**Introduction**

This paper aims to explore the properties and ontological status of an important subset of technical artifact, tooling. I define tooling as the set of all technical artifacts designed and deployed explicitly in the service of manufacturing new artifacts. Conventional examples of tooling are machine tools such as the engine lathe and vertical milling machine, and cutters such as endmills and carbide inserts. In the context of a factory or workshop, tooling is the set of objects directly *necessary* for the manufacture of whatever is being manufactured.In this paper I seek to characterize the identifying attributes of tooling and argue that tooling, like scientific instruments, is a discrete type of technical artifact, identifiable by both its physical properties and its function. This paper is divided into two parts. The first examines the functional properties of traditional examples of conventional tooling, such as machine tools. The second part extends this examination to computational systems and argues that general-purpose computing devices such as CPUs and GPUs are tooling artifacts. I will begin by explaining my definition of tooling, then situate it within the framework of technical artifacts as described in Kroes (2010) and Houkes & Vermaas (2014) using a novel definition to distinguish the tooling subset within the universal set of technical artifacts.

**Tooling**

Within the engineering, manufacturing and production disciplines, “tooling” is a jargon term referring to the collective machines, templates, molds, jigs, fixtures, and other equipment used to manufacture, assemble, or process products, components, or materials in an industrial setting. Like all instruments, tooling is mind dependent (Houkes & Vermass, 2014); and I argue that holds particular epistemic significance in that its goal is to make material the idealized intentions of the designers using it. Tooling is the mechanism by which humans attempt to translate idealized[[1]](#footnote-1) knowledge into material reality.[[2]](#footnote-2) High precision machining allows designers to realize their designs at a level of accuracy indiscernible from perfection when viewed at the macroscopic scale. This property gives tooling a special epistemic significance among instrument kinds; it is the technology that translates the ideal into the real.

**From Tools to Tooling**

Tool use and development is fundamentally coupled with human knowledge systems. Tools are integral to human progress because they both allow effective exploitation of the environment and foster efficient transfer of knowledge between people.

While considering the statement above, I looked for examples of tools that don’t carry epistemic cargo and concluded that the marriage of exploitation systems and knowledge systems is an integral property of tools, and does well to characterize the evolution of tools throughout human (pre)civilization and the evolution from tools to tooling. For example, the stone axe is a tool that does not necessarily require elaborate knowledge of its possible and “appropriate” applications to be effectively used; it is likely that a human user will quickly learn that the stone axe can be used to enhance abilities already present in their bodies, namely bashing and tearing[[3]](#footnote-3). While transfer of knowledge from expert users should improve a novice user’s capabilities with a stone axe, the tool does not require much epistemic infrastructure.

As tools developed, so did the epistemic infrastructure supporting them. Consider the tools of neolithic agriculture, many of which were essentially advanced implementations of the stone axe, fashioned to achieve specific agricultural tasks such as plowing, sowing and reaping (Fowler et al., 2014). These tools not only required training and understanding to use effectively, but importantly, each tool was a component in a larger system of tools required to carry out a large-scale epistemically complex operation.

Skipping ahead 10,000 years or so, let us consider the screwdriver. While operation of a screwdriver may not require integration of complex knowledge, the tool system which it belongs to (threaded fasteners) is a vast constellation of precisely manufactured, application-specific tools with an epistemic infrastructure that is only fully comprehended by expert engineers and machinists.

The sequence above is intended to illustrate that the evolution of tools and tool use can be characterized in terms of an evolution from embodied interactions to epistemic interactions; indeed, the primary function of all tools is to abstract away the weakness and imprecision of the body while sharpening the precision of epistemic-to-material translation. In this sense, tools have always been progressing toward tooling, and it appears that this process of automation will continue ad infinitum. The total automation of physical labor is already a reality in some contexts, and the automation of epistemic labor increasingly so.

While the precise boundaries of the industrial age are fuzzy, I believe that the primary force that drove it was the transition from tools to tooling. This transition happened gradually and by degree, but at the point that the human body is abstracted out of the physical control loop dictating a given tool’s operation (the tool gains the property of autonomy), tooling and hand tools became *different kinds* of instruments. In support of this argument, I have selected four properties that I believe specifically identify a technical artifact as tooling: precision, generality, autonomy, and productivity. The following equation describes tooling in set builder notation, and each property is described below it.

Equation 1: Let T denote the set of all tooling, where each technical artifact t is an element of U, the universal set of technical artifacts. A technical artifact t is included in T if and only if it possesses the properties of precision (P1), generality (G), autonomy (A), and productivity (P2).

