Digital Konditorei:
Programmable Taste Structures using a Modular Mold

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Figure 1 Two design options for *Three Colors Mousse Cake* and their arithmetic and graphic representations: (A) prioritizes grouped sour-strawberry structures; while (B) contains higher dessert volume, alternating sour-strawberry and bitter-dark-chocolate tastes.

ABSTRACT

Digital Gastronomy (DG) is a culinary concept that enhances traditional cooking with new HCI capabilities, rather than replacing the chef with an autonomous machine. Preliminary projects demonstrate implementation of DG via the deployment of digital instruments in a kitchen. Here we contribute an alternative solution, demonstrating the use of a *modular (silicone) mold* and a *genetic mold-arrangement algorithm* to achieve a variety of shape permutations for a recipe, allowing the control of taste structures in the dish. The mold overcomes the slow production time of 3D food printing, while allowing for a high degree of flexibility in the numerous shapes produced. This flexibility enables us to satisfy chefs' and diners' diverse requirements. We present the mold's logic, arithmetic, design and special parts, the evolutionary algorithm, and a recipe, exploiting a new digital cooking concept of programmable edible taste structures and taste patterns to enrich user interaction with a given recipe.

Author Keywords

Food, kitchen, cooking, dessert, mold, design, fabrication.

ACM Classification Keywords

H.5.2. User Interfaces: User-centered design.

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INTRODUCTION

A recipe is *a set of instructions for preparing a particular dish, including a list of the ingredients required* [29]. Usually, this *list of ingredients* is a fixed set of materials and quantities. However, some dishes hold the potential to render many variations on the final flavors and aesthetics, to satisfy different requirements from different diners (especially in limited choice restaurants, [31]).

To explore such a possibility, researchers have deployed digital technologies in the kitchen, and integrated them into cooking via hybrid recipes. In *Digital Gastronomy: Methods & Recipes for Hybrid Cooking*, the authors present recipes that merge manual and digital cooking, allowing cooks to personalize the tastes, structures and aesthetics of dishes [27]. In their *Coral Reef Concept*, Mizrahi et al. introduced the concept of "Programmable Structure and Composition" by 3D printing. There, the authors contributed a parametric procedure to personalize the taste of soup by controlling the quantities of sauces served in *3D-printed* edible tofu containers, thus allowing a new type of creative digital cooking interaction.

Digital Gastronomy (DG) envisions a gastronomy culture that relies on the ability to control taste locally, thus allowing for programmable taste patterns. Yet, 3D food printing has a number of limitations that may hinder or even prevent users from creating certain complex structures, particularly in parallel. Production of food by additive manufacturing of edible substance consists of two steps: forming the material into a 3D structure, and stabilizing (or cooking) it via molecular transformation. While 3D printing of edible structures is on the rise [19,22,23,35], their production (shape-forming) time is slow, and not practical in the setting of a restaurant kitchen. We aim at accelerating this stage by replacing 3D printing of food with a casting procedure, using a modular mold that supports a high number of shape permutations.

In this work, we apply a hybrid-cooking paradigm to dessert-making, using a 3D-printed modular mold, manual dessert-making techniques, and a parametric design procedure. The contribution of this work is twofold. First, we present our design for a modular silicon mold of a dessert that allows for a high number of design possibilities, encouraging the chef to interact with recipes in a way that allows dishes to be personalized. Second, we demonstrate how computational tools such as graph formulations and genetic algorithms can be used to assist cooks in *optimally arranging* the mold to control taste structures in a dessert (see Fig. 1). We describe the technical aspects of our work in detail, but first we start by reviewing work from the realms of cooking, HCI, and digital design and fabrication.

RELATED WORK

The hybrid interactive cooking procedure continues a line of research into hybrid tools, as presented in several projects on craft and digital fabrication and design [7,20,43,44,46]. Cooking resembles craft in its deep cultural roots and its potential to evoke meaning and creativity through the making practice [1,14]. Thus, the revolution in digital fabrication technology [12] and the potential it holds for cooking [24] have driven research into the new territory of Digital Gastronomy [45].

Within the HCI community, recent research papers discuss eating habits, diet, and the food media [4,11]. In other fields of CS, researchers have conducted theoretical studies on the semantics and procedural relationships in recipes [2,18,26,37]. As parametric design is the process by which design is generated through algorithmic procedures [32,36], we see a great potential to connect digital capabilities with parametric design, and focus our research in this area.

