Thermoplastic Kilnforms: Extending Glass Kilnforming Techniques to Thermoplastic Materials using Ontology-Driven Design

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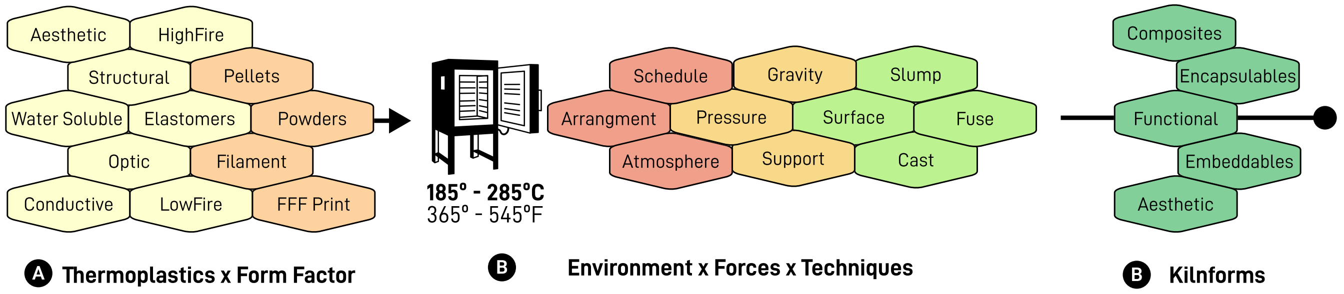

Figure 1: The Kilnforming Ontology. An ontology derived from glassworking is used to organize (A) the space of functional and aesthetic thermoplastics by their form factor and firing behaviors. When heated with a kiln, (B) environmental conditions, forces, and techniques inform how thermoplastics are deformed, resulting in (C) the space of thermoplastic kilnforms.

ABSTRACT

The ecology of thermoplastic materials is rapidly evolving, enabling an exciting landscape of functional, aesthetic, and interactive forms. Despite their utility in fused filament fabrication (FFF), an even larger and untapped design space exists for thermoplastics. In this work, we introduce a design method that leverages similarities with a more mature medium (glass) to guide a material-centered exploration of a new medium (thermoplastics). Through a collaboration between domain experts in thermoplastics and glass, we synthesized an ontology of kilnforming techniques and developed an annotated portfolio of thermoplastic kilnforms that capture generative design directions for altering the phenomenological qualities of plastic, prototyping metamaterials, and composite forms, and engaging with other material practices. We discuss how material parallels can continue to expand the role of thermoplastics as a design material and how ontology-driven design can serve as a means of localizing, questioning, and generating material knowledge.

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CCS CONCEPTS

• **Human-centered computing Interaction design process and methods**; *Empirical studies in interaction design*.

KEYWORDS

thermoforming; material exploration; composites

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1 INTRODUCTION

Manipulating materials with heat is a time-honored practice that has led to a variety of grassroots innovations across many communities of practice (CoP)[1]. While each technique has been adapted to suit the unique behaviors of materials, they share strong parallels often inspired by "other adjacent and parallel practices, from which lessons are learned, innovations borrowed, procedures copied" [18, 84]. Despite the interconnectedness of formgiving techniques, the

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[1] Communities of practice are used to describe knowledge generation and learning environments that form when "a group of people share a common concern and learn how to do it better as they interact regularly" [45].

insular nature of communities of practice has made crosstalk difficult, limiting the ability to interconnect, consolidate, or synthesize knowledge generated from CoPs to inform material practices.

Within university makerspaces, thermoplastics have become a staple material primarily due to their widespread availability in a filament form factor within commodity 3D printing [13]. Despite their utility in fused filament fabrication (FFF) techniques, the range of thermoplastic formgiving techniques available within makerspaces remains limited compared to more mature mediums like paper, clay, and glass. So how might knowledge of materials that share common behaviors, which we term *material parallels*, be used to *expand* the expressivity and functionality of material forms, *improve* the reliability, sustainability, and ease of use of fabrication processes, and *map* a more complete design space of formgiving techniques?

This work explores one such material parallel between thermoplastics and glass. Although structurally dissimilar, thermoplastics and glass exhibit a similar 'glassy state' when heated, allowing them to behave with different degrees of malleability. This malleability serves as the central mechanism for enabling thermoforming techniques such as fusion, extrusion, slumping, blowing, and pulling. Drawing from knowledge engineering practices, we propose that domain knowledge from these two practices can be synthesized into a knowledge graph known as an ontology that can be effectively used to transfer material knowledge between practices and inform material-driven design workflows. In this work, we propose that relational ontologies can be used to formalize and consolidate domain knowledge across CoPs into structured *concepts* that can be used to identify larger design spaces and guide material practice. To communicate the value of ontologies in design, we contribute:

- A principled, structured, and shareable ontology of practice-based material knowledge describing the interrelationships between plastic and glass.
- We describe an ontology-driven design process used to extract a set of design principles to adapt kilnforming to a range of thermoplastics form factors. Kilnforming describes a subset of thermoforming techniques widely used in ceramic and glass CoPs that uses a kiln, i.e., an insulated heating chamber [30].
- We develop an annotated portfolio of exemplars that operationalize how kilnforming can leverage the broad optical (polycarbonate), structural (PLA/ABS), electrical (conductive PLA), and elastic (thermoplastic polyurethane) properties of thermoplastics to enable novel aesthetic, functional, haptic, and electronic artifacts.

While scoped to glass and plastics, the Kilnforms Ontology can be used to inform the design of other thermoforming and casting processes under active investigation within the Human-Computer Interaction (HCI) research community, including metal, silicone, wax, chocolate, resin, soap, plaster, concrete, biomaterials, and gelatin. Since many smart materials have close material parallels to existing materials, smart material researchers benefit from our work understanding how ontologies can be used Consolidate knowledge across CoPs.

In this paper, we first map how personal fabrication research draws from thermoforming practices and present a schema for synthesizing domain knowledge into an ontology. Then, from an ontology-guided material exploration, we synthesize a set of kilnforming design principles and annotate a collection of exemplar artifacts with morphological experiments and material characterizations. Finally, we use these artifacts to describe the larger material ecology of thermoplastics and how ontology-driven material exploration can be used to localize, question, and generate material knowledge and facilitate craft-based processes.

2 RELATED WORK

Thermoforming is a prototyping technique for creating geometries from materials that soften when heat is applied. In contrast to subtractive or additive manufacturing techniques, thermoforming deforms the raw material, reducing material waste and fabrication times. We review research within the Human-Computer Interaction community that leverages thermoforming as a rapid prototyping tool with thermoplastics. We juxtapose the techniques in HCI research against adjacent material practices and other material investigation approaches.

2.1 Ontologies in Design

Ontologies are effective in representing domain-based knowledge across different communities and are part of a much larger practice within knowledge engineering [41], natural language processing [16] and machine learning [11], education [72], and disease mapping [54]. Although ontologies are most often used to organize or visualize domain knowledge [89], they remain underutilized in design practice due, in part, to the knowledge engineering practices required to develop them. Creating an operational ontology requires domain experts to communicate with knowledge engineers to structure their understanding into a set of shareable *concepts* [64]. They must then draw relationships (e.g., ***is_a***, ***has_a***) to establish connections between concepts before going through multiple iterations with ontology users until the encoded concepts and relations can be used to make useful queries or inferences [19]. In some situations, contextual information can heavily influence the effectiveness of ontology queries or inferences in practice [63].

Ontologies are most practically used to annotate information. Liu et al. demonstrated that natural language processing techniques could be used to take unstructured design documents (e.g., a description of a prototype) and extract design ontology concepts (e.g, Material, Function, Property, Fabrication) to support faster information retrieval of design information. Many continue to use ontologies to drive design decisions and interactive systems. Freitas [20] used an ontology of user abilities to identify changes needed in a user interface to support accessibility and generate an adaptive UI to satisfy those requirements. Macias et al. [52] demonstrated how an ontology-based representation of the knowledge contained within a web page could be used to drive design decisions for authoring dynamic web pages. Similar to our goal of enabling knowledge transfer between communities of practice, Castro et al. [15] introduced the Human-Computer Interaction Design Ontology (HCIDO) as a way to bridge HCI and Software Engineering concepts. To our knowledge, our work on bridging glass and plastic material

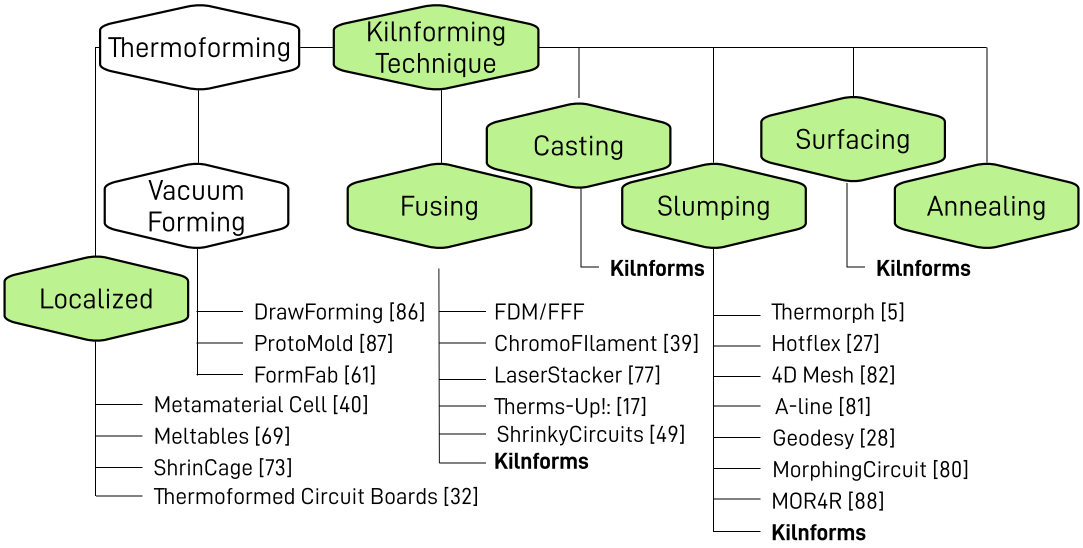

Figure 2: The Kilnforms Ontology organizes kilnforming techniques into five types – work in HCI has focused largely on localized heat, fusion, and slumping.

knowledge represents the first application of a formal ontology towards a material design practice.

