One-page Summary

Towards Personalized, On-demand Manufacturing
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Manufacturing used to be personalized. Prior to industrialization, manufacturing globally was artisanal, designed to produce low-volume products customized to individuals needs and interests. As the world industrialized, first textiles and then a windfall of other goods were for the first time available as cheap, mass-produced goods as standardization gave rise to economies of scale. From washing machines to cars, this led to widespread increases in standard of living as these products' availability grew and prices dropped. However, over a hundred years have passed since the first Model T rolled off Ford's assembly plant in Detroit, and besides the organizational innovations of lean manufacturing pioneered by Toyota in the 1950s, manufacturing at the turn of the 21st century remained in many ways unchanged from a century ago. But with the spread of digital manufacturing over the past two decades, a suite of new technologies has reinstated the ability for modern production tools to produce personalized artefacts. The operation of Moore's Law since 1965 has collapsed the prices and form factor of computational fabrication machines. Widespread adoption of Computer Aided Design (CAD) tools and advances in generative models, fueled by AI, are lowering the barrier to production for organizations and laypeople in ways that are fundamentally disrupting not just what can be made, but by whom. From misinformation, to social media addiction, to workforce disruption, society and legislation have been playing catch-up with the upheavals of the digital information revolution for almost 50 years. To get out ahead of the upheavals that digital fabrication is already shaping, understanding the emerging technologies and their impact is required now.

Manufacturing infrastructure in 2023 is still largely characterized by the same features that described Ford's automotive plants in 1923. Large capital costs for hyper-specialized machines are designed to mass-manufacture huge quantities of identical parts to generate the economics of scale required for profitability. These industries are conditioned for waste via overproduction and non-reyclability, costly warehousing leading to product degradation and obsoletion, and unabsorbed environmental externalities. But over the past two decades, digital manufacturing has set manufacturing on a radically new path. Characterized by digital design, automation and customization, wrapped in a hardware package that's inexpensive compared to traditional manufacturing infrastructure, technologies like 3D printing have disrupted manufacturing industries by affording users the ability to rapidly and inexpensively produce customized parts of almost arbitrary geometries from a single design file. In the late 2000s, the cheapest 3D printer commercially available cost $10,000; a desktop printer can today be bought for $100. In a span of just 20 years, digital manufacturing has gone from producing *parts* to producing *products* in domains spanning household items, robots, textiles, wearables, and medical devices. Engineers have now consolidated printers and electronic manufacturing processes into singular machines capable of on-demand manufacturing, that print artefacts from robots to wearables at the push of a button. A system called LaserFactory, published by MIT scientists in 2021, introduced a vertically integrated machine capable of manufacturing fully-functioning robots and customized devices like electronic health wearables within minutes. Parallel to the ability to fabricate personalized hardware automatically, the ability to design them automatically is emerging in tandem. While generative models in AI have been widely popularized by the appearance of Deepfakes in video creation, related technologies are already being employed to leverage AI to design hardware.

The advancement of on-demand manufacturing over the coming decades has the power to transform society in fundamental ways by enabling physical artefacts to be designed and distributed in the same way digital ones are today. Ubiquitous access to personal computers and internet has meant that almost anyone, anywhere can access digital products, from songs to software, with a click. Physical products may soon be designed analogously, by and for users empowered to print appliances, drugs, clothes and medical devices adapted to their needs, locally and on-demand. Distributed manufacturing won't just let people build what they *can* buy in today's marketplace, it will let them build what they *can't* buy. For exmaple, discrete product categorizations, exemplified in S/M/L t-shirt sizes, can shift to continuous spectra, enabling an equitable transition towards a more socially inclusive economy. However, these technologies are equally likely to engender social pitfalls. Algorithmic and curatorial decisions will need to dictate what is made, and by whom. Risks of fabricating weaponry and other misuse pose serious challenges to regulation. The potential for plagiarism and re-fabrication of branded products will warrant new mechanisms to watermark and certify authentically manufactured artefacts from counterfeits. The emergence of on-demand manufacturing is likely to have far-reaching social and economic consequences, requiring both will and foresight in the design of regulatory frameworks before pitfalls can manifest. At its heart however, personal manufacturing stands to democratize manufacturing so that more people can create what they need, at lower cost. Ultimately, personal manufacturing offers a chance to unyoke the physical artefacts we produce from decades-old technology, curtailing over-production, transportation emissions, and supply instability while addressing the full diversity of personal and technical needs of the 21st century.