Considering food production technologies, recent products and research projects have enabled digital applications of 2D graphic patterns to food elements [10,17,30,39,42]. FOODINI [9] is a 3D food printer that uses a paste extruder. ChefJet Pro by 3D Systems is a 3D printer based on the solidification of edible powders [47]. 3DS Culinary Lab [3] explores the potential of food printing in the hands of top chefs. Wang et al. 3D fabricate shape-changing noodles that transform from 2D sheets to 3D shapes when they interact with water during the cooking process [41]. Sun et al. differentiate the world of 3D printing from robotics-based food manufacturing technologies that automate manual processes [35]. Yet, robots still hold a more significant place in research and the development of digital food production, as we can see in the extensive discussion of the field [5,13,21,34,38,40].

THE MODULAR DESSERT MOLD

Unlike 3D printers and robots, molds are already widely used in pastry and cooking. An edible substance with low viscosity is cast into a mold, then solidified by heating, cooling, or another molecular reaction that impact its inner structure. Molds are usually made of silicone, but can also be made of plastic, glass, or metal. They help to stabilize the shape of the cast material and refine the aesthetics of cakes and desserts, a key part of the pastry kitchen. Yet, the form of a dessert produced by a given mold cannot be modified. Molds apply a given shape to the prepared food, and do not allow for design interactions and modifications.

Recently, a pastry chef from Ukraine named Dinara Kasko has developed 3D printing-based molds that allow for new aesthetics in dessert making [16]. Although Kasko's work is an impressive use of digital design, unlike direct 3D printing of an edible substance, where each print can render a different shape, these 3D-printed molds still provide only one possible design for a given mold.

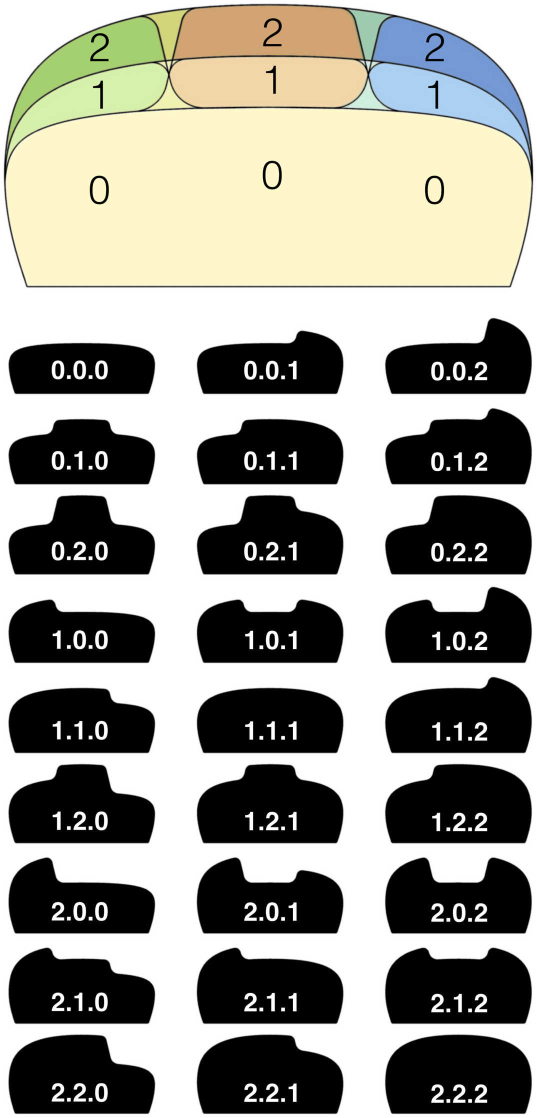

Figure 2 Dessert-structure rib (DSR), consisting of three base-3 bits and 27 possible DSR permutations.

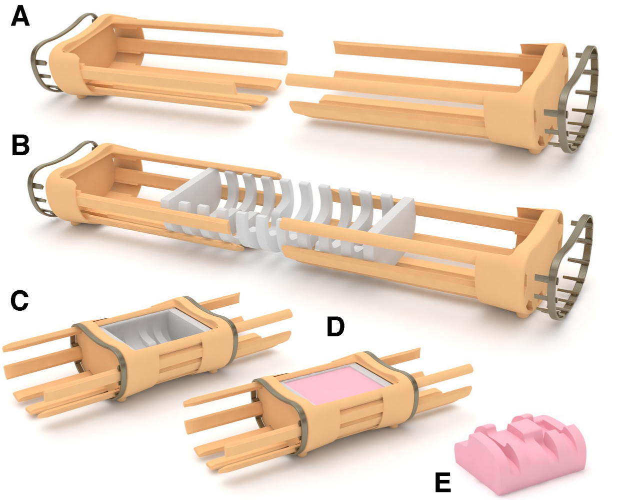

Figure 3 (A) A 3D-printed Nylon 12 clamp that holds the silicone mold-ribs in their place (B-C). The casting of the edible substance resembles traditional casting (D-E). Rendering by V-Ray.