2.2 Exploring Material Design Spaces

Design spaces serve as a mechanism to communicate effective and ineffective combinations of design variables in artifacts. Computational approaches, such as combinatorial design, structure design spaces using design dimensions or models. These spaces have been used analytically to understand the capabilities of input devices [14] or to guide design exploration [22]. When these spaces become computationally complex, constraint-based approaches are used to refine acceptable design combinations [9]. The utility of these approaches in design becomes highly dependent on how the design space was constructed and the ability to instantiate design derivations [43].

Current interaction design patterns for facilitating material encounters leverage interactive simulations that provide more opportunities for material experimentation. When factoring design spaces for physical materials, morphological experiments have been shown to communicate design directions effectively [46, 57]. Others have developed material interfaces that make it easier to perceive material feedback and manipulate materials; however, this has been primarily limited to paper [74], electronic [75], and textile-based practices [23, 50, 55].In contrast, material-driven design uses a reflective approach to motivate design intention [74], elevating the material to the role of the design agent. Other design patterns have leveraged interactive simulations that provide more opportunities for material experimentation. One promising alternative is to guide material investigation instead; Murer et al. [62] proposed such a framework around unmaking, formalizing the natural curious actions of taking apart and probing the origins of mechanisms of a found object to engender creative and critical thought. Our work acts as a synthesis approach — we use a theoretical model (i.e., ontology) to motivate design intention; however, the model is constructed from practice (i.e., material-driven design processes). Our ontology formalizes the existing material understanding within glassworking practice to motivate the design exploration of an underdeveloped medium like plastic.

2.3 Thermoformed Materials

HCI researchers have applied thermoforming techniques to a range of materials, including glass [12, 38], thermoplastics [6, 28, 32, 80–82], wax [7, 31, 65], and chocolate [37, 47, 58]; more broadly, these techniques are used in metalworking, glassblowing, and sugarworking practices. Many thermoforming practices are highly dependent on the temperature ranges required to achieve a malleable material. In some cases, additional modifiers are required to alter the rheology of the material for extrusion (e.g., chocolate). While glass malleability occurs approximately between $1320°C$ to $1723°C$, thermoplastics operate in ranges nearly 7 times cooler ($\approx 185°C - 285°C$). Despite the need for specialized equipment, material practices have adapted ways of using similar and more accessible practices. For instance, glassblowers without access to a desktop gloryhole furnace often practice with sugar ($\approx 60°C$ to $186°C$) and more ubiquitous sugarworking equipment to refine their glass handling techniques. Similarly, a large body of HCI research uses more heat-friendly polystyrene ($\approx 60 - 270°C$) to prototype plastics forms without specialized equipment [33, 49, 79, 83]. Some thermoforming practices forego the need to soften materials - additive manufacturing processes like selective laser sintering allow geometries to be formed from heating powdered, typically metallic, materials [42].

2.4 Working with Heat

Applying heat to materials like thermoplastics is typically achieved through hot air blowers [33, 40, 69] or torches. Localized heating elements such as strip heaters [8], defocused laser cutters [59], heat gun-wielding robotic arms [61], vacuum system for heating interactive molds [86, 87], and resistive joule heaters [27] have been down as effective methods of selectively and precisely applying heat to regions of plastic materials.

Hot ends, which aim to completely melt materials, are effective for extrusion techniques like fused filament fabrication, pulling fibers [44], electrospinning [68], and glass 3D printing [34]. Warm water (32 – 43°C) has been effective for hand molding polystyrene pellets, while a heated water chamber (up to 100°C) has been used to deform a wider range of thermoplastics [5, 39, 83]. Conventional ovens (38 – 233°C) are effective for polystyrene thermoforming and compatible with solder reflow and silver ink integrated electronics [49][2]; microwave ovens were shown as effective for manipulating acrylic [88]. Kayzer's desert manufacturing investigations revealed how focused light could be used to sinter sand into the glass (1400 – 1600°C).

This work introduces kilns (72-1240°C) as a new addition to this heat-forming ecology. While already widely used in glass thermoforming, kilns remain underutilized within plastic thermoforming. We show how kilns can provide access to techniques that require higher temperatures or controlled heating or cooling, such as fusion, compositing, firepolishing, and sintering, while exploring new workflows, including batch production.

2.5 Thermoforming Techniques

Slumping. One thermoforming technique requires materials to be heated just past their glass transition temperature, which allows them to deform but still maintain their overall shape. Slumping techniques leverage gravity as a force for bending and stretching geometries. By suspending a thermoplastic sheet in a laser cutter, LaserOrigami [59] a defocused laser was used to selectively apply heat to regions and allow gravity to create folds, curves, and other 3D geometries. Leveraging jigs, researchers have used hot air blowers to slump complex 3D shapes [8, 69], similar to how molds are used in traditional glass slumping. Applying heat locally becomes easier when heating geometries with low specific surface area (SSA), i.e., the ratio of surface area to the mass of a geometry. Popular within the DIY community, the Hairy Lion model [1] was designed to have thin and separated hair geometries which can be rapidly heated and "combed" to create an impressive fur texture. In this work, we demonstrate how kilnforming techniques can also achieve localized thermoforming by altering geometries to achieve target SSAs using clay as an insulating material.

Shrinking and Expanding. Global heating approaches are useful in situations where the deformation of materials can be readily controlled and is especially common in plastics with different expansion and compression behaviors. ShrinkyCircuits [49] used existing thermoforming practices with Shrinky Dink, a popular craft material and shape-memory polymer made from polystyrene, to create plastic embedded circuits and leveraged the shrinking behavior to enable traces with higher conductivity. By printing flat thermoplastic composites with different coefficients of expansion (COE), Thermorph created self-folding geometries activated when the composite was submerged in a heated water chamber [5]. Similarly, researchers have designed actuation mechanisms by altering the infill pattern (and, by consequence, specific volume) to enable developable forms from meshes [83] and shrink-fit forms[73]. Kilnforms expands on these techniques by precisely controlling the heating and cooling of thermoplastics; by printing layers of different materials and later fusing them in the kiln, we show experiential workflows for creating impromptu variations in geometric design.

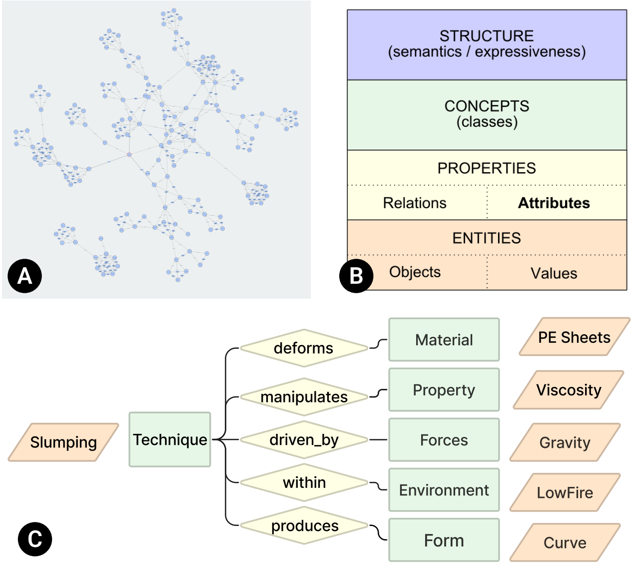

Figure 3: The Kilnform Ontology A) is encoded in the Semantic Web-friendly OWL format; B) uses the entity-attribute-value model to structure domain knowledge within glass and plastic forming; C) organizes the space of kilnforming techniques with five core relationships; nodes in orange signify objects of their respective classes.

Fusion & Composites. When heated past their melting point, thermoplastics can fuse to each other, creating welded joints, laminated sheet composites, and forms that encapsulate other objects. LaserStacker demonstrated how laser cutters could be used to selectively laminate sheets of plastics together [77]. Encapsulating functional materials during the 3D printing process has become an effective strategy for enabling interactive artifacts. Hotflex [27] integrated resistive heaters to heat and deform a form post-fabrication. Thermorph [5] layered multiple thermoplastics in a composite structure; however, this technique is limited to extrudable materials. Kilnforming expands the design space of heterogeneous composites to achieve a wider range of functional forms.

3 THE KILNFORMS ONTOLOGY

Every domain has a unique knowledge base that is developed over time by a community of practice. Ontologies have been used as a way to formalize this knowledge into `concepts` that are interconnected with ***relations***[3]. Such ontologies serve to (1) unify the

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[2] n.b. Thermoforming with solder and other lead-containing materials is not food safe.

[3] We adopt the entity-attribute-value model to present elements of the Kilnforms Ontology in this paper: `Titlecase` to signify concepts and their corresponding ***attributes***,

representation of knowledge from different terminologies and vocabularies, (2) to permit inference and reasoning, and (3) serve as a form of annotation [70]. In design, the hierarchical structure of concepts within an ontology can be used to organize design information and drill-down through different design decisions. We synthesized the Kilnforms Ontology[4] to formalize the knowledge around formgiving techniques that use a kiln.

3.1 Ontology Design Process

The goal of the Kilnforms Ontology (Figure 3) was to structure the domain knowledge found within glassworking so that it might guide the exploration of thermoplastics when subjected to kilnforming techniques. We conducted a two-hour workshop following best practices in ontology development [64] with two glass domain experts and the paper authors. The workshop took place within a working glass studio to better facilitate conversation and dialogue with the materials, tools, and people found within a living practice.

Domain Experts. G1 is an internationally recognized glass artist whose work focuses on the combination of glass, metals, and ceramics and the overlap between scientific processes and art-making processes. G1 serves as a glass instructor in undergraduate and graduate education. G2 is an artist and a glass studio technician with 25 years of experience; G2's artistic practice extends and hybridizes glass and ceramic techniques, regularly using and creating custom large-format kilns (architectural glass kiln-forming).

Scope. We first synthesized a set of material competency questions to constrain the scope and function of the ontology.

- What forms can be created using a kiln and glass?
- How does one manipulate the kiln to achieve different forms?
- How do the material's properties contribute to the final forms?
- How does one assess the compatibility of different materials and kilnforming techniques?
- How does one operate safely with different kilnforming techniques?

