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Making the Computational Physical Through Digital Craftsmanship

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The forms that can be created through computational methods are infinite in both their number and complexity. However, in order to exist in the real world, the given form must be negotiated with reality through a material. The most direct and accessible form of digital to material translation is 3D printing. However, much of the knowledge required to perform this digital-material translation exists in an embodied state, taking a form similar to the embodied knowledge of craftsmanship. There are underappreciated constraints in all materials that must be taken into account when making with any given process, and the use of 3D printing to give materiality to ethereal, computationally generated forms highlights these constraints. Metal foundry, as an example of one of the oldest forms of traditional fabrication, can be made to utilize computational design by using 3D printing as an intermediary step between computation and craft. Through the examination of several works of sculpture and works in progress, this paper demonstrates the strengths, shortcomings and general use of 3D printing as a form of expressing the computational in the physical, and will use foundry as an example of an extension of this.

1. Introduction

The constraints of digital forms are almost entirely defined by those creating them. Reality rarely affords this same luxury to the forms that exist within it. The most direct and accessible way to take the digital and bring it into reality is 3D printing, which has been used effectively by the collective, the studio, and individual for countless projects. 3D printing bridges the gap between computational creativity and the constraints reality imposes, reshaping what forms can be brought into existence from the creative vision of the artist, designer or engineer by translating a 3D model into an actual 3D object. Despite this nearly direct translation, the 3D printing process is still constrained by the embodied rules of the materials it uses. A kind of craftsmanship, like that found in more traditional forms of fabrication, is required to produce something with this embodied set of rules. Foundry, in a similar way, offers the opportunity to use much more robust and enduring materials, using a craftsmanship that has been iterated over in more traditional forms of fabrication, production and art making for thousands of years (Treyger n.d.). Unlike 3D printing, due to the processes involved in most metal casting, foundry can not fully take advantage of computer aided design fundamentals on its own. By using both processes, through an embodied, combined craftsmanship of both the traditional and the digital, the two processes can be used to create forms, sculpture and components that they would not be able to without the other.

In the same way that previous pieces have combined other forms of traditional sculpture with computational design through the use of a combined craftsmanship, metal foundry, through the intermediary step of 3D printing, is more than capable of being used in as a tool for the expression of computational creativity, to create forms that could not otherwise be made in foundry, and to allow the control and adaptability of 3D printed objects to take advantage of the strengths of the heavy materials of foundry.

1.1. Digital and Traditional Methods of Production

There are already multiple examples of ancient or traditional forms of art being reproduced through modern technologies. The same fundamentals of translation between those traditional techniques and modern ones exist for the translation between digital design, 3D printed plastic and foundry as well. Several of the works of Tobias Klein and his collaborators demonstrate this translation of material through the use of both traditional and digital craftsmanship. In *Chemical Skin*, Klein uses UV activated materials to allow 3D printing to behave in a similar way to Chinese pottery, a traditional form of craftsmanship, by extending and augmenting the function of the 3D printer. He and his collaborators create parallels between the process of painting and firing glazes within the process of 3D printing, which while closely replicating the original work, still leaves many of the same artifacts common in that method of production (Klein and Leung 2018).

In Klein's examination of *Vessels of Vanitas*, he details how much of an impact the limited, non-tactile experience of working with digital "material" can have on the shape and form of an object. By making the semi-natural form of the Rococo in such a non-traditional way, the forms are able to take on qualities and shapes that would be impossible to create, or even envision, through the use of only hand tools (Klein and Kraemer 2019). Ultimately, the only effective way to reproduce those forms physically would be to use 3D printing. These show that some forms that were previously impossible to make in traditional methods of making can now be made through an application of CAD principles. 3D printing is the mediating element between these forms and the traditional making practices.

The augmentation of these traditional artforms through the application of 3D printing demonstrate just how useful a tool it can be to extend what these artforms are capable of. In the same way that Klein and his collaborators extended the Rococo and pottery, 3D printing can extend foundry. The traditional knowledge of the craftsman, and the embodied knowledge of that practice is what combines with the technical knowledge of the digital to form what Klein describes as digital craftsmanship (Klein 2018). Digital craftsmanship is the same type of knowledge applied to a digital medium as opposed to a material one, and can be brought into the material through the use of 3D printing. In the same way that 3D printing and foundry interact, these two kinds of craftsmanship will as well.