One technique to overcome this limitation of analog casting is to use a modular mold. While the casting is still analog, the modular mold can have many assembly permutations that will provide a huge number of shapes. A similar idea has been implemented in ceramics. Sharan Elran has designed a mold composed of 14 different pieces that can be rearranged in a different sequence before each cast, resulting in more than 6×10^9 unique permutations [8].

For this research we developed a modular silicone mold for a personal dessert. The mold comprises a linear sequence of mold-ribs 8 mm thick. The arrangement of the ribs can be easily modified, and the user can decide how many ribs to use, i.e., what the final size of the mold should be. Overall, eight or nine ribs can render a medium-sized personal dessert, allowing the cook to easily create desserts in sizes from very small to large enough to serve multiple diners.

Each mold-rib represents the negative space of a positive dessert-structure rib (DSR), where DSR=($A_{(3)}$,$B_{(3)}$,$C_{(3)}$). In other words, DSR consists of three base-3 bits (A, B & C, see Fig. 2). Thus, the number of rib permutations is 3^3=27. Hence a simple base-27 identifying number can be assign to each dessert n-ribs arrangement:

$$[DSR^0, \dots DSR^n]_{(27)} = \begin{bmatrix} DSR^0_{0bit} & DSR^0_{1bit} & DSR^0_{2bit} \\ \vdots & \vdots & \vdots \\ DSR^n_{0bit} & DSR^n_{1bit} & DSR^n_{2bit} \end{bmatrix}_{(3)}$$

For example, the following three-rib structure:

$$\mathrm{AC2}_{27} = \begin{matrix} 1 & 0 & 1 \\ 1 & 1 & 0 \\ 0 & 0 & 2 \end{matrix}$$

In regards to the DSR design, we create a convex outline for structural stability and aesthetics. DSR$_{min}$= (0,0,0) and DSR$_{max}$= (2,2,2) are variations on the same convex function (see Fig. 2). All DSR permutations are built upon a base structure (the off-white color in Fig. 2, DSR$_{min}$) that physically holds a dessert structure. Hence, the differences in the height ratios between the DSR central bit and its side bits create an uneven bits volume. The DSR thickness (8 mm) and resolution (3 bits) are both functions of an effort to minimize the number of rib permutations while keeping sufficient detail resolution. This is, of course, an initial design, and future iterations are expected to explore a variety of outlines, resolutions, and rib permutations.

To create our dessert modular mold, we designed and 3D printed, by selective laser sintering (SLS), a Nylon 12 clamping structure that can hold up to 20 mold-ribs (see Fig. 3). Brass rings served as clamp-lockers.

Each mold-rib is made of SORTA-Clear® 40 silicone, a white, translucent, food-safe rubber, which cures at room temperature with negligible shrinkage and features high tensile and tear strength [33] (see Fig. 5). To prepare each of those 27 mold-ribs, we 3D printed, with stereolithography, 27 small plastic molds to cast the SORTA-Clear silicone; each plastic mold represents the negative shape of a different DSR symbol (see Fig. 4).

To summarize, our modular mold is made up of 27 different mold-ribs. As each rib is unique (no repetition), they can be re-arranged in different sequences, resulting in $27!/(27\text{-}n)!$ permutations of molds with n ribs at the length of 8xn mm.

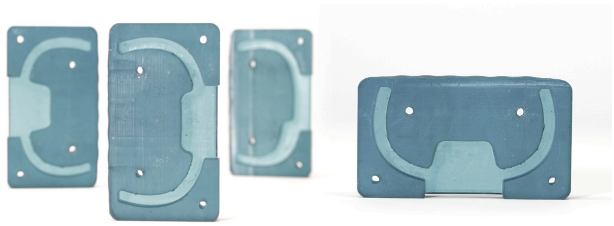

Figure 4 3D-printed plastic molds made by stereolithography for silicone casting of the 27 rib-molds.