The ontology thus serves to describe concepts found in the kilnworking workflow. From a hylomorphic workflow, we include how materials are chosen, prepared, and configured within a kiln, how a heating schedule is designed, and what kilnforms are produced as a result of this process. For morphogenetic workflows, these concepts are extended to provide analytical power to describe the behavior and expression of material forms as they arise. Some glassworking techniques such as `VacuumFormingTechnique` or `GlassBlowingTechnique` arose during the workshop that could be achieved within a kiln but would require significant and expert modification to a traditional kiln. We included them as related concepts in the ontology but, due to practicality, excluded them from further experimental consideration.

Procedure. Using a shared collaborative visual editor (FIGMA), we discussed each question in turn and populated the editor with images, videos, and links to ground the discussion around glass and kilnforming. All parties participated in enumerating and defining important terms and concepts within the document. The group used vertical grouping to indicate hierarchical relationships; proximity was used to indicate some attribute or relation. This document was then iteratively edited offline over a span of two weeks to allow new concepts and terms to surface; the workshop participants reconvened to review the document and further refine taxonomic relationships. Disagreements on vocabulary or concepts and boundary instances were isolated and resolved through discussion.

The ontology was then populated from personal experience and literature on glassworking techniques and iteratively refined when boundary conditions were met. The informal ontology in FIGMA was then transcribed into the Ontology Web Language (OWL) using the Protégé ontology editor.

3.2 The Kilnforming Schema

The ontology contains 146 concepts, 14 object properties, and 57 data properties. These concepts are used to annotate a total of 61 instances, including examples from literature and this work[5].

3.2.1 The Material. In our ontology, a `Material` concept is described by its:

- `PhysicalMaterial` (e.g., BorosilicateGlass, PolylacticAcid (PLA)), specifically a physical substance that provides information about optical, physical, mechanical, thermal, and electrical behaviors.
- `Form` (e.g., Pellet, Filament, ThinSheet) describes the physical geometry of the material; this is an especially relevant consideration since each geometry heats up differently based on its surface area.

Describing a `Material` through these two concepts serves to communicate the ways in which materials can be configured to accept or resist heatwork. For example, Polycarbonate (`PhysicalMaterial`) has the highest melting temperature of the thermoplastics we investigated but becomes more cooperative when used as a thin sheet, rod, or pellet `Form`. Conversely, Polycaprolactone (PCL) has one of the lowest melting temperatures and is amenable to being shaped when in a block and thick sheet forms.

3.2.2 The Kilnforming Technique. The `Technique` concept describes how a `Material` is transformed or coerced into a different `Form`. From a practice-based perspective, the space of techniques is best organized by the firing requirements of the process. Glass practitioners specifically delineate among `HoneyTechnique`, `LiquidTechnique`, `RubberTechnique` and `LeatherTechnique`.

Each `Technique` is linked via relations to concepts that can fully annotate the process and can be used to explain the theoretical basis of the Technique. A `Technique`:

- ***deforms*** a `Material` (the input)

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italic forms (***is_a***) to signify a relation between two concepts, and hierarchical notation (`A`>`B`) to signify that `A` is a superclass of `B`, i.e., hypernyms and hyponyms.

[4] The Kilnforms Ontology is available as supplementary material through our GitHub repository

[5] The ontology can be viewed for review using the open-source Protege Editor Protége

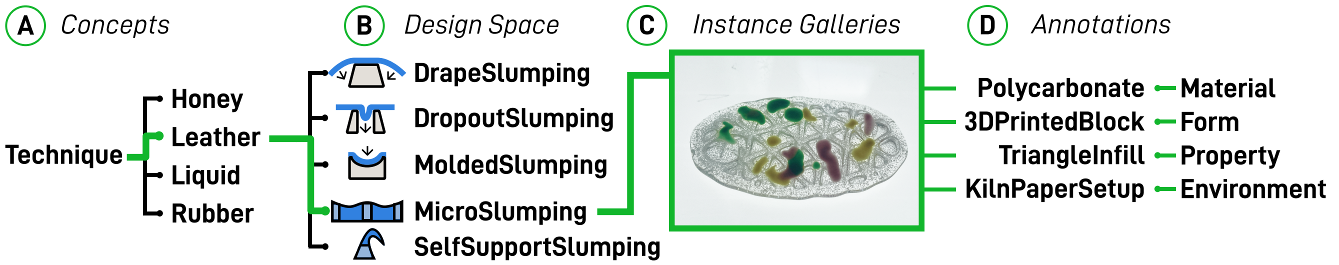


Figure 4: Design Spaces, Galleries, and Annotated Kilnforms. A) The ontology is used to organize the space of kilnforming techniques, B) sibling concepts are used to organize a design space, C) instances form kilnforms galleries; D) each instance is annotated and documented (green line) with the decisions that were made to achieve the form.

- ***manipulates*** a specific Property of a Material – a Property includes the physical, mechanical, thermal, and geometric properties of the Material.
- ***driven_by*** internal or external Force; most techniques used within the kiln rely on Force > Gravity > WeightedForce to alter forms, but more advanced techniques will employ Force > Gravity > WeightedForce.
- occurs ***within*** a specific Environment which describes the practice-based details for achieving replicable and successful firings from a kiln, including the Arrangement of sample components and their KilnLocationEnvironment, the FiringScheduleEnvironment of the kiln, and the ExteriorKilnEnvironment of the kiln. The ReleaseAgentEnvironment is used to describe the strategy for removing the material from the setup.
- produces a Form (the output) and organizes the space of outputs into a design space usable by HCI practitioners. We specifically delineate the types of form factors, functionalities, and aesthetics of developed forms.

4 ONTOLOGY-DRIVEN DESIGN PRINCIPLES

Recalling or finding the concepts in the ontology when working with material remains a tedious task. To support the development of a mental model for how these properties are used in practice, we synthesized a set of guiding design principles from ontology.

4.1 Principle 1 - The Malleable Forms of Thermoplastics

Thermoplastics exhibit different mechanical properties when heated. The elasticity graph shows (Fig. 5), thermoplastics can exist in four different malleable forms controlled by temperatures between glass transition temperature (T_g) and melting point(T_m). These forms are used to organize the space of kilnforming Techniques:

- Rigid In its most common form, thermoplastics are hard and brittle below their T_g. Some elastomers, like TPU exhibit flexible mechanical properties.
- Leather Thermoplastics become leather-like between T_g and T_m. Gravity-based deformation techniques, such as SlumpingTechnique and DrapingTechnique, are common and work well for capturing high-level details.

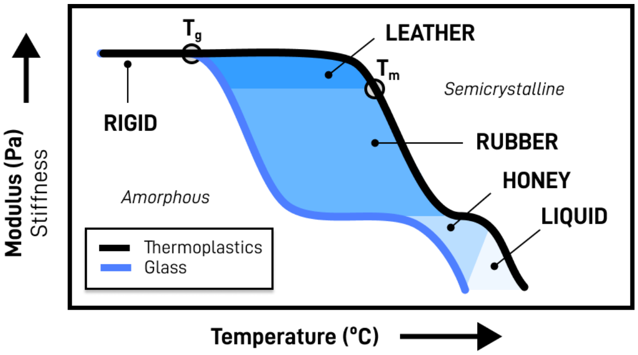
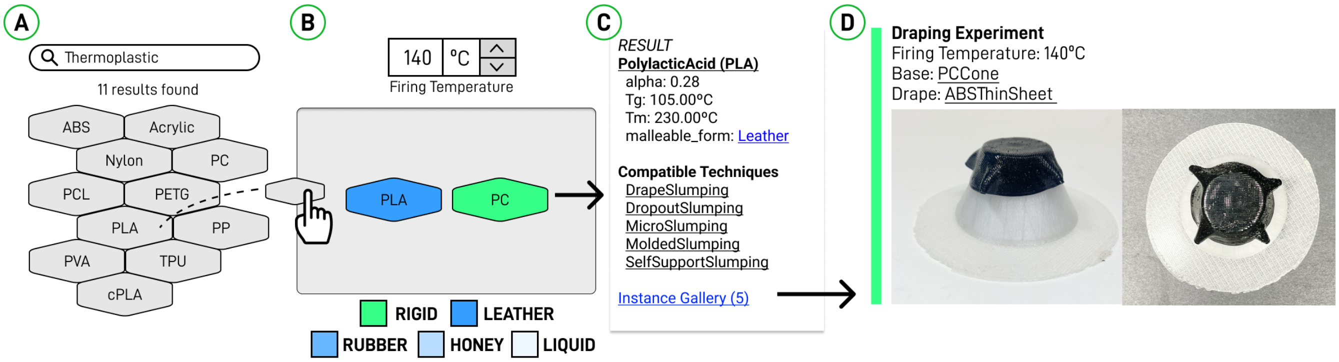


Figure 5: Stiffness Graph for Glass and Thermoplastics. Materials exhibit different mechanical properties when heated; the rubber plateau in thermoplastics is less pronounced, making the jump from Leather to Honey state relatively abrupt, bypassing the Rubber form. VanderWaalForce **present in glass prevents it from fully exhibiting liquid-like behaviors.**

- Rubber-Honey When heated to its T_m, thermoplastics start to exhibit physical and mechanical properties akin to a thick liquid. In this state, geometries start to collapse and enable techniques such as FusionTechnique, SurfacingTechnique, and ExtrusionTechnique. This form is especially useful for creating hybrid geometries that attach through ArrangementEnvironment, WovenForm, or EdgeJuxtapositionEnvironment and achieve different levels of fusion (FullFuseTechnique, ContourFuseTechnique, TackFuseTechnique).
- Liquid When above its T_m, thermoplastics further reduce their viscosity enabling the space of KilnCasting techniques. These techniques can be used to reclaim plastics and achieve elementary geometries such as ropes and puddles. In this state, most techniques used on Rubber-Honey forms can be applied to Liquid forms, resulting in the thermoplastics capturing more intricate details. Notably, glass exhibits an internal Force > VanderWaalForce not present in thermoplastics – this is an important creative behavior in glass kilnworking that makes fired glass naturally form round and 6 mm (1/4 inch) thick geometries and never fully exhibit liquid-like properties.