*Precision:* Tooling is not used for measurement, but it is produced according to precise measurements[[4]](#footnote-4). Precision is the critical attribute that makes mass production possible and enables strictly prescribed make plans.

*Generality:* Tooling of all scales, from a single endmill to a 5-axis machining center, is designed with replaceability and generality in mind. Tooling systems are designed within highly specific structural and functional parameters, but the intended use of a tooling system is not strictly defined by its designers. While some tooling is more general than others, all tooling systems[[5]](#footnote-5) are designed to accommodate a range of applications.

*Autonomy:* Tooling operates independently of direct operator control. While an operator may be involved in the assignment of a tooling task, they are never in direct contact with the with tool or exerting free control over it. By this definition, hand tools are not tooling.

*Productivity:* Whether by additive, reductive or formative processes, tooling produces changes in the material substrates it works on. Many types of artifacts may be involved in the manufacture of products, but if they do not produce changes in the material substrate being manipulated, they are not tooling.

While each of these properties were present in tooling that existed prior to the first industrial revolution (e.g. the printing press), asynchronous advancements in each property were involved in sparking the next three industrial revolutions. Broadly speaking, advances in generality enabled mass production and sparked the Technological Revolution, advances in autonomy sparked the Digital Revolution, and advances in productivity, particularly in the realm of data manipulation, sparked the current industrial revolution. Across each of the four industrial revolutions, the precision of tooling and tooling techniques has increased dramatically, with machining tolerances shrinking by about two orders of magnitude (Roe, 1916; Gresik, 2016) and present-day microfabrication technologies such as EUV photolithography and two-photon 3d printing operating at the sub-micron scale (Peeters et al., 2017; Geng et al., 2019).

**On Tooling as an instrument subset**

In the interest of exploring the ontological status of tooling, I have attempted to situate it within the ontology of technical artifacts described in Houkes & Vermaas (2014). While only hinting at the material realities of product design, the authors do well to recognize the modern state of production design and manufacturing. They acknowledge that design and manufacturing are discrete activities characterized by both the division of labor and division of intentions between designers and makers. They define the production process as consisting of a use plan (*up*) proposed by a designer and a make plan (*mp*) implemented by a maker and proceed to describe what feels like an elegantly-comprehensive ontology of instrument subclassification, yet it is somehow completely devoid of instruments that make other instruments (tooling). In the Houkes & Vermaas classification, tooling would fall under…………………..

General-purpose tooling is not designed in the sense proposed by Houkes & Vermaas, it is engineered. Its use plan does not describe the specific activities it ought to be used for, rather it (loosely) describes the range of activities it may be capable of. Indeed, general purpose tooling is capable of activities that its designers never conceived. General purpose tooling is value engineered to meet criteria related to durability, capacity, accuracy and speed, but it is not designed for a specific use plan.

During my very brief study of ontology, I’ve often wondered if it is petty to worry about narrow subclassifications of things; it seems that the most elegant propositions are simple, grand, and to some degree timeless. As I’ve quarreled with this thought, I’ve come to decide that tooling is not some mere special interest, but a fundamental artifact kind in that it breathes life into technology. While tooling is certainly a mind-dependent instrument in most cases, it is possible that we are nearing a point where the autonomy of tooling obviates human intervention, and tooling becomes fully (human) mind-independent. This is the promise and threat of abstracting away our mental and physical work to advanced information systems.

Machine agency: Try to find something.

**Control Systems**

Before I introduce the argument that computers are tooling, I want to take a moment to point out that the motivations that drove machine and computer technological development are largely the same. Revisiting my definition of the set of all tooling, a latent property emerges out of the four requisite properties (precision, generality, autonomy, and productivity) is *control*. Improvements in any of the four properties result in a higher-agency system. Control weaves a thread through all advancements in technology, from stone axes to steam engines to computers. While the connection between heavy machinery and computers may not seem obvious at first, these technologies are deeply connected from the perspective of control. At its simplest, this control can be observed in the spatial precision of machine tools. Machine tools are characterized by control of translational movement, their movement along a chosen axis is tightly controlled, and movement out of parallel with that axis is restricted. Additionally, automated, closed-loop control systems have featured heavily in machine design since before the first industrial revolution. The centrifugal governor, a closed-loop control system made famous in association with the Watt Steam Engine, was invented in the 17th century for the regulation of water wheels and windmills (Bellman, 2015). The centrifugal governor was a sort of mechanical computer, which produced reliable and repeatable outputs in response to its inputs. This sort of reliability was one of the chief motivations for building computers, well before it was realized that a computer could operate as a universal Turing Machine.