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Manufacturing used to be personalized. Prior to industrialization, manufacturing globally was artisanal, designed to produce low-volume products customized to individuals needs and interests. As the world industrialized, first textiles and then a windfall of other goods were for the first time available as cheap, mass-produced goods as standardization gave rise to economies of scale. From washing machines to cars, this led to widespread increases in standard of living as these products' availability grew and prices dropped. However, over a hundred years have passed since the first Model T rolled off Ford's assembly plant in Detroit, and besides the organizational innovations of lean manufacturing pioneered by Toyota in the 1950s, manufacturing at the turn of the 21st century remained in many ways unchanged from a century ago. But with the spread of digital manufacturing over the past two decades, a suite of new technologies has reinstated the ability for modern production tools to produce personalized artefacts. The operation of Moore's Law since 1965 has collapsed the prices and form factor of computational fabrication machines. Widespread adoption of Computer Aided Design (CAD) tools and advances in generative models, fueled by AI, are lowering the barrier to production for organizations and laypeople in ways that are fundamentally disrupting not just what can be made, but by whom. From misinformation, to social media addiction, to workforce disruption, society and legislation have been playing catch-up with the upheavals of the digital information revolution for almost 50 years. To get out ahead of the upheavals that digital fabrication is already shaping, a close look at the emerging technologies and their impact is required now. And to understand where we're going, that starts with looking how we got here.

Manufacturing infrastructure in 2023 is still largely characterized by the same features that described Ford's automotive plants in 1923. Large capital costs for hyper-specialized machines are designed to mass-manufacture huge quantities of identical parts to generate the economics of scale required for profitability. As mass manufacturing spread across industries and plants metastasized across the globe, the accumulating costs of both mass manufacturing and mass consumerism have come more clearly into view. Conditioned for waste via overproduction and non-reyclability, costly warehousing leading to product degradation and obsoletion, and unabsorbed environmental externalities, the World Economic Forum reported in 2022 that manufacturing is now responsible for a fifth of global carbon emissions and over half of global energy consumption. A single factory represents just one node in a global supply chain network of manufacturers and assembly plants, and the Environmental Protection Agency reports that transportation now contributes over a quarter of global carbon emissions. The yoking of production to these supply chains has hinged delivery of crucial supplies of microchips and medical devices to global economic and political stability. The vulnerability of this network was made plain when in 2021, a 6-day blockage of the Ever Given in the Suez Canal caused up to 60-day shipping delays in $60 billion of trade and grounded 5% of the world's container fleet. Moreover, once delivered, the standardized artefacts produced by this network remain in many instances ill equipped to meet the modern needs and interests of particular use-cases and individuals. Companies developing hardware that push the boundaries of innovation have turned to fabricating their technologies in-house, and individual users that stray from bodily norms such as able-bodiedness and handedness find themselves unaccommodated for by the demands that economies of scale place on the mass manufacturing paradigm.