RESULT
PolylacticAcid (PLA)
alpha: 0.28
Tg: 105.00°C
Tm: 230.00°C
malleable_form: Leather

Compatible Techniques
DrapeSlumping
DropoutSlumping
MicroSlumping
MoldedSlumping
SelfSupportSlumping

Instance Gallery (5)

Draping Experiment
Firing Temperature: 140°C
Base: PCCone
Drape: ABSThinSheet

Figure 6: Malleable Form Calculator: A) The ontology is used to query all instances of the `ThermoplasticMaterial`, B) a composite design UI allows a user to probe how different thermoplastics behave at a specific firing temperature, C) thermoplastic's properties are used to identify its α value and predict material state (Leather); a few compatible `LeatherTechnique` are presented; D) querying instances that match the specified thermoplastic combination provide concrete examples of similar kilnforms.

Note that at its critical temperature (T^*), thermoplastics begin to disintegrate – some thermoplastics, such as acrylic, can produce toxic fumes; for safety, it is recommended that thermoplastics not be heated past T^* (see 10.1 *Safety*).

4.2 Principle 2 - Working with Uniform and Non-uniform Heating

Plastic forms rarely heat up evenly. Each thermoplastic has intrinsic thermal properties that define how quickly it heats up and enters its malleable forms, but its geometry also plays an important role in its thermodynamics. A `ThinSheetForm` is an ideal form factor since it exposes the largest surface area for heatwork to occur. Alongside `Pellets`, `RodForm`, and `FilamentForm`, form factors with larger specific surface areas heat up quickly and uniformly. In contrast, a `BlockForm` form factor can have its exterior and interior existing in different malleable forms; these effects can be mitigated by altering the `holdTime` of a firing schedule, allowing more time for heat to permeate to the entire form. While most techniques benefit from uniform heating, this can also be used to purposely control the behaviors of different geometries in a kilnform. For example, clay can act as a heat sink - by filling a hollow 3D-printed form with clay, interior geometries can remain intact while the exterior surface can be heated to its `Honey` form – this can effectively `Surfacing > FirepolishTechnique` the exterior of the print and remove 3D printing artifacts.

4.3 Principle 3 - Working with Forces

While it is possible to hand-manipulate plastic forms, we describe the `Force` in play within a closed kiln environment. `GravityForce` remains the common force across all kilnforming techniques – as such, `ComponentPlacementEnvironment` patterns are used to maximize the effects of gravity. Kiln furniture and molds are used to create `DrapeTechnique`, `SuspensionsTechnique`, `TiltArrangementEnvironment`, and `PoursTechnique`. These patterns can be further augmented with `WeightedForce` to further exaggerate deformations. Although a closed kiln environment makes it difficult to introduce external forces like pressure from external pumps and vacuums, adding water to closed forms with ventholes can be used to introduce steam pressure and balloon forms.

Gravity works in tandem with `SupportForce` forces such as those from molds; when considering 3D printed forms, `SupportForce` forces can also be influenced by metastructures such as walls (thickness) and infill (pattern; density) geometries. Transparent thermoplastics are especially adept at revealing internal interactions between gravity and support forces in 3D-printed forms.

4.4 Principle 4 - Compositing Thermoplastics

One affordance of using kilns is the ability to apply heat globally and simultaneously heat and form different materials. Since each thermoplastic has different melting and glass transition temperatures, it is important to keep track of the malleable forms of each respective thermoplastic. To fuse a composite of multiple thermoplastics, every thermoplastic must be brought to its `Honey` form. We used the ontology to create an example semantic application – a Malleable Form Calculator (Figure 6). The calculator simplifies the process of determining an appropriate firing temperature. Given the unique thermoplastics P in a composite and the firing temperature (T_f) of the kiln, the calculator pulls the respective T_g and T_m properties and computes the malleable form as follows:

$$\alpha_P = \frac{T_f - T_g}{T_m - T_g} \tag{1}$$

The α-value is then mapped experimentally to observed `Rigid` ($\alpha < 0$), `Leather` ($\alpha \approx 0.5$), `Honey` ($\alpha \approx 1.0$), and `Liquid` ($\alpha > 1.0$) forms.

4.5 Principle 5 - Multistage Kilnforming

Placing a kilnform through multiple firings can be used to create more complex geometries. For example, choosing thermoplastics with low melting temperatures (`LowFireMaterial`) like polyethylene can be an effective strategy for achieving techniques such as `Encapsulation`. Thin sheets of polyethylene require less thermal energy to achieve a `Honey` form necessary for fusion and to fully encapsulate a heat-sensitive material; conversely, in multistage processes, first fusing a `HighFireMaterial` such as polycarbonate can serve to minimize the deformation of the encapsulated layer in subsequent cooler processes (e.g., adding decorative elements with `LowFireMaterial`). A kilnforming "undo" is possible by taking material back to its `Liquid` state. Counteracting `VanderWaalForce` requires `Force > WeightedForce` or `Force > PressureForce` found in industrial kiln processes. Unlike glass, `VanderWaalForce` forces are not present in thermoplastics and do not limit the ability to reclaim flat sheets from recycled thermoplastic.

5 MORPHOLOGICAL EXPERIMENTS

After the initial construction of the ontology, we identified key morphological experiments needed to confirm the validity of glass-based methods on thermoplastics. These experiments characterize factors for the two main most common kilnforming techniques: `Fusing` and `Slumping`. The experiments follow similar constructions to those used in glass practice, including `CoefficientOfExpansion` fusion tests in different configurations (top/side/slot) and `SelfSupportSlumping` and `DropSlumping` tests for understanding gravitational forces in the kilnforming process. Results from these experiments are included as annotated instances within the Kilnforms Ontology.

5.1 Setup & Materials

To accommodate for the different types of thermoplastics available, we scope our characterization to sample from `LowFire` thermoplastics such as polyethylene (PE) and polyvinyl acetate (PVA), and `HighFire` thermoplastics such as acrylonitrile butadiene styrene (ABS), thermoplastic polyurethane (TPU), polycarbonate (PC) PVA, and conductive polylactic acid (cPLA). To connect kilnforming to digital fabrication practices, we also constrain tested artifacts to 3D printed forms, mainly `ThinSheets`. The thermoplastics were chosen to span a diverse set of physical and functional properties that are commonly used by the HCI community and described by the Kilnforms `ThermoplasticMaterial` concept.

All experiments were conducted in an empty Digital Ceramics Kiln (Skutt KM1222-3). We mitigated effects from non-uniform heating within the kiln (`Environment > KilnLocationEnvironemnt`) by placing all samples in the center of the kiln on the kiln floor. A 6" kiln paper was used between all samples and the kiln shelf to prevent adhesion and minimize thermal conduction interactions with the shelf.

5.2 Strip Fusion Experiment

As a kilnforming technique, `FusionTechnique` involves two or more materials that are layered or juxtaposed and heated past their melting temperature(s). During the fusing process, the `FiringScheduleEnvironment` (i.e., firing temperature over time) is used to control (1) the degree of fusion and (2) the extent to which characteristics are maintained (e.g., dimensional accuracy, surface textures). Achieving an adequate amount of fusion while retaining shape and features remains a challenge for composites that fuse materials with more than one melting temperature.

In order to generalize fusing behaviors, we conducted a series of fusion experiments with TPU, PC, and ABS strips (see 8). These fusion tests also operate to understand the compatibility of different thermoplastics with each other; in glass practice, this is determined by the rate at which glass expands (`CoefficientofExpansion`). Firing temperatures were chosen to span the range of melting temperatures of each thermoplastic studied ($180°C$ - $260°C$). Fusion samples were prepared by layering strips to a uniform base material (ABS) and fused with a one-minute hold time (i.e., peak temperature was maintained for one minute); each strip was placed to overhang to support adhesion testing. Thermoplastic strips were FDM-printed, and the detailed dimension of the strips is given in figure 7).

The degree of fusion and texture retention of the strips were assessed by 3 raters with knowledge of fusion techniques on a 5-point semantically anchored Likert scale. The alpha value, described by Equation 1, is used to provide a common scale for melting temperatures. The results (Figure 8) indicate that a smooth texture can be reliably obtained with $alpha > 1.0$, confirming geometries collapse when plastics enter their `Honey` form; although the fusion tests confirm that $alpha > 1.0$ achieves tack fusion, it also confirms that a non-permanent adhesion occurs when plastics are underfired (i.e., in their `Leather` form). Moreover, no sample was defective from uneven expansion and contraction, indicating that `COE` exhibits less of an influence on thermoplastic composites. Unlike glass, this indicates a wider range of compatible thermoplastic composites.

When thermoplastic enters its Honey state, the thermoplastic's viscosity reaches a state where it behaves like an adhesive. Only the thermoplastic which has entered its Honey or Liquid state can adhere to other materials in a composite structure. So, to make a fully-fused composite structure, the firing temperature must be above the lowest melting temperature of constituent materials. Furthermore, solidifying after heating at high temperatures makes plastics rigid in nature. Thus, thermoplastics become more fragile.

5.3 Self-Supporting Slumping Experiments

Pyrometric cones are materials that have been shaped into self-supporting geometries similar in shape to a tilted cone. When fired, these cones undergo a physical change in their structure, making them unable to support their mass which causes them to distort. When made from materials with known behaviors, the degree of deformation from their original form is used to identify the highest temperature reached during the firing process [26]. Inspired by the pyrometric cone practice, we conducted a set of experiments where thermoplastic forms were 3D printed into self-supporting geometries on a common plate (dimensions are in Figure 9). To understand how varying geometries of thermoplastic responded to `Heatwork`, we used cylindrical geometries to readily control both surface area and cross-sectional area. Since TPU filament is composed of complex rigid and flexible segments in their polymer structure [67], we constrained this experiment to PC and ABS filament.