Control systems and machine precision have advanced in concert with one another, as they were developed in pursuit of many of the same goals. While effective machine tools predate effective computer systems, they share a common evolutionary path. In many ways, these two fields of technology address complementary aspects of the same tooling property, autonomy. Where machine tooling abstracts away *physical* responsibilities from the human operator, computational tooling abstracts away *mental* responsibilities from the operator. It should be noted that the first computer numeric controlled (CNC) machine went into operation in 1952. Far before the development and deployment of desktop PCs in offices and homes, computer-controlled machine tools were an indispensable part of the precision manufacturing ecosystem.

**Computers Are General-Purpose Tooling**

Perhaps ironically, the technical bottleneck that hamstrung full-scale development of Charles Babbage’s difference engines was that the metalworking techniques of the era could not economically produce the parts at the required precision, which eventually lead to the British government abandoning funding of the project (Babbage, 1864). While the Babbage engine was not the first programmable computational device, it was the first general-purpose computer in the sense that it was Turing complete, automatic, and explicitly designed to automate a broad domain of mental labor performed by humans (mathematical calculation). I will spare the reader a detailed history of early computers, but I mention the Babbage engine to demonstrate that the goal of computational systems has long been to automate mental work that would otherwise be performed by humans, in the context of *general-purpose use plans*.

While early computers were deployed in service of traditionally mathematical problems, by the mid-20th century it was understood that a Turing-complete computer could theoretically compute any computable algorithm. By the 1950s, computers were already being applied to problems outside of traditionally mathematical domains, for example the Georgetown-IBM experiment of 1954 demonstrated Russian to English text translation using an IBM 701 computer (Hutchins, 2004).

General purpose computers are like factories without make plans. The power of the computer is its adaptability to any task describable by the designers (programmers) using it. Computer engineers seek to maximize the computational throughput of a system, within the boundaries dictated by practical and economic feasibility, but they are unconcerned with intended end-user experience. Like machine tooling, computer hardware is not designed in the sense described by Houkes & Vermaas whereby an instrument has clearly defined use plans and make plans. Computer hardware is engineered to meet specifications related to capability and capacity. The design aspect of computational systems is addressed in software. Software serves as both the make plan and use plan in a computational system. A computer without software running on it is a collection of tooling waiting for a make plan.

While CPUs are manufactured according to unfathomably precise and complicated make plans, they are designed with maximally unbounded use plans. This is the dual nature of general-purpose tooling.

Software as a Make Plan:

* Conventional computers are limited by the instruction sets of their processing units, but these are formal constraints rather than practical ones. A Turing-complete system can approximate any function, so a computer is only limited by its outputs and timescale.
* In the space of all possible software, we have an infinitely extensible make plan.
  + Read back to the MP paper to get some arguments going

Hardware & Agency

* Most matter is programmable, and all tools are (the human swinging the hammer is the software) but tooling has been fashioned expressly to be programmable.
* Computers store and sculpt information. The logic gate is the cutter, memory is the fixture, instructions are the machines, and software is the make plan.
* CPUs don’t require that many degrees of freedom to maintain flexibility. x86 ISA has vastly more operations than RISC-V, and we are seeing a rise in specialized ICs that are designed to fulfill more specific intentions (e.g. tensorrent’s RISC-V hardware).
* The push towards specialization is including a lot of inference-only hardware, interesting in that it has a strictly defined capability to run software (neural networks) that are defined by their flexibility to approximate any function, and have been shown to be Turing-complete without requiring access to external memory.

**On Dedicated and Flexible Computational Tooling**

In this section, I discuss the concept of general-purpose and specialty to­­­oling as it pertains to computational tooling. All tooling is designed and deployed to manufacture products, but those designs range from generic to application specific.

Early in the development of this paper, I considered flexibility a required property of tooling. After some consideration, I termed this property “generality,” but stated the caveat that while *tooling systems* are general purpose, some tooling is developed for singular, specialized applications. For example, injection molding tooling, specifically the molds themselves, are not general-purpose. Injection molds are clearly a type of tooling. They are designed and deployed in the service of production. However, they are not designed with reconfiguration or flexibility in mind. In fact, they have very tight item definitions, use constraints and are mostly useless outside of their primary function. Injections molds are an example of what I term “dedicated tooling.” Tooling which is application specific to the production of a single product. Other examples of dedicated tooling include product-specific jigs and fixtures, cutting dies, and application-specific integrated circuits (ASICs). As the objective of this paper is to argue that computers are digital tooling, I think it is necessary to explore the degree to which they are general-purpose or not. As stated earlier, I am confident that CPUs are general-purpose tooling; in fact, general-purpose computation is the most stable property across CPUs of all eras and instruction set architectures. However, not all computational devices are governed by the operation of CPUs. In the following paragraphs, I will present a few case studies on the relative tool-flexibility of several integrated circuit architectures.