But over the past two decades, digital manufacturing has set manufacturing on a radically new path. Characterized by digital design, automation and customization, wrapped in a hardware package that's inexpensive compared to traditional manufacturing infrastructure, technologies like 3D printing, CNC milling and laser sintering have disrupted manufacturing industries by affording users the ability to rapidly and inexpensively produce customized parts of almost arbitrary geometries from a single design file. Popularized by widespread reporting on 3D printing, it's tempting to see the various trinkets and toys produced by the cheapest printers today and write off the miniaturisation of yesteryear's factory down to the size of a microwave as something inconsequential. But that evaluation would be blind to two developments; first, the rapid improvements in the most advanced printers. Additive manufacturing has been the de facto method for rapid prototyping and tooling across industries for over a decade, but by 2015, production of end-use parts represented 51% of additive manufacturing services [1]. New Balance, BMW and Invisalign are just few of a growing list of established mass manufacturers that have turned to additive manufacturing to produce flagship products, from shoe soles to orthodontics, at mass volume. In 2014, Made In Space 3D-printed a ratchet aboard the International Space Station from a file uplinked moments before. And until recently, the fuel injector for the European Space Agency's flagship Ariane 6 rocket was painstakingly assembled from 248 individually machined components; now it's printed in one go as a monolithic piece of nickel-based alloy. In the medical device industry, 3D printing is actively used to fabricate personalized implants, prosthetics, and most recently, drugs. In 2015, the US Food and Drug Administration approved the use of the first 3D-printed drug, and researchers have since printed tablets that for the first time offer patients their required drug dosages with personalized timed-release profiles [2]. Parallel to development of the most advanced printers, the second blindspot in underestimating the trajectory of digital manufacturing is the exponential growth of the sector as a whole. It is the form of exponential growth that led Gordon Moore to conjecture in 1965—to much public skepticism—the future appearance of "such wonders as home computers". Known today as Moore's law, he observed that over five years, a doubling had been occurring in the capacity to integrate components into a fixed size of integrated circuit, and suggested it could happen for another ten years.

He was wrong; it happened for another fifty years. The trajectory of digital manufacturing appears to be following this trend. From the mid 2000s, Wohler Associates has reported sustained exponential growth in 3D printers sold globally. Sales had grown 10-fold to 20,000 by 2011, to over 200,000 by 2015, and to over 2 million annual sales in 2021, estimated by Forbes at a market valuation of $10.6 billion and counting. This is fueled in part by the continued expiration of key patents, starting with Stratasys' patent on Fused Deposition Modeling in 2009 and continuing with patent expirations related to performance materials, particularly metals, in 2014 and 2016. In the late 2000s, the cheapest 3D printer commercially available cost $10,000; a desktop printer can today be bought for $100. This hundred-fold drop in both price and size is for a desktop machine capable of creating parts more geometrically complex than many production machines today. However, for a machine to create a product in a modern sense, it must also be able to fabricate the electronics that imbue it with function. Companies like Voltera and BotFactory today sell desktop machines capable of printing functional printed circuit boards (PCBs) in the same form factor and price point as a commercial 3D printer. These are being used in both industry and academia to rapidly build circuit boards for devices ranging from kitchen appliances and wearables to robots. Practitioners have now consolidated printers and electronic manufacturing processes into singular machines to print artefacts from robots [3] to flexible electronics [4] at the push of a button. A system called LaserFactory [5], published by MIT scientists in 2021, introduced a vertically integrated machine capable of manufacturing fully-functioning robots and customized devices like electronic health wearables within minutes. The machine consists of a $150 add-on to a lasercutter which extends the laser's subtractive manufacturing capabilities with a conductive extruder, to deposit circuit traces, and a pick-and-place mechanism, to place components. In an accompanying software tool, users can drag-and-drop components and wires from a parts library onto a canvas to design a device, and then print it with a click. In 10 minutes, the machines manufactures a fully functional quadrotor that flies directly out of the platform; in 8 minutes, it prints a sensorized electronic health wristband tailored to the users's wrist, ready for use. Parallel to the ability to fabricate personalized hardware automatically, the ability to design them automatically is emerging in tandem. While generative models in AI have been widely popularized by the appearance of Deepfakes in video creation, related technologies are already employed for hardware creation. AutoDesk, one of the worlds leading CAD developers, has employed generative design in its flagship product since 2017 to suggest and complete users' CAD designs based on functional needs like load requirements. That same year, Autodesk published a tool equipping users with similar abilities for design and assembly of electronic circuits. ChatGPT, AI's most recent phenomenon, can generate printable files for objects based on natural language alone.