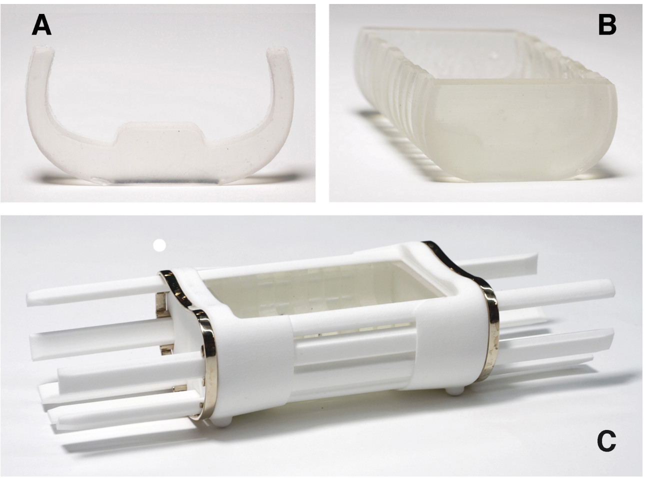

Figure 5 (A) A SORTA-Clear® 40 silicone rib-mold (DSR symbol A); (B) a linear assembly of 10 ribs, which are then clamped (C) to prepare the mold for casting the edible substance.

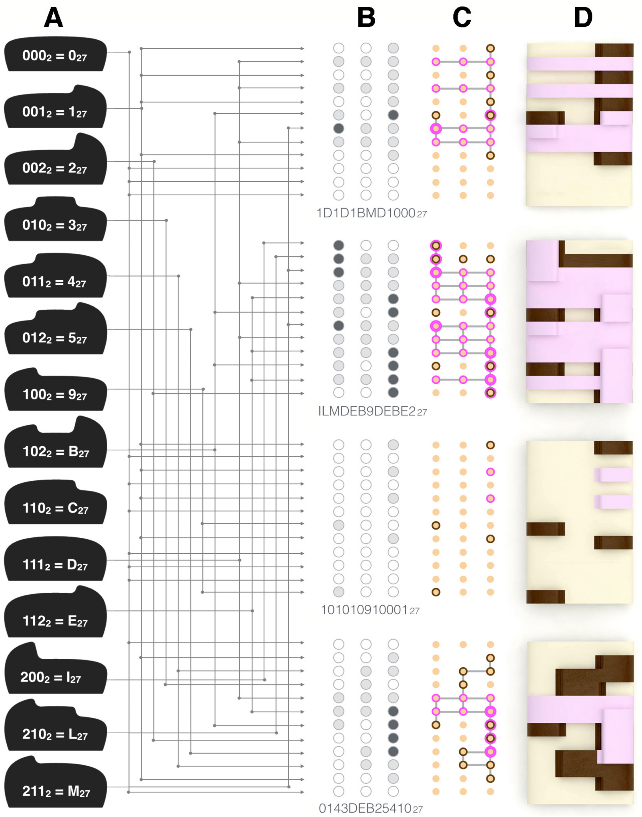

Figure 6 A given DSR group can be arranged into many dessert permutations, enabling pastry chefs to interact with a given recipe and create many design and taste options. (A) An exemplifying set of DSRs and its bit 27-base arithmetic (B). The DSR matrix is the underlying topology of the dessert graph, which represents taste structures (C) in the final dish (D). Rendering by V-Ray.

TASTE STRUCTURES AND REPRESENTATION

Unlike traditional pastry, the modular dessert mold allows cooks to render a variety of different final dishes from the same ingredients, resulting in a large degree of design freedom compared to traditional molds (see Fig. 6A).

The arrangement of the DSRs controls the dessert topology. This arrangement is expressed via differentiations in the DSRs' bits (0,1,2), as well as their heights (see Fig. 6B). It is important to note that the DSR central bit differs in its volume from the right and left bits. The rib's total volume can be calculated with the following formula:

$$\mathrm{DSR_{Volume}} \cong$$
$$8\times\left(1693 + \begin{bmatrix} DSR_{0bit} & DSR_{1bit} & DSR_{2bit} \end{bmatrix} \cdot \begin{bmatrix} 0.87 \\ 1.37 \\ 0.87 \end{bmatrix}\right)_{mm^3}$$

where 1693 mm^2 is the rib's surface when DSR = $0_{27,}$ 8 mm is the thickness of each rib, and [0.87, 1.37, 0.87] is the bits' area coefficient.

The basic height (or volume) topology of the dessert has an important role in the cook's interaction with the recipe. Since casting requires the dessert base to be turned into the mold upside down (Fig. 3C and Fig 5C), the high bits are the lowest in the mold, thus forming a depression in the casted material. Hence, creating a dessert using several different cast substances allows the chef to control the taste distribution. For example, in a dessert made from materials with different flavors (such as sour, bitter, and sweet), the mold can serve to form taste structures.