The embodied knowledge of craftsmanship is stored in an object being produced, in the same way a mathematical equation is stored on a piece of paper (Wilson and Clark 1999). Not only is this knowledge stored in any tooling marks left by a process, but as later demonstrated, is inherent to the structure of that object. The object can not be brought into existence without a negotiation with reality, and this negotiation is done through craftsmanship. The material and the craftsmanship required to work with it are inseparable, but can be translated from one material to another due to similarities between process. Zheng and Nitsche (2017) describe this inseparability in their analysis of the combined usage of ceramic pottery and LED lighting to create novel decorative forms. They use this example to highlight the need to relay on the embodied knowledge of the expert they worked with to create these forms, and how everything from the shape of the object to the glazed use to finish the surface of them has an effect on the electronic components of the form. It also shows, through the authors' anecdotes, the importance if interdisciplinary research and exchange of information from areas outside academia. This outside knowledge is a sorely underutilized part of making and creativity in the context of computational arts, and so collaborations like those previously mentioned have the capacity to better both parties by bringing more and more outside knowledge into academic circles.

2. Embodied Material Translation

In the case of 3D printing and foundry, both are essentially additive processes. Both require a disposable supporting structure in order to bring certain forms into being. These support structures leave marks on the final process that must be removed manually. There is an embodied process in the object and the material it is made out of in the same way that there is an embodiment of the craftsmanship necessary to create it. When creating an object in digital space, there is still a kind of embodied knowledge, even if it does not exist physically. Digital craftsmanship is used to first create this form, and when 3D printing it, that craftsmanship must then communicate with the physical in order to render that digital form into reality. The form being made passes through several different modes of being, and is affected by every translation to each. In a similar way to translating between languages, a form must be made within the constraints of the material. Some details will be lost, and others added, but the fundamental form will be the same if translated correctly. Also like spoken or written languages, the rules and constraints of a material can be used to accentuate the form or emphasize certain elements of the design.

2.1. The Embodied Language of 3D Printed Plastic

The process of 3D printing, regardless of the material used, consists of building up layers of material on top of one another. In order to print certain forms, it is necessary to create a kind of scaffolding that can support the material being added, so that the object being produced doesn't fall apart before it is finished, and so that there will be material to build up layers upon. While designed to be removed from the final object, this scaffolding will still show through in some ways on whatever is produced. What's more is that those marks of process will be just as prevalent on the interior of the object produced as they will be on the outside, and should be taken into just as much consideration when working with an object that has been 3D printed, regardless of material. These marks of process can be seen more obviously when certain processes are applied to a 3D printed object. Some examples of these artifacts can be seen in Figure 1.

Exterior Artifacts The scaffolding required to build overhanging layers on top of pre-existing ones do not always come off cleanly. Occasionally, remnants of the scaffolding can be fused to the main body of the object and will have to be removed manually. Artifacts can also be introduced into the surface of the object if the temperature of the material or the speed of the printing head is not constant, or within manufacturer recommendations.

Interior Artifacts Unless printing an object that is completely solid, the object will be filled with geometric pattern in order to support the rest of the surface and provide structure to the form. These patterns can be exposed if the surface has been finished aggressively, such as with heat or sanded down to past the outer layers in the case of plastic. They will also be visible if a transparent material is used.

Printing Errors The layers of a 3D print may not fuse correctly, resulting in something that looks closer to a birds nest or bowl of spaghetti than the object being produced. There is usually no recovery from this state. The head of a 3D printer may also clog, resulting in a half made object. In both cases, the objects may have to be reprinted.

Finishing Plastic 3D printed plastic can be smoothed and sanded through traditional means, but it can also be smoothed chemically through the limited application of some solvents, such as turpentine. This process may leave the surface tacky if too much is applied. While plastic can also be painted, it is important to ensure that a given paint won't react with the plastic when applied, as it may deform the outer layers of the print. Plastic can also be smoothed through the limited application of heat, such as with a heat gun or bunsen burner. The printed layers will blend together, but too much heat may deform or burn the plastic.