In a span of just 20 years, digital manufacturing has gone from producing *parts* to producing *products* in domains spanning household items, robots, textiles, wearables, and medical devices. Those familiar with Star Trek's Replicator machines may be disappointed not to see "Earl Grey tea, hot" on this list, but advances in the culinary sciences have seen food printed that adapt its texture to influence satiety and calorie intake. These digital machines are accomplishing this breadth of production not using the expensive, specialized equipment used by traditional manufacturers, but by consolidating general-purpose, digital manufacturing technologies into single inexpensive machines. These machines aren't being designed for use by trained engineers to fabricate standardized products, but for lay users to build products that are customized and personal. Nevertheless, observers of today's cheapest mass market 3D printers may be hesitant to use these simple, albeit versatile, printers to foreshadow a coming personal manufacturing revolution. In a similar vein, the "personal" part of personal computing was not always anticipated, but its history may illustrate how an equally personal, on-demand manufacturing paradigm might unfold.

Computing until the 70s was the domain of the few; large, expensive mainframes were used exclusively by scientists and required technicians to operate. Thomas Watson, the president of IBM, prophesied in 1943 that "there is a world market for maybe five computers." A third of a century later, a similar pronouncement was made by Ken Olsen, the founder of DEC. Once the largest computer company in the world second only to IBM, and featuring prominently in Tracy Kidder's Pulitzer-prize winning book on computing's rise, Ken quipped "there is no reason anyone would want a computer in their home." Six years later IBM's personal computers were outselling DEC's by ten to one. As Moore's Law kept operating, computing became available on chips, and while these were cheaper and smaller than ever before, individual chips were manufactured with custom-built logic in their architectures that yoked them to specific applications. But with the development of VLSI technology which allowed fabricating large numbers of MOS transistors in high densities, a whole CPU could be fabricated across just a few chips. Then in 1971, at a fledgling company called Intel, Federico Faggin created the Intel 4004. The first to fit a general purpose CPU into a small commercial silicon chip, its functionality wasn't hardwired, but could rather be customized via programming. Users suffered a loss of efficiency, to be sure, but the losses accrued in efficiency were more than made up for in affordability and versatility. A single chip could now produce a variety of digital products on-demand, customized by and for individuals' needs and interests, hearkening the information revolution and providing the basis of the ubiquitous personal computing we know today. Starting with factories and ending with today's programmable 3D printers and PCB machines, we can chart the history of creating physical parts from the analogous mainframes of manufacturing to the programmable chips of today. And just as in 1971 for computing, our chips today—our 3D printers, our PCB machines—are no longer fragmented. These disparate processes have for the first time been consolidated into a single unit that foreshadows what we can be tempted to call a general purpose CPU for manufacturing; a general purpose Central Manufacturing Unit (CMU).

The emergence of CMUs over the coming decades has the power to transform society in fundamental ways by enabling physical artefacts to be designed and distributed in the same way digital ones are today. Ubiquitous access to personal computers and internet has meant that almost anyone, anywhere can access digital products, from songs to software, with a click. Equally important, they can create them too. Previously, record labels exerted hegemony over music distribution, while today anyone can record and upload tracks to Spotify; tech giants controlled software production, whereas individuals today are empowered to create and upload apps to online market places. Physical products may soon be designed analogously, by and for users empowered to print appliances, drugs, clothes and medical devices adapted to their needs, locally and on-demand. Importantly, distributed manufacturing won't just let people build what they *can* buy in today's marketplace, it will let them build what they *can't* buy. Discrete product categorizations, exemplified in S/M/L t-shirt sizes, can shift to continuous spectra, enabling an equitable transition towards a more socially inclusive economy. Manufacturing capabilities can be situated in remote environments that lack the economics and infrastructure to access market-based commidities. However, when consumers are empowered with agency to design and customize products, traditional marketing and advertising mechanisms are likely to be overturned, if not extinguished. Observing recent developments in generative and large language models, tools like deepfakes and chatGPT may well be deployed in their place.