We found at the T_g of ABS (105°C), both small ABS and PC cylinders (5 mm) were distorted (Figure 9A). Theoretically, 105°C should have bent all ABS cylinders and left the PC cylinders intact (T_g = 140°C); however, due to the difference in thermal mass between each cylinder, it takes more time for thicker cylinders to heat up. `HoldTime`, the time spent at peak temperature, must be held for a long duration to bend all ABS forms. At the T_g of PC (140°C), all cylinders bent, confirming the theoretical outcome. As encountered

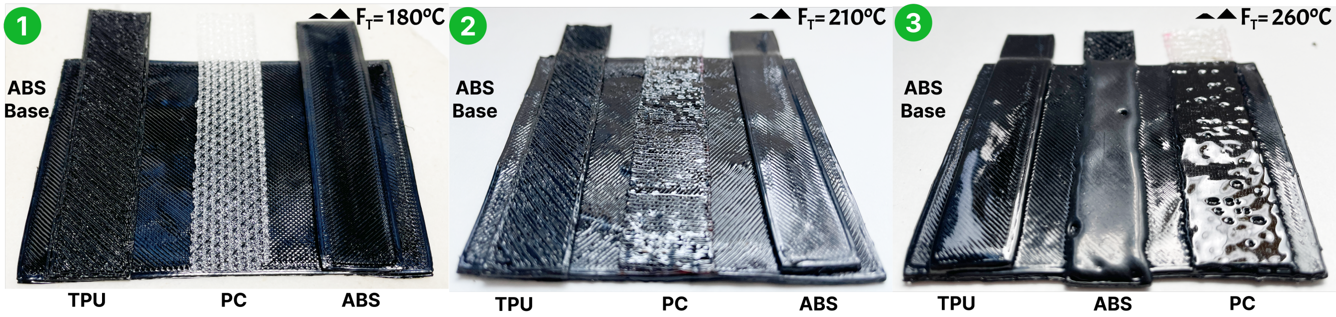


Figure 7: Level of fusing and surface texture experiments, 1. Fusing Temp.: 180°C, 2. Fusing Temp.: 210°C, 3. Fusing Temp.: 260°C

in the 105°C experiment, the HoldTime was insufficient to heat up the large PC cylinder (Figure 9B). This indicates the cross-section will determine the degree of deformation that will be experienced.

Despite all geometries being printed 82°oriented towards the base edge, the fired forms showed slumping in random directions (Figure 9B). This indicates that for thin geometries, both `Force > GravityForce` and `Force > KilnFurnitureSupportForce` from non-uniform heating within the kiln have a role in shaping kilnforms.

5.3.1 *Dropout Slumping Test.*

`DropoutSlumping` is a technique where the material is placed over a lifted structure and allowed to freefall through openings in the structure. Although used to make vase-like forms, we use dropout forms to characterize the slumping behaviors of thermoplastics. For this experiment, we created a clay structure that contains circular holes of varying diameters. Thermoplastic strips of differing densities were placed to slump over the holes; additional material was allowed to overhang past the edge of the mold and also assess `DrapeSlumpingTechnique` behaviors. This configuration allowed us to inspect the interactions between `Force > SupportForce` and `Force > GravityForce`.

Although the thin sheet forms were heated to their `Leather` state, heatwork was not sufficient enough to make the sheets sufficiently malleable to go through the circular holes in the clay structure; this was further complicated by the limited effects of gravity with the thin mass of the sheet. Thus, no dropout slumping was observed around mold-supported regions. In contrast, draping around unsupported areas was observed. The weight of the large overhanging portion of the thermoplastic strip enabled slumping. This indicates that dropout slumping requires heating thermoplastics to their `Honey` state or integrating external forces such as weights to achieve more pronounced deformations.

6 ANNOTATED PORTFOLIO

Ontologies have been used to unify vocabularies, support inference and reasoning, and annotate artifacts; however, their use within design practice is largely absent. We present an annotated portfolio [51], or a collection of design artifacts, as a means of capturing the similarities and differences between different kilnforms. We document our iterative design process and describe how the ontology was used to drive both hylomorphic and morphogenetic ways of making [35]. We present three artifacts specifically chosen to annotate the `Technique` space within the ontology, specifically `SurfacingTechnique`, `FusionTechnique`, and`SlumpingTechnique`.

One of the core reasons for presenting our work as an annotated portfolio was to showcase other material parallels that exist across different material practices (Jewelry Design/ Multi-material Fabrication/ Wearables). The artifacts depicted serve to showcase material explorations with both functional and aesthetic applications and broad material ecology. Due to having a large number of

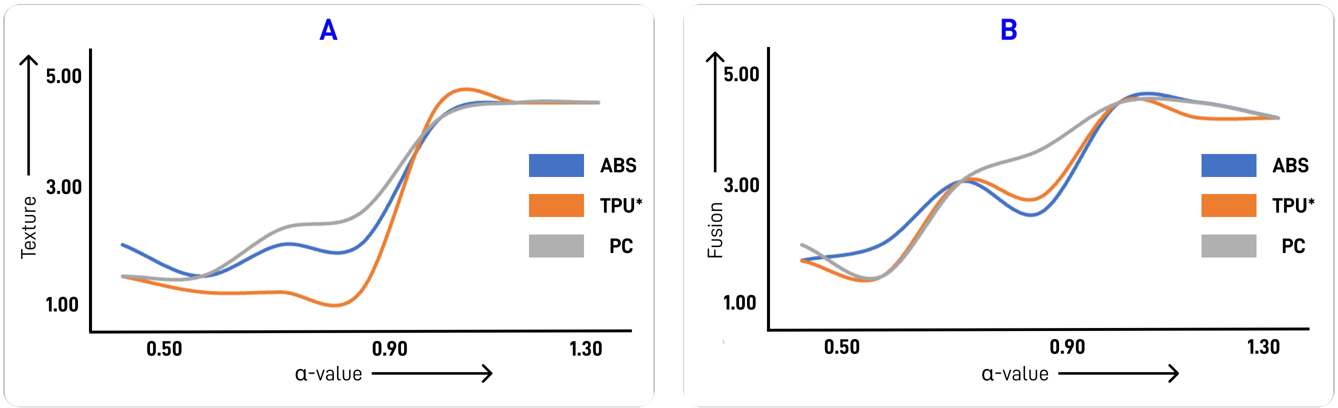


Figure 8: α value, texture, and fusion. A. Relation between texture and α value. B. Relation between Fusion and α value.

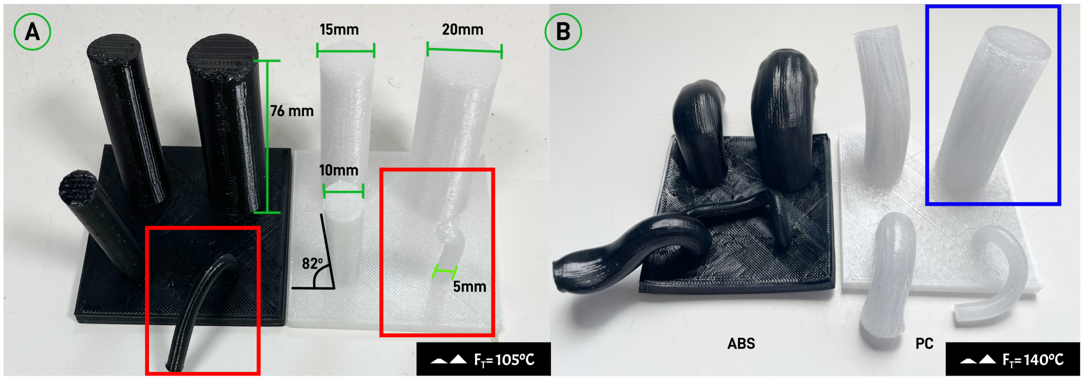


Figure 9: Free standing test. A. Behavior ABS and PC at T_g of ABS. B. ABS and PC at 140°C.

design entities, we annotated our artifacts with high-level design decisions that could (1) document our design process when using a design ontology, (2) provide sufficient information to guide future material explorers in navigating material behaviors, and properties, and (3) foreground failure to document tacit knowledge-generating from working past and with mistakes. We minimized annotations that would constrain creative exploration.

The artifacts serve to describe how applying the ontology to a design process provided insights for refining the ontology, how the exploration led to novel thermoplastic kilnforming techniques and opportunities for ontology-driven creativity support tools.

7 ANNOTATED PORTFOLIO: INFILL-FUSED BRACELET

7.1 Concept

Jewelry has been explored as a site for wearable interactions and shows promise as an aesthetic public display [66]; however, to realize its potential as a fashion technology, there remains a need to further enhance aesthetic expression. Most jewelry is made from precious materials such as gold, silver, and gems as a result of their rarity and cultural significance. In contrast, plastics in consumer culture are seen as disposable and unpleasing [21]. When viewed from a phenomenological perspective, glass engages more of the senses – qualities that Tsaknaki [76] described as appreciating the material sensuality or 'sensory experiences of interacting with materials. *How might plastics exhibit similar qualities as precious materials?*

7.2 An Accident - Morphogenesis

We 'stumbled' upon the material sensuality of plastics when we overfired a 3D-printed PC plastic base during a `SelfSupportedSlumpingTechnique` experiment. As opposed to the slight deformations of cylinder geometries, the thermoplastic completely collapsed, losing all prior definitions in the geometries and exhibiting a smooth, polished surface.