Fig. 1. (a) The supports required to print an overhanging object. (b) A 3D printed object smoothed with a heat gun. The heat warped the plastic to show the structure inside the object. (c) The aftermath of a failed print. Images by author.

2.2. The Embodied Language of Metal Casting

The foundry process consists of liquid metal being poured into a mould and given time to solidify. An object is given form not by removal of material, but by the shaping of a set amount of material by the mould. Other materials, such as sand or ceramic, must be used as well, and are usually consumed by the process. The construction of these moulds can sometimes take days, depending on the method used and the size of the object. Part of this mould making process involves creating a network of plumbing for the metal to safely flow into the mould, which will then have to be removed later, in a similar way to the supports and rafts of a 3D print. This network is usually referred to as sprue, gates or runners, depending on their size and their role in the network of the pour (Treyger n.d.). An example can be seen in Figure 2.

Gating The application of gates onto the surface of the object being cast will remove a section of surface detail. When the gating is removed by the maker, the only thing left in that place will be small lumps of excess metal, which will then have to be smoothed down and retextured by hand.

Air Pockets As liquid metal rushes into the mould, air must be pushed out through either a porous material or a specially made channel. However, in cases where the air cannot escape while the metal is still forming, these air pockets will show through on the final product, either as nodules or indentations on the surface.

Incomplete Pours In some situations, an air pocket may be so large that it prevents the formation of a large portion of the object. In other cases, part of the mould may collapse in on itself, leading to a similar effect. When the object is removed from the mould in either of these cases, it will have a large cavity.

Finishing Cast metal can be refined by mechanical and chemical means, such as through sanding blasting, mechanical polishing, or through the application of chemicals called patinas to change the texture, colour and sheen of the surface. Most metals can be brought to a high degree of polish, unlike 3D printed plastic. One of the most important processes in finishing the metal object is the complete removal of the excess material left by the mould.

Fig. 2. The hole in the side of this sculpture was caused by an air pocket, whereas the texture on its surface was caused by the metal hardening before it could fill in the entire. A patina was then applied to darken and highlight these textures, using them as sculptural features left by the process. Image by Elizabeth Tsu (2021).

3. Using 3D Prints with Metal Foundry

Snelling et al. (2013) discuss the use of 3D printed materials in the process of mould making for metal casting. The study finds that using a 3D printed material could negatively impact the tensile strength of cast objects, and while this fact should be considered, it should not dissuade from it's usage. However, this study focused on the use of 3D printing material that is specifically designed for metal casting, and may not be available to those with consumer grade printers. The following section will outline experimentation with using consumer grade PLA plastic in the context of three different foundry techniques with mixed results.

3.1. Moulds for the Lost Wax Process

Lost wax is the process of rendering an object in metal by first sculpting it in wax to be used as a positive to create a mould of ceramic around that wax form. The wax is then melted out of the ceramic, which is fired to make a heat resistant mould for casting metal. When attempting to render a pre-existing object in metal through this process, a mould of it would be made by submerging it in some form of media such as silicone or alginate, where wax would be poured to make the wax positive. However, 3D printing offers an alternative to this by allowing the direct creation of a mould for the wax positive, without the need for a physical original object.

In the example shown in figure 3, a cavity was modeled into a cube by performing a boolean difference between said cube and the desired object. The cube was then sliced digitally into several components so that the desired object could be removed without damaging the wax form. It was then printed in PLA plastic.