Digital manufacturing also opens the opportunity to fundamentally restructure our ability to handle waste. By 2025, urban populations are expected to produce six million tonnes of rubbish daily, sufficient to fill a line of rubbish trucks 5,000 kilometres long every day [6]. But the existence of trash is grounded in a lack of information about the contents and processes with which products are made—and by extension, how they can be unmade. The digitization of product architectures, and the parameterisation of their manufacturing, can open new opportunities not just for recycling old products, but for remanufacturing them for new use cases. In pursuit of this circular economy, the mayors of Boston, Paris, Mexico City and others have opened fabrication labs across their cities and pledged to become at least 50% self-sufficient by 2054. By geographically realigning production and consumption in this way, urban environments—predicted by the UN to house 68% of the global population by 2050—can overhaul supply chains. Bloated from back-and-forth shipping for sequential product assembly by disparate manufacturers, today's supply chains are crippling to the environment, urgent delivery needs and packaging requirements. By distributing manufacturing to consumers, carbon footprints from transportation, packaging and even retail space can be fundamentally curtailed.

The emergence of CMUs is equally likely to engender social pitfalls. Algorithmic and curatorial decisions will need to dictate what is made, and by whom. If technologies fall under proprietary ownership, decisions are at risk of falling to companies, and a concentration of wealth for first adopters risk furthering inequality and class division. Risks of fabricating weaponry and other misuse pose serious challenges to regulation. The potential for plagiarism and re-fabrication of branded products will warrant new mechanisms to watermark and certify authentically manufactured artefacts from counterfeits. As with autonomous vehicles today, responsibility for these risks must be allocated to someone, be it governments, designers, consumers or insurance brokers. With production in the hands of consumers, equally significant is the risk of exacerbating environmental damage from overproduction and waste if strategies to regulate materials and recycling are not in place. With manufacturing distributed, new conglomerates might be grown, not to sell products but high quality designs and recyclable materials, shifting dependency from parts to materials in a move that may simplify not just stockpiling but material regulation too.

Manufacturing innovations will shift monotonous, hazardous, physical manufacturing jobs to become increasingly cognitive, creative and safe. However as manufacturing turns to knowledge workers, a reshoring to developed countries of manufacturing jobs is likely to follow as a zero-sum penalty to today's manufacturing nations. Moreover, the ability to pick-and-place manufacturing geographically may position manufacturers to foster resiliency to—and exploitation of—both trade barriers and currency shifts. The Covid pandemic has already catalysed multinationals to regionalize production closer to Western markets. In 2022, the US launched the AM Forward initiative to spur domestic additive manufacturing and supply chain resiliency, and its CHIPS and Science act approved $280 billion to do the same for semiconductors. As manufacturing becomes more distributed, key government roles in trade regulation may require reinvention or discarding. To prevent growing inequality, universal access to manufacturing, like those proposed for internet access, may require debate, and a bipartisan bill already introduced in 2018 advocates for this in the US' national interest. The emergence of a personal manufacturing paradigm is likely to have far-reaching social and economic consequences, requiring both will and foresight in the design of regulatory frameworks before pitfalls can manifest. At its heart however, personal manufacturing stands to democratize manufacturing so that more people can create what they need, at lower cost.

It was the "personal" lure of simple early computers—blogging, content sharing—that seeded not just the personal computer's development, but its image as a toy with the reigning minicomputer industries, right before it shattered them. The use of early 3D printers for personal expression risks having done the same with today's manufacturing industries, but we have yet to see how digital manufacturing will complement or replace its predecessors; cameras didn't replace artists, it enabled people to create meaningful physical artefacts without needing to be artists themselves, and that was a good thing. Personal manufacturing offers a chance to unyoke the physical artefacts we produce from decades-old technology, curtailing over-production, transportation emissions, and supply instability while addressing the full diversity of personal and technical needs of the 21st century. The road to personal computing wasn't signposted, but from its history, we may find a blueprint for a highway to Personal Manufacturing.

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