM, the new industrial revolution will reinforce the need for supercomputing's usability, proficiency, and legality. Official positions taken on other Information Age issues leads to the conclusion that powerful computation and simulation are essential. The White House declares broadband a utility[213] and the United Nations elevates it to a basic human right alongside healthcare, shelter, and food.[214] It seems a small inferential hop from a right to access information on global networks to a right to store and process it.

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210. *See* Reuven Cohen, *Compute Derivatives: The Next Big Thing in Commodities?*, FORBES (Oct. 2, 2013, 10:48 AM), http://www.forbes.com/sites/reuvencohen/2013/10/02/compute-derivatives-the-next-big-thing-in-commodities.

211. *See* Murch, Answer to *Could the EC2 Infrastructure Be Used to Efficiently Launch a 51% Attack?*, STACK EXCHANGE (Sept. 14, 2011, 8:59 PM), http://bitcoin.stackexchange.com/questions/1063/could-the-ec2-infrastructure-be-used-to-efficiently-launch-a-51-attack.

212. Jeff Barr, *Taking Massive Distributed Computing to the Common Man – Hadoop on Amazon EC2/S3*, AMAZON WEB SERVICES (Feb. 27, 2008), https://aws.amazon.com/blogs/aws/taking-massive/.

213. Jon Brodkin, *Broadband Is a "Core Utility" like Electricity, White House Report Says*, ARS TECHNICA (Sept. 22, 2015, 10:20 AM), http://arstechnica.com/business/2015/09/broadband-is-a-core-utility-like-electricity-white-house-report-says/.

214. Randall Lane, *The United Nations Says Broadband Is Basic Human Right*, FORBES (Nov. 15, 2011, 12:47 PM), www.forbes.com/sites/randalllane/2011/11/15/the-united-nations-says-broadband-is-basic-human-right/.

Cloud supercomputing and simulation, even if slightly restricted, could have major downstream consequences for innovation. Apart from its relation to CAM, the cloud may be the most general-purpose computing tool in history. The PC, while general purpose in that it can utilize a variety of software, still must run that software on local, static hardware with limited resources. The PC is therefore inherently limited. The cloud, in contrast, can be flexibly adapted to almost any problem, including in hardware configurations, operating systems, and, most important, scale. The characteristics of the cloud—on-demand, pay-per-use, and location independence—open entirely new business models and service offerings that drive innovation.

As we move into a simulation economy, mass computation looks to be an essential ingredient, if not the most critical resource, in creating physical objects. As Part III explains, CAM's power will only reach its pinnacle through supercomputing. Computation is therefore tethered to the long-term success of the new industrial revolution. Withhold powerful computation from many researchers today and they would be impotent to contribute to their field. Withhold powerful computation from ordinary people in the era of distributed creation and they will be stuck in the mode of factory consumption, prevented from exploring, defining, or creating the things useful to their unique context.

Cloud supercomputing and power simulation is one of the most prescient cases for a policy of permissionless innovation. Permissionless innovation "refers to the notion that experimentation with new technologies and business models should generally be permitted by default."[215] This policy is contrasted with a "precautionary principle" in which developers have the burden to show new technologies will not harm society.[216] Adam Thierer explains that the rapid development of the Internet was primarily caused by a permissionless policy, and argues regulators should adopt a similar posture to allow for 3D printing to flourish.[217] A primary reason to adopt this

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215. ADAM THIERER, PERMISSIONLESS INNOVATION: THE CONTINUING CASE FOR COMPREHENSIVE TECHNOLOGICAL FREEDOM, at vii (2014).

216. *Id.*

217. Adam Thierer & Adam Marcus, *Guns, Limbs, and Toys: What Future for 3D Printing?*, 17 MINN. J.L. SCI. & TECH. 817 (forthcoming 2016) ("In practice, 'permissioning' innovation can raise the cost of doing business by

hands off policy is that individuals and small organizations, the core participants in the new industrial revolution, do not have the resources to overcome the precautionary principle's burden.[218] For example, it is difficult and expensive for them to comply with licensing, auditing, and reporting requirements. Cloud supercomputing extends new manufacturing power to the same groups and for the same creative purpose. As this Article explains, innovations in design through supercomputing will eventually be indistinguishable from innovation in CAM manufacturing.

Another reason for adopting a permissionless perspective is that many technologies provide their own solutions.[219] For example, the cloud is not just used to generate DoS attacks, but also to defend against them in a rapid computer provisioning known as a "cloud burst."[220] Similarly, there will be counters to physical viruses. We are likely to see a new generation of cyber security industry that operates on the interface between information and reality.

Because the cloud is the most general-purpose computer of in history, the long-term driver behind the new industrial revolution—and may even become as important as broadband Internet—cloud supercomputing and the high powered simulations that run on the cloud must remain freely accessible. As a fundamental resource used in defining other innovations, supercomputing and high powered simulation are textbook examples of what should remain a permissionless technologies. After all, how can a finite committee, legislature, or assembly ever understand the consequence or balance the risks of restricting a pool of resource that is *infinite*?

VI. CONCLUSION

Jason, a commercial fisherman, wants to both increase revenue and lower regulatory compliance risks. He launches CAD software containing a plugin for fishing net design and

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creating barriers to new entry and competition. . . . As a result, precautionary regulatory prescriptions or bans can limit innovations that yield new and better ways of doing things.").

218. *Id.*

219. *See id.*

220. *See, e.g.*, CLOUDFLARE, https://www.cloudflare.com/ddos/ (last visited Mar. 19, 2016).

begins to parameterize his problem.[221] He inputs the species that dwell in the waters he trolls, specifies common hazards such as kelp, and describes aspects of his vessel such as hull shape and power. He downloads a digitized schedule of current fishing regulations that includes, for example, permissible catch size of every species.

After gathering the inputs, Jason's CAD software automatically contacts a cloud service provider and provisions thousands of servers.[222] The service provider verifies that the inputs originate from Jason and a trusted federal source. Moments later, the simulation's Monte Carlo method randomly wriggles digital fish as the net drags through virtual seawater at the speeds of the vessel. In less than a day the results are back in the form of a CAD file. The net's mesh size is just large enough to allow under-limit fish through. Additionally, special shapes allow certain species to escape the net uninjured. The net's material is exceptionally light because the net is no bulkier than needed for the specific boat and catch.

Jason instructs his temporary computer to transmit the design file both to the federal government for certification and to a security firm for analysis. Government servers independently check the net's operation and assess its environmental impact. The security firm combs through the net's design searching for malicious structure. Jason receives a registration number from the federal government and an acknowledgement his design, as far as the firm can tell, is free of errors.

Finally, Jason transmits the CAD file to a CAM printing service to be made by multi-material 3D printers using advanced polymers. The simulation cost is about a thousand dollars, the printing process a few thousand more. But the new net will drastically cut operational expense, both in fuel required to drag the net and the reduction in catch sorting. We have a retort both for seventeenth century Leibnitz and twenty-first century regulators: any computational tool, no matter how powerful, is made for those who sell little fishes.

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221. The author was surprised to find simulation software already used in trawling net design. *See Product*, ACRUXSOFT, http://www.acruxsoft.com.uy/en/product.html (last visited Jan. 11, 2016).

222. *See* Mings, *supra* note 119.

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