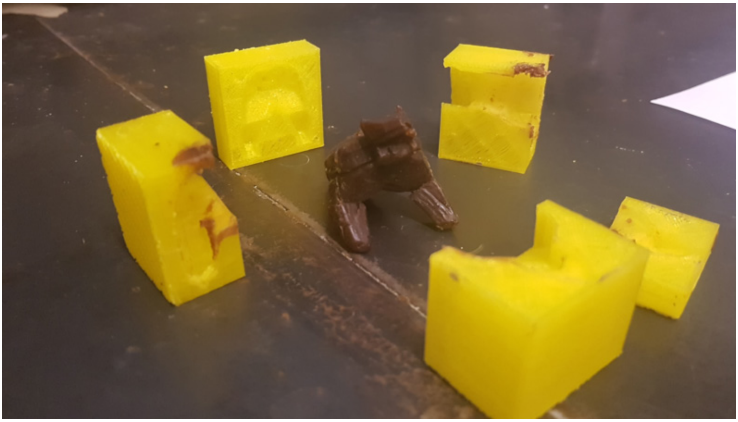
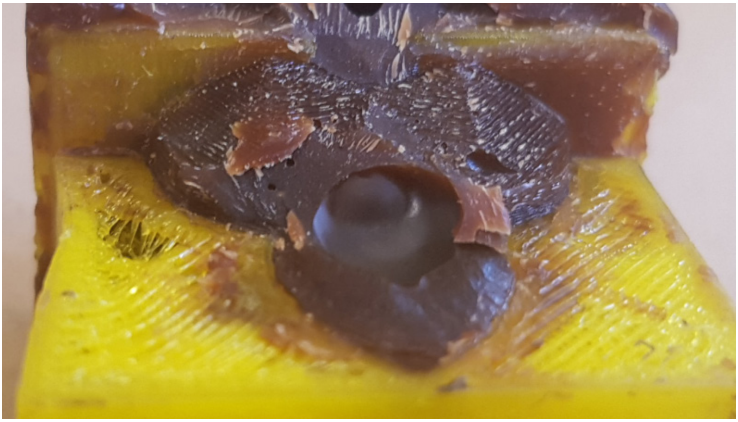


Fig. 3. The components of a 3D printed mould, and the closest thing to a full wax rendering of the desired object achieved by this method placed in the center. Image by author.

While the printing of the mould components were successful, the heat from the liquid wax ended up melting the plastic around it, fusing the wax and the plastic together in such a way that a release agent could not be used to separate the two. Several attempts were made with varying heat of wax. In the attempts with cooler wax, the wax would not fill the entire mould. If the wax was too hot, it would destroy the mould and spill into the gaps between the inner and outer walls, as seen in figure 4. However, in figure 5 we can see the artifacts that the 3D printing process would have left in the final version had the wax positive been cleanly removed from the 3D printed mould.

Fig. 4. The remnants of a 3D printed mould that hot wax was poured into. On the right of the image, it is possible to see where an interior cavity of the 3D printed mould was filled with wax. Image by author.

Fig. 5. Surface detail from the layers of the 3D printed plastic can be seen on the wax. Small particles of plastic can also be seen stuck in the wax. Image by author.



This failure could potentially be alleviated by using a more heat resistant plastic such as ABS, or by using 3D printed clay or cement (Rael and Fratello 2018). While printing more robust materials would change the language of the print by increasing the distance between layers, or the texture of the surface, they would allow for any mould made out of them to be heat resistant to the hot wax. It is also more than apparent that if the PLA moulds can not handle the heat from melted wax, they absolutely *should not* be used with the metals commonly used in foundry.

3.2. 3D Printing and the Sand Casting Process

While a much quicker and more simple process, sand casting imposes certain limitations on the kind of objects that it can produce. In order for a mould to be created for the sand, an object must not have any overhangs that would disrupt the removal of the object from the sand. If an object were to have an overhang, it would take with it some of the sand inside the mould, potentially destroying it. Since this process requires the creation of two halves of a mould, the object must cleanly pull away in both directions.

Figure 6 illustrates the changes suggested by the foundry operator in order to use the given 3D printed components. These changes were made after a short deliberation, in which he outlined the requirements of his foundry's process. Without his expertise applied to the form of the object through the changes suggested, it would not be possible to produce. Of course, it would have been equally impossible without his technical skill in mould making as well.

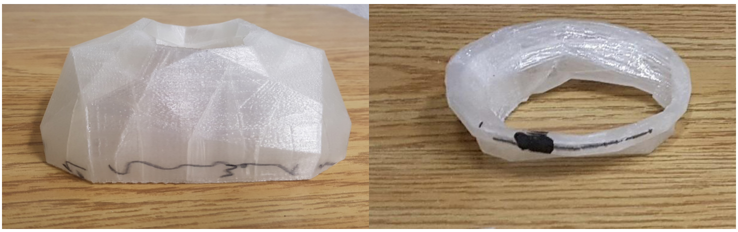


Fig. 6. The plastic original of a 3D printed object to be sand cast. Markings in black clay and pen are modifications suggested by the foundry operator. These changes to the geometry of the object were trivial to make to the original CAD files, meaning a new object could be printed the same day. Image by author.