We used the ontology to localize what had occurred, moving from `LeatherTechnique` to `HoneyTechnique` and `LiquidTechnique` – we observed that overfiring caused the artifact to enter its `Liquid` state and realize a technique known as `KilnCasting` > `PuddlingTechnique` used to reclaim glass or create gem-like forms and `SurfacingTechnique` > `FirePolishingTechnique` which is used to remove textural artifacts or round edges of a glass form. Upon closer inspection of the transparent polycarbonate base, we encountered the top layer of the print acted as a `ThinSheetForm` that was `Draped` over the supporting infill structure(Gyroid, 20%

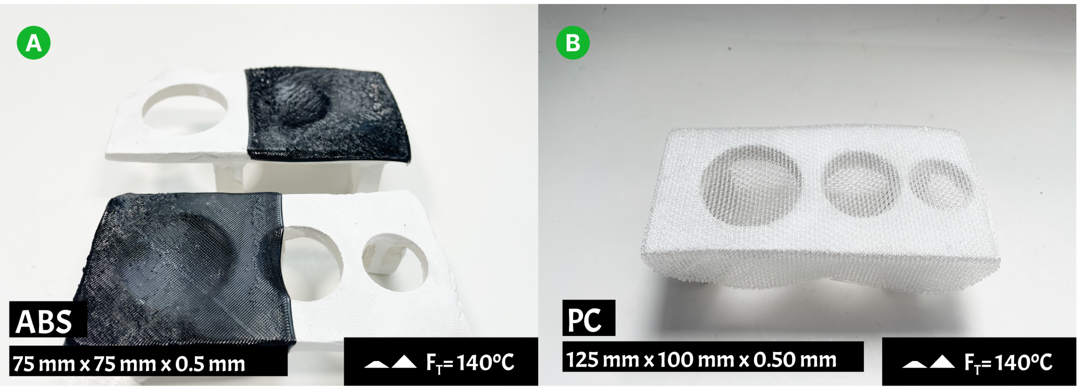


Figure 10: DropoutTechnique & DrapeTechnique. Regions around the circular holes provide uniform support, whereas overhangs only provide partial support. A) ABS at 140°C; B) PC at 140°C

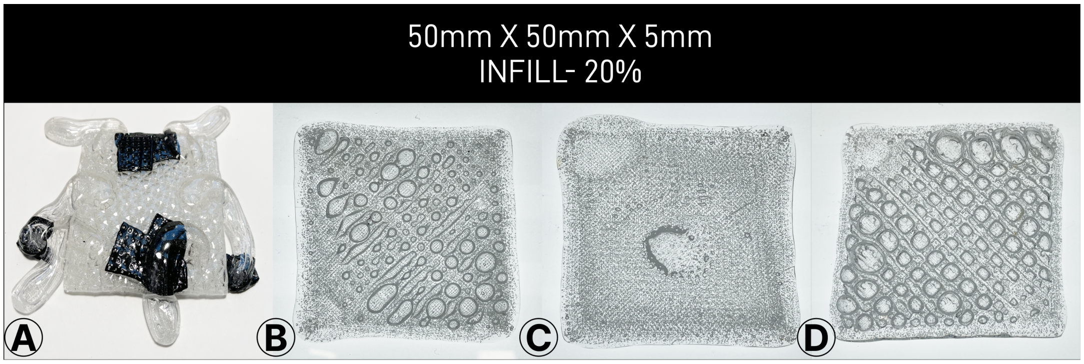


Figure 11: Infill. A. Morphogenesis – a 'failed' slumping experiment. Applying the `MicroSlumpingTechnique` to infill patterns fired to 230 °C: B. Octate, C. Gyroid, and D. Cubic

infill), effectively slumping the top layer of the form into a smooth, dense gem-like form with a visually complex texture. This material encounter allowed us to approach plastic as a metamaterial where the internal microstructure of the form is exposed as a design variable [36]. By viewing infill as a `Support` structure, we extend the Kilnforms Ontology with a new hybrid `SlumpingTechnique` and `SurfacingTechnique`, which we term `MicroSlumpingTechnique`.

7.3 MicroSlumping with Infill Patterns: Pressure and Bubble Artifacts

In order to develop `MicroSlumpingTechnique` as a formal kilnforming technique, we replicated our microslumped artifact (50 mm x 50 mm x 5 mm; 20% infill, 1 mm wall thickness) with different infill patterns available in commodity slicers: cubic, gyroid, and octate (Figure 11B-D). To capture the transparent, vitreous, and gem-like feel of glass, we constrained our experiments to clear polycarbonate (PC) plastic; these PC forms were fired to their `Liquid` state.

As shown in Figure 11B-D, only a few samples achieved `MicroSlumpingTechnique`; instead, these samples created bubble artifacts. The air trapped within the infill structure had expanded; due to the thinner wall thickness in these samples, `Force > PressureForce` forces were able to inflate the microstructure producing thin membranes similar in feel to disposable bubble-wrap. Counteracting bubble artifacts within the `MicroSlumpingTechnique` technique requires thicker walls to counteract the inflation forces, denser infill structures to distribute air pressure or ventholes.

The ontology was used to identify and provide context to other `PressureForce` driven techniques; as seen within glassworking practices, `PressureForce` is the basis behind many `BlowingTechnique`; although outside the scope of the ontology, some kiln techniques have modified this technique by trapping water into a glass form and using the steam pressure to inflate the glass.

7.4 Fusion and Encapsulation

Within glass practice, aesthetic jewelry forms are created using a `FusionTechnique` where glass fragments of different colors (`Form > Fritz`) are fused to a common substrate. We used scrap ABS pieces and fused it on the surface of PC plastic (Figure 12A). In order to achieve a `FullFuseTechnique`, a firing temperature of 230°C was needed to bring PC to its `Honey` state and ABS to its `Liquid` state. For fusion, a `HighFireMaterial` such as PC works well as a base for medium and low-fire plastics such as PE and ABS.

We continued to explore fusion with more complex forms, this time creating a continuous circular necklace structure by fusing 50 mm metal chains segments into 25 mm microslumped plastic gems by following the `Environment > ArrangmentEnvironment > ComponentPlacementEnvironment` principle of most fusion techniques (Figure 13A; `Honey` state; 230 °C). Black ABS gems were `FirePolished` to evoke qualities similar to smooth,

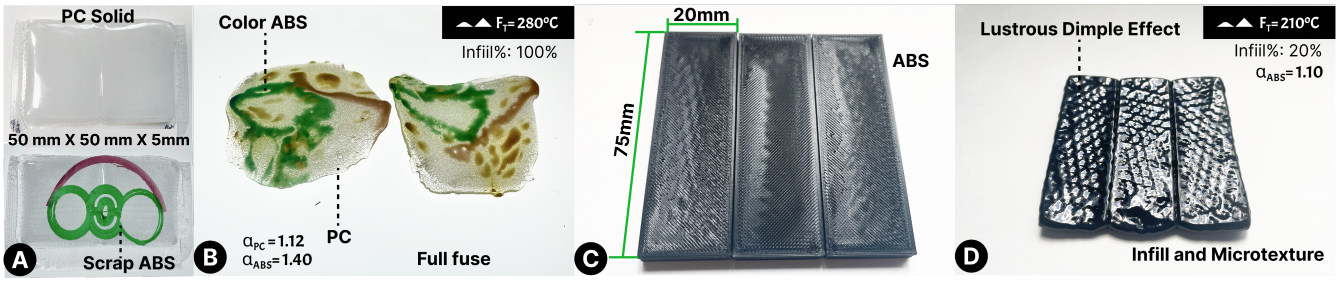


Figure 12: Fusion and Microtexture. A. Arrangement of color 3D printing scraps materials and solid thermoplastics before fusing process, B. Fused color thermoplastics heated at 230°C, C. Thermoplastic solid with 20 % infill before subjected to the slumping process, D. lustrous dimple effect from Microslumping produce.

Figure 13: Thermoplastics as a Precious Material. A. An initial `TackFuseTechnique` **of gold chains onto thermoplastic gems, B. a PC 'geode' is** `Microslumped` **using a triangle infill and** `EncapsulatedFused` **to gold chains to form a necklace, C.** `FirePolishedTechnique` **thermoplastic gems.**

glossy obsidian, while PC gems were microslumped (30%, 3 mm wall; triangle infill) to expose a visual 'geode' texture. This fusion experiment achieved only a `TackFuseTechnique` — the attachment between chain and thermoplastic primitive shapes was unconvincing, and the chain connections were clearly visible. The structure of the chain prevented the plastic from encapsulating it; although bringing the thermoplastic to its `Liquid` state could remedy the level of fusion, it would result in a loss of other geometric features.

To achieve a `FullFuseTechnique`, we added an additional thermoplastic wafer to the construction; this wafer would melt over the chain and fuse with the layer below, achieving a new type of fusion we term `EncapsulatedFuseTechnique`. This technique indicates a wider material ecology that can interface with thermoplastic kilnforms – notably, we achieved a fully integrated mechanical connection; we see additional value in achieving structural integration with conductive materials.

7.5 Reflection

The morphological dimensions explored in our jewelry design revealed qualities not often associated with 3D-printed plastics. Firing to the `Liquid` and `Honey` states allowed the forms to be `Surfacing > FirePolishTechnique`, creating a smooth and dense gem-like form; when coupled with microtextures from the `MicroSlumpingTechnique` of the top layer over the infill pattern, these gems began to exhibit visual textures reminiscent of geode stones. Although created from a regular and precise machine-fabrication process, the thermoplastic gems show qualities of hand-crafted artifacts, including rounded edges and organic quality in how the infill pattern has been exposed. This indicates a potential for a post-processing step like kilnforming to remove artifacts of machine processes and allow the more sensual qualities of thermoplastics to enter the design conversation. These processes also indicate other functional advantages, including improving the optical qualities of transparent thermoplastics, strengthening materials by removing anisotropic behaviors from the FDM 3D printing process, and interfacing with other materials. Unlike design tools that capture 'correct' design construction, our ontology-driven exploration also provided an instance to annotate an alternative design direction – 'bubble-wrap' kilnforms induced from trapped air. We argue that ontologies can provide spaces for both 'positive' design galleries for supporting ideation and creativity but also 'negative' design galleries that have commensurate value in articulating material behavior and enhancing the material literacy of the practitioner.

8 ANNOTATED PORTFOLIO: COMPOSITE HINGE

8.1 Concept

`CompositeFusing` involves fusing one or more materials with different melting points. To support this kilnforming technique, we devised a MalleableFormCalculator discussed in Section 4.4 to help understand the behaviors of different thermoplastics within the same kiln firing. To understand the composite fusing process in practice, we engaged in a hylomorphic process with the design intention of making a hinge. A hinge is a mechanical component that connects two materials and provides motion with one degree of freedom. Hinges are largely used off-the-shelf due to the difficulty of fabricating both the knuckles and leaves of a traditional hinge mechanism. While 3D-printed hinges are possible, there remain issues with achieving the same mechanical performance as a metal hinge.