555 Timer:

Integrated circuits tend to be flexible by design. In most cases, they are designed with modularity in mind. For example, the “555 timer” is an 8-pin integrated circuit that can function either as a timer, delay, pulse generator, oscillator or flip-flop simply by manipulating the current entering its inputs. The 555 timer has a defined set of capabilities but was designed to work in a variety of configurations to serve a variety of purposes. The 555 timer is not a highly flexible tool, neither is it dedicated. CPUs and other Turing-complete hardware architectures are examples of highly flexible digital tooling.

ASICs:

By contrast, an ASIC is characterized by application-specificity and a lack of flexibility. As with injection molds, lack of flexibility is justified by efficiency. For example, a BitMain Antminer ASIC, designed and deployed to mine Bitcoin, is vastly faster and more energy efficient at mining Bitcoin than a comparably-priced GPU, however it cannot drive a Turing-complete computer. One could never make art, conduct science, or socialize online using a BitMain Antimer. ASICs such as the Antminer are *dedicated* digital tooling.

NorthPole:

NorthPole is a next-generation neural inference architecture developed by IBM Research (Modha et al., 2023). It has a variety of energy-saving features that make it an attractive alternative to GPUs for running ANNs, but in service of the current discussion I will focus on one: it is inference-only. The NorthPole chip does not train ANNs, nor can it. It cannot run general purpose software or serve as the processor for a general-purpose computer. However, it can run inference on any neural network that can fit in its memory. NorthPole essentially becomes a hardware instantiation of the neural network that is loaded on it. In this sense, NorthPole differs from an ASIC in that it could be used in a huge range of applications, though it is nowhere nearly as flexible as a CPU. Northpole, and neural inference chips in general are notable because we are likely entering an era in which the “intelligent” digital devices we interact with are no longer powered by general-purpose computers. NorthPole is an example of digital tooling that is dedicated and flexible at once.

FPGAs:

Field Programmable Gate Arrays (FPGAs) are integrated circuits that are designed to be configured by the end-user “in the field”. FPGAs contain an array of programmable logic blocks, and a hierarchy of reconfigurable interconnects that allow the blocks to be wired together to fit whatever intention the user desires. For example, an FPGA could be programmed to fit a highly specific application, such as military-grade signal processing, or it could be programmed into a fully functioning general-purpose CPU. FPGAs are a highly flexible subclass of digital tooling.

Within the set of all tooling, there is general-purpose and special-purpose tooling. I believe that the current thrust of technological development favors general-purpose tooling. A potential example of this would be the shift away from injection molding toward 3d printing. Technologies such as generative AI and 3D printing show the possibility of a turn away from mass production in favor of mass customization.

Conclusion

* Tooling is a distinct class of technical artifact, providing a translational layer between ideal and material reality.
* Tools have existed for hundreds of thousands of years, but tooling, in the fully modular and reprogrammable sense, is much newer, and is rapidly changing. It’s possible that today’s tooling will at some point be as crude as prehistoric hand tools.
* Digital tooling has accelerated the output and development of both material and epistemic products. While previous advances in tooling abstracted away the physical limitations of human bodies, today’s advances are abstracting away the physical limitations of human brains.

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1. While many tool systems translate ideas into reality, for instance those used to construct architecture, only in the realm of precision manufacturing are tolerances fine enough to consider the possibility that the idealized form is made material. In disciplines such as architecture, lack of precision is a necessary evil. [↑](#footnote-ref-1)
2. One might say that artists translate mental idealizations to reality, but I argue that art is seldom done in the attempt to translate a perfect idealization of form into the material world. When this has been attempted in art, as with minimalism, the tools employed tend to be the same as those used in industrial production. [↑](#footnote-ref-2)
3. At a microscopic scale, all cutting is tearing. [↑](#footnote-ref-3)
4. The dimensional regularities of tooling imbue it with a sort of “thing knowledge” as described in Baird (2004). Rather than making measurements, tooling imposes measurement. [↑](#footnote-ref-4)
5. Note that I use the term “tooling systems.” In some cases (e.g. injection molds, customized endmills) individual pieces of tooling may be specially designed for the product they are being used to manufacture. However, these tools must conform to specifications of the tooling system they integrate with. Customized tools are not designed with generality of product in mind, but they are general to the tooling system they are part of. [↑](#footnote-ref-5)