In addition to this, sand casting creates more artifacts which must be removed manually, as shown in figure 7. While the surface detail of the 3D printed material still shows through, the rough surface creates more air pockets where nodules of metal can form when the mould is poured. The texture left by the complete removal of the gating network can be seen in figure 8.

Fig. 7. A bronze version of the object in Figure 4. While the detail left by the 3D printing process can still be seen, nodules of metal can be seen on the surface, caused by the irregular surface of the plastic original. Image by author.

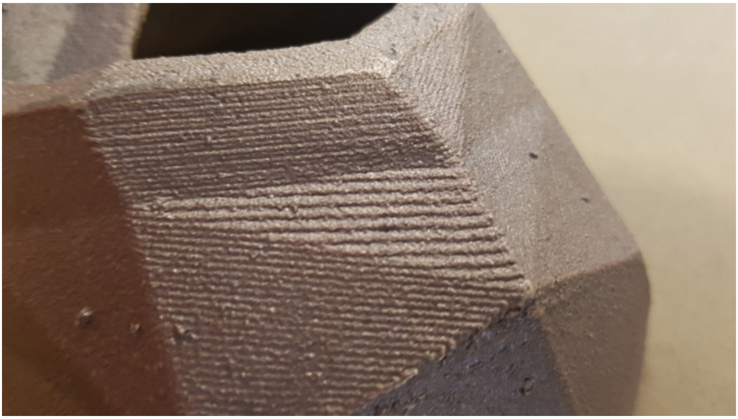
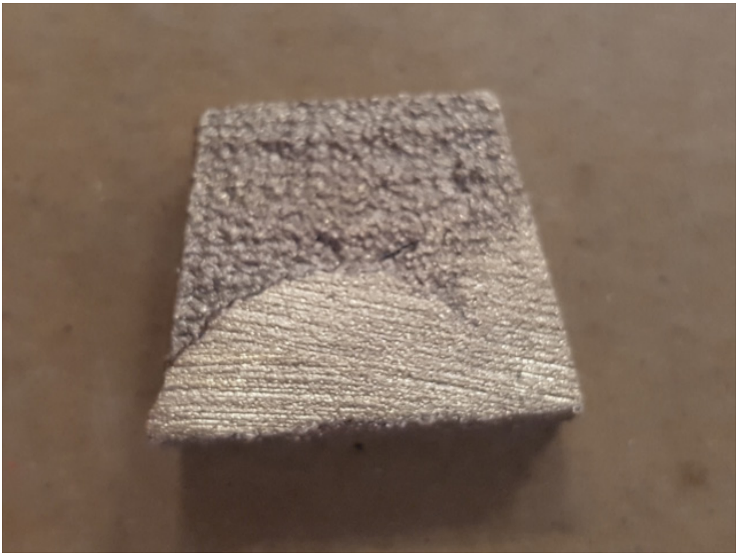


Fig. 8. Another component cast in bronze. The change in surface texture was left by removing the connective gating between that allowed the metal to flow into the object. Image by author.



3.3. 3D Printing and the Process of Burnout

A 3D printed object can be used in a burnout in a similar way to using a piece of styrofoam or biological material such as a porous wood. This use of the printed object provides the highest levels of detail, including the previously mentioned artifacts from the process of printing, such as the layering of plastic shown in figure 9. This method is most similar to lost wax casting, in which foam objects are gated, covered in some kind of ceramic or plaster, and then burnt out in the same way a wax mould would be.

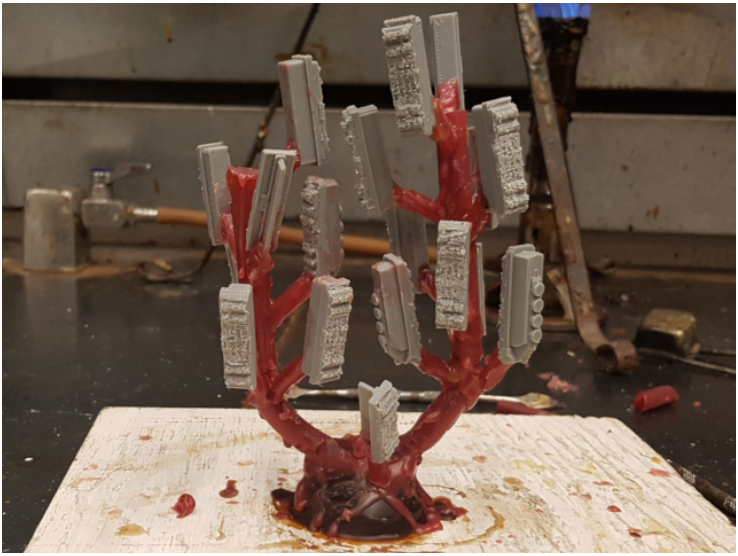


Fig. 9. Several 3D printed components in preparation to be burnt out. They are connected with wax to a central point where the liquid metal will be poured. Image by author.

The artifacts left by this process are very similar to the ones left by the lost wax process, and include the details lost in the connection points between the gating and the 3D printed objects. Most of these can be removed by hand tools such as a hacksaw and file. The removal of these artifacts can often damage or remove the texture left by the 3D printing process. While this process does create a high quality metal rendering, the burning out of material, especially plastics, can create harmful vapours. It also completely destroys the original object in order to create the mould. In figure seven, several 3D printed objects have been attached to a wax framework. This was later covered in plaster to create the mould, then burnt away to create a cavity for the metal to take the form of. The end result of this process can be seen in figure 10.

Fig. 10. The structure in Figure 7 after it has been used in the burnout. Both the plastic and wax have been replaced by metal, but still retain their original textures. The gating will have to be manually removed. Image by author

4. Conclusion

The synthesized use of two materials is not as simple as using one, then the other. Each process of creativity brings with it its own processes, which will change not only the final appearance of the object, but may fundamentally change its structure, its geometry, and what it can be used for. This is just as applicable to the ethereal material of the computational arts. There is a negotiation between one material and the other, in the same way that there is a negotiation with reality to first bring an object into being. The process of making with material acts as a set of embodied rules for its use. The way that these materials interact with each other to create the final form of a sculpture or component is a culmination of both sets of rules for each material. In the same way that translating a passage of text from one language to another will subtly change its meaning due to the grammar and vocabulary of the two given languages being similar, but not quite identical, the subtle difference in the properties of each material will change the final form. Like those languages, it requires a thorough knowledge and understanding of both to be utilized to its fullest extent.

In order to fully utilize a material, process or medium, an understanding of its embodied language will be necessary. While there may be academic sources on any given material, the most effective way to gain this understanding is through direct participation in the making process, or a participation in the oral tradition of whatever community is most involved in that particular form of making, be that a loosely organized internet community, or a private industrial practice. The knowledge that these communities possess may not be as well documented academically, but is just as important when working with the practicality of a material as an academic foundation. Additionally, a closer study or interaction with these groups may allow their knowledge to be incorporated into the broader body of academic knowledge.

3D printing has been shown to be useful to directly create moulds for metal to be poured into. PLA plastic, one of the most popular consumer grade printing materials, is able to be used in some aspect of the printing process with mixed results, and only if that part of the process does not directly interact with high heat. A more robust study into the effects of using this material, and other 3D printed materials, in the same way that Snelling et al. could provide useful insight for future directions of research. As another possible avenue to apply 3D printing to foundry, 3D printed ceramic could be printed, and then fired to create a mould without the need for any wax, in a similar way that Snelling et al. used sand and binding agent. Using any of the methods stated previously, gating and channels could be created parametrically with specially designed software. Alternatively, the gating network could be printed, either out of plastic or wax, and could then be used to create a ceramic mould in a more traditional way.

Additionally, further study into the differences between the method described in this paper and methods like CNC milling and more common fabrication methods would be useful in placing 3D printing in the broader context of metalworking, and as an intermediate step to augment other methods. Similarly, other processes such as laser cutting cardboard for use in burn out, for example, would benefit from a similar exploration. Finally, as the technology of metal 3D printing becomes more prevalent and widely available, the translation between the digital and the material becomes even more direct, which itself warrants its own study in terms of how this streamlining affects the realization of digital forms.

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