8.2 Process - `Environment > ComponentPlacementEnvironment > Interleaved`

In order to create a hinge by compositing thermoplastics, we decided to employ a `FusingTechnique` for welding two leaves made from PC to a flexible 'barrel' made from flexible TPU. These thermoplastics were chosen by querying the `ThermoplasticMaterial` concept in the ontology and selecting materials that exhibited the functional qualities desired (i.e., strength and elasticity). We prototyped three different hinges and varied the firing temperature to 190 °C and 230 °C to assess for fusion as well as dimensional accuracy. The results, depicted in Figure 2A-B, confirm that a firing

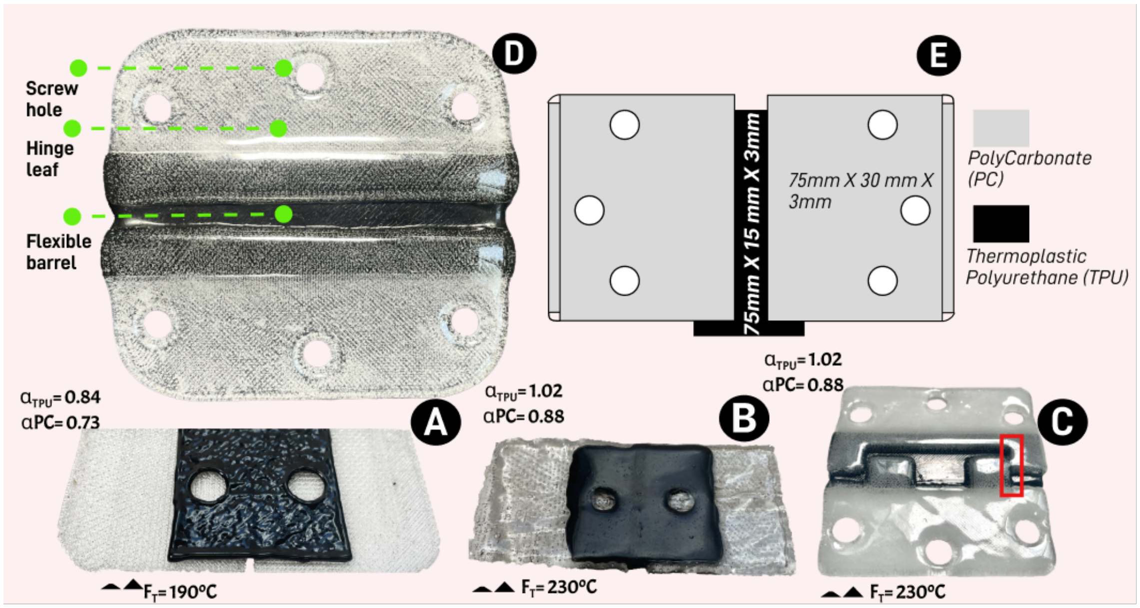


Figure 14: Hinge Formation. Functional hinge design using PC and TPU filament materials at 100% infill with varying thickness. A) At 190°C unfused, B) At 230°C, completely fused, C) Fused hinge at 230°C, D) Functional hinge design, E) Schematic arrangement of leaves and barrel of a hinge.

temperature where all components of the composite reach a `Honey` state is needed to achieve full fusion.

In Figure 2C, we show a medium-fidelity prototype that incorporates the look of the knuckle mechanism from a traditional hinge mechanism. This configuration, once fired, did not have enough clearance between the leaves, causing the digits of each knuckle to fuse to each other and prevent any movement. Closer inspection of the ontology explained that this type of fusion (ComponentPlacement > `ComponentPlacement > SideBySideArrangmentEnvironment`) is a way of joining pieces of glass together at their seams and is used to reduce the `HoldTime` needed for a layered construction to fully fuse. We corrected the design by removing the knuckles and providing enough clearance between the barrel and hinge – the final hinge was able to articulate to 90 °(Figure 14 D). The fusion process did result in a loss of dimensional accuracy with the holes on the leaves (8% shrinkage factor) and a loss of the leave's planar form – we expect this effect to be more pronounced when thermoplastics enter their `Liquid` state; instead, the interleaved layers created a `Environment > ArrangementEnvironment > TiltArrangmentEnvironment` arrangement often used to have control of the direction of gravitational forces.

8.3 Reflection

For the hinge artifact, the ontology provided guidance for the selection of functional materials, the appropriate firing temperature via the MalleableForm Calculator, and a means of diagnosing and naming the errors and artifacts that arose during the iterative design process. The hinge construction was created from simple geometries; within a kiln, the hinge fabrication process could easily be turned into a batch fabrication method and introduce a new scale of production atypical of CNC fabrication processes. While a functional hinge was produced, there remain opportunities to improve the dimensional accuracy of the form – the placement of elements within the kiln, often done by hand, remains the most error-prone. Jigs can be used to support replicability, however, glass practices often value the natural variation that occurs from human and material interactions. Kilnforming can benefit from plastic simulations that can better predict behavior, especially pooling, shrinkage, and stretching of plastic on non-uniform substrates. Like the hinge, other functional composites can be made using `FusionTechnique` that make use of the optical, mechanical, electrical, and thermal repertoire of thermoplastics.

9 ANNOTATED PORTFOLIO: BREADBOARD DESIGN

9.1 Concept

Breadboarding is an electronics prototyping technique that allows an electronicist to establish reversible electronic connections between several components. The shape of a traditional breadboard is rectangular; Zhu et al. [90] introduced a fabrication technique for curved breadboards that could be shaped to fit sites on the body and enable wearable breadboard prototyping. We build on these efforts to understand the affordances of a kilnforming approach for creating a composite like a breadboard.

9.2 Design Process

Our breadboard prototype was made of *connection rails* 3D-printed from conductive PLA (cPLA; ProtoPasta); these rails were later

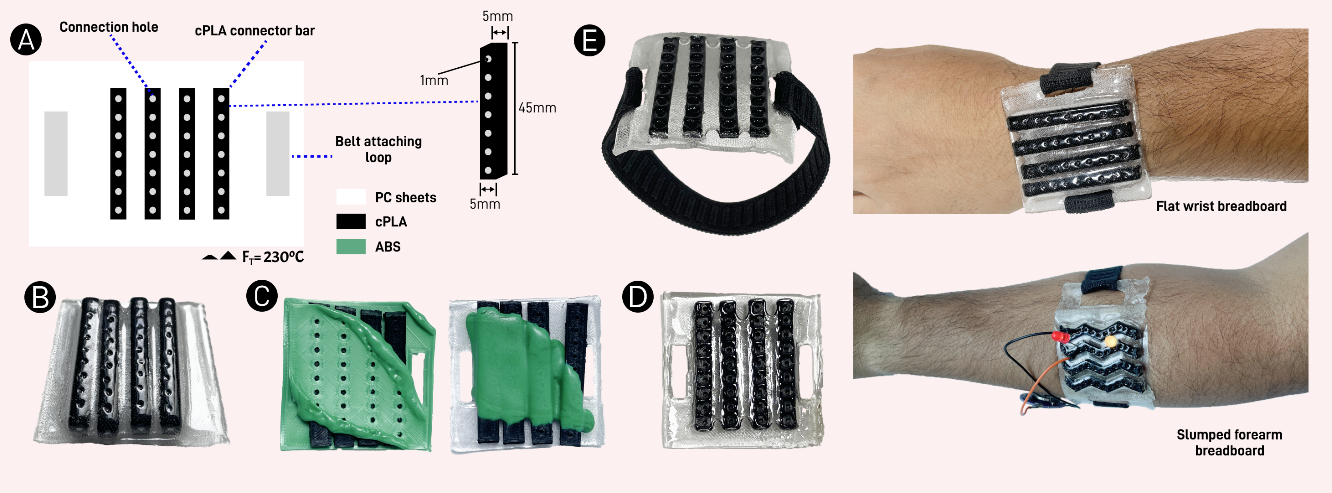


Figure 15: Encapsulated Breadboard. A. Schematic diagram of a breadboard, B. Initial version breadboard C. Mixed filament breadboard, D. Workable breadboard, E. Slumped breadboard with elastic belt.

encapsulated between two layers of polycarbonate (PC). The breadboard form was then `DrapeSlumped` over a curved mold representing the curvature of the arm. Lastly, an elastic band was attached to the kilnform and placed on the arm (Figure 15). The making of this breadboard represents a multistage firing and incorporates both `FusionTechnique` and `SlumpingTechnique`.

Encapsulation. PC was used as the encapsulation material to provide the widest compatibility with other thermoplastics in the composite (at 230 °, all thermoplastics are in their `Honey` or `Liquid` state). Various iterations of the connection rails were made before selecting the thickness of cPLA to avoid introducing excessive resistance and provide enough depth for the legs of through-hole electrical components; we found that 1 mm diameter openings were large enough to withstand the firing process. The firing process did cause the cPLA to exhibit a `SinteringTechnique` effect, roughly halving its overall resistance. This sintering effect aligns with Lo et al.'s observations when shrinking silver ink traces on pre-stretched polystyrene [49]. The final connection rails were modified into a zigzag shape to demonstrate aesthetic variability.

During the encapsulation firing stage, cPLA was fired to its `Liquid` state, however, rather than collapsing, the high density and low surface area of the cPLA bars (compared to other elements in the composite) caused the cPLA to heat more slowly, maintaining its geometries intact. Figure 15C demonstrates that the encapsulation layer is quicker to heat up – when ABS was used as the encapsulation material, it quickly reached its `Liquid` state and became less predictable. The final prototype modified the PC encapsulation layer to have holes to remove the need to tediously drill holes to expose the conductive material.

Slumping. Lastly, the breadboard was `Slumped` into a curved form by `DrapeTechnique`, the encapsulated cPLA structure over a curved `MoldSupportForce` resembling an arm made from clay. The breadboard was heated to 140°C (`Leather` state) with 1 hour of `HoldTime`. The final slumped breadboard (Figure 15E shows that a `Leather` state was sufficient to deform a thick form like the breadboard structure but requires a longer `HoldTime` to allow materials to 'cook'. A simple LED circuit was used to validate the functionality of the board.

9.3 Reflection

Breadboard making demonstrated a complex multistage process that includes `EncapsulationTechnique`, `FusingTechnique`, & `SlumpingTechnique` techniques together. We developed a breadboard where several 3D-printed conductive filament bars were integrated and enclosed with two layers of fused PC materials. Although complex, the breadboard was formed out of many elementary components – a rail and two layers of plastic. This provided great flexibility in testing out different connection patterns. From a breadboard design perspective, the elementary building blocks could enable new design patterns that deviate from the power-ground rails on opposite sides of a block and instead incorporate radial power-ground rails that more readily afford parallel circuit construction.

10 DISCUSSION

In our material exploration, we synthesized an ontology sourced from the glass community as an initial map into thermoplastics kilnforms. We moved through the ontology, tested the compatibility of different techniques on plastics, and refined the ontology to include modifications (e.g., firing schedules) and extensions (e.g., `MicroSlumpingTechnique`, `EncapsulateFuseTechnique` operationalized within an annotated portfolio of functional and aesthetic artifacts. We first present safety and precautions for HCI practitioners in adopting kilnforming within their practices. Then, using Frankjaer & Daalsgard crafting model [25, 71], we discuss how our ontology-driven design approach extends and complicates craft-based practices and present a roadmap for research into ontology-driven creativity support and design tools.

10.1 Safety

In our work, we demonstrated that kilnforming is an effective and generative technique for enabling thermoplastic fusion and slumping. While uncommon within digital fabrication practices, the use of kilns is ubiquitous within ceramics and glass practices. Despite traditional kilnforming operating at temperatures typically above $500 \deg F$, electric kilns are safely used within the home, schools, and personal studios [3, 10, 53].

The largest obstacle in using electric kilns is their non-intuitive control interface which typically consists of a 10-key pad that is used to program complex firing schedules. Human error, as was encountered in our experiments, can lead to misconfigured settings that can result in temperatures that burn plastics. While some kilns offer graphical user interfaces for overcoming these errors, it is important to institute operational checks for analog kilns to verify appropriate configurations. Our setup used ventilated kilns, as is common for ceramic firing, as an extra precaution. A vented kiln is common within ceramic practices and an effective strategy for minimizing harm from vapor and fume byproducts of the heating (and burning) process. All our firings were done in the presence of oxygen, however, many safety issues can be further mitigated by firing in the absence of oxygen using a technique known as pyrolysis [24]. Although requiring more sophisticated equipment, the use of the pyrolysis technique in plastic waste management holds promise as a means of enabling safe personal fabrication and plastic reuse.

When applied to thermoplastics, kilnforming techniques are effectively enabled within temperature ranges supported by conventional ovens. Unlike ovens, kilns offer additional functionality and safety features, including more precise control of the heating and cooling behaviors and fume venting. Since glass artifacts are created in a kiln, we also conducted different experiments and created different artifacts in the kiln environment. Our use of the kiln offered safety benefits, batch production, and controlled heating. Many of the techniques described could be transferable to a conventional oven; we view ontology inference and querying as the next frontier for identifying and validating compatible techniques. Regardless of the heating method, we highly recommend that the heating environment used for kilnforming thermoplastics be avoided in food preparation [88].

In kilnforming experiments, we encountered low-risk issues since the used thermoplastics were sourced from commercially available desktop 3D printing filament form factors. However, care should be taken to understand how non-filament thermoplastics such as Teflon and Polyvinyl Chloride (PVC) can produce harmful gasses when heated [4, 17]. Common makerspace materials like acrylic sheets, when heated above 170 °C, are liable to generate toxic fumes [2, 4]. Furthermore, when firing beyond a thermoplastic's melting temperature, these materials can start to decompose into toxic chemicals such as butanol, hydrogen cyanide, carbon monoxide, and styrene [85]. The Kilnforms Ontology includes a preliminary `Error` and `Hazard` concept to annotate errors and hazards encountered in our material exploration. As a structured way to disseminate knowledge, we view ontologies as a valuable resource to improve material literacy for the safe operation of kilnforming techniques.

10.2 Localizing

Navigation Strategies. From an outsider's perspective, 3D printers give the impression that plastics exist either as a solid or melted form. In creating the Kilnforms Ontology, we found that a thermoformed material like glass can exist in four different states, each with its own personality. In mimicking kilnforming techniques for glass, we were able to adapt the high-level glass approaches to account for the nuances of thermoplastic behaviors. This did require us to "fill in the blanks" to achieve a functional ontology capable of being used to localize and diagnose different thermoplastic behaviors. At the time of writing, the ontology holds 158 concepts and, in its current state, is readily navigable; for larger ontologies, the current tree map or graph approach for visualizing ontologies is insufficient. Methods of finding relevant information within an ontology mirror classical problems in information retrieval. The use of the α value (Equation 1) in classifying the malleable form of thermoplastics was especially valuable in looking up compatible kilnforming techniques. To provide a more direct query, we see potential in a connected creative environment supplying information to localize the practitioner within a concept space. For example, while thermoplastics are found as filaments for 3D printing, they also exist in many everyday objects – the ability to distinguish plastics by sight or feel remains a challenge. The `ThermoplasticMaterial` concept could be used to support the user in the manual identification of discriminable features or automatic classification using sensed physical properties.

Adapting to Parallel Materials. Although the ontology was scoped to glass and plastics, the stiffness graph used to compute α could be computationally extended to stiffness graphs of other widely used heat-activated materials such as wax, sugar, or chocolate. However, every practice has its own set of unique innovations that should be acknowledged within a more generalized ontology of thermoforming. The need for knowledge engineering expertise has made ontology development a largely centralized activity [48]. As a result, distributed approaches, such as folksonomy (crowd) and collaborative systems, have sought to enable ontologies that are information complete, evolve, and maintain consistency [29]. These folksonomies have been an important way for communities of practice to curate, organize, and locate relevant content; for example, the #resintok TikTok hashtag is used to connect content and people within the resin working community. Crowd approaches also show promise in scaling the number and quality of positive and negative annotated instances, as Moradi et al. encountered when observing the glazy.org ceramics community [56]. However, like most crowd-based systems, it requires the careful design of intrinsic motivators, microtasks, and content quality filters.

10.3 Questioning

Identifying Parallels. The glass comes in many different formulations – a glass practitioner must be especially conscious that they choose compatible glasses (similar `CoefficientOfExpansion`) to avoid fracturing their glass pieces. While experimenting, we found `COE` plays a less significant role in understanding the 'compatibility' of thermoplastic material, making thermoplastic kilnforming a much more forgiving practice. Instead, we encountered `GlassTransitionTemperature`, `MeltingTemperature`, and `ThermalMass` as parallel design concern that plays a stronger role in understanding the fusion, slumping, and surfacing behaviors of different thermoplastics in a composite.

Negative Examples for Reframing Error. Although cracks, fractures, bubbles, and collapsed structures are generally 'undesired' qualities, craft-based processes are well suited for recasting these artifacts into functional and aesthetic forms. Our accidental slumping experiment that seeded the `MicroslumpingTechnique` technique serves as an example of a curious moment where "resolution and decision is suspended in order to probe" [25]. As one of the affordances of ontologies, the ability to exhaustively annotate instances (examples) holds promise in overcoming one of the largest limitations of craft-based practices – the fact that material encounters are often personal and cannot be fully shared with others, especially when the crafter is unable to probe and question "what happened?". As part of our infill experiments, we included negative examples of bubble artifacts as annotated instances within the ontology. These annotations aid in the crafter being able to replicate the instance and recreate the experience. These annotations can also allow them to interconnect other instances and concepts with the ontology in order to reason through their own design intentions (e.g., show me all `Force > PressureForce` annotated instances).

10.4 Opening

Supporting Morphological Inquiry. Materials inquiry, or solving specific problems associated with materials, opens a new dimension for the craft practitioner. Frankjaer and Daalsgard [25] describe two strategies for problem-solving – an analytical approach or an approach that fosters insights. In the analytic side of our material investigation, we formulated morphological experiments for testing different formgiving variables. In our slumping experiment, we generated geometries that differed by cross-sectional area and subjected them to the same firing temperature to make sense of their behaviors. This only forms a part of the picture – many other formgiving variables for 3D printing alone can benefit from the investigation, including infill density, wall thickness, infill pattern, and layer height. Ontologies and procedural form generators could be combined to automate the process of creating geometries that allow crafters to more readily explore morphological dimensions.

Ontology-sourced Bricolage. Throughout our design process, we encountered that kilnforms had a proclivity to be made out of elementary building blocks. We often found ourselves reprinting thermoplastic forms used for one artifact to form another and thinking through different forms from the available thermoplastic 'extras' that had accumulated. This proclivity towards modular forms indicates that thermoplastic kilnforming could be synthesized into a bricolage practice [78]. Toolkits could provide functional and aesthetic thermoplastics in a variety of form factors such as `ThinSheetForm`, `PelletForm`, `RodForm` in addition to 3D printed forms to aid with exploration and experimentation *in situ.* The ontology could be used to understand the bricolage 'completeness' of a toolkit by assessing whether each concept is represented and available. Such primitives could be formally characterized to provide the practitioner with information on the heatwork needed to achieve the different malleable thermoplastic forms.

Scaleability. Large-scale production is one of the largest challenges for heat-based rapid prototyping techniques [40, 60]. Unlike manual heating techniques such as heat guns, kilns support batch production that can serve as an intermediate solution between bespoke printing and mass manufacturing. As opposed to FDM printing, heating bulk artifacts allows kilnforming techniques to be more effective in producing simultaneous batches more reliably with significantly less maintenance. While some other fabrication techniques have shown the ability to modify an artifact after it has been 3D printed [27, 40], thermoplastic kilnforms can continue to be modified through multistage firings. For fabrication, kilnforming extends applications of thermoplastics past filament for a 3D printer and opens a space for more diverse form factors, including sheets, meshes, and woven structures.

Limitations. Ontologies help articulate a common vocabulary that practitioners from different communities of practice (CoP) mutually benefit from. By linking shared efforts across COPs, we view ontologies as providing critical information for designing digital fabrication technologies that can support a wider breadth of formgiving traditions to encourage adoption by the broader community. Despite bridging shared knowledge, ontology development requires more stakeholders and continuous iteration and improvement. Since material practices are embedded with tacit and experiential knowledge, ontology development requires practice-based validation. We focused our ontology development on kiln-based methods, however even in this constrained scope, it was not possible to exhaustively explore each concept; high-level techniques such as `BlowingTechnique`, `VitreographyTechnique`, and `OpenFaceTechnique` remain underexplored.

11 CONCLUSION

In this work, we presented Kilnforms, an ontology-driven material exploration of plastic kilnforming fabrication techniques. While kilns remain a tool for creating forms in glass and clay-based materials, we show how thermoplastics can leverage existing material knowledge to enable aesthetic and functional shapes and composites through slumping and fusing techniques. The techniques are described in a shareable ontology and are used to annotate exemplar artifacts and guiding design principles. We demonstrated how slumping and fusing could be used to leverage the expanding repertoire of thermoplastic materials. The ontology is designed to further support the synthesis and exchange of material knowledge across communities of practice and continue to enhance our material ecologies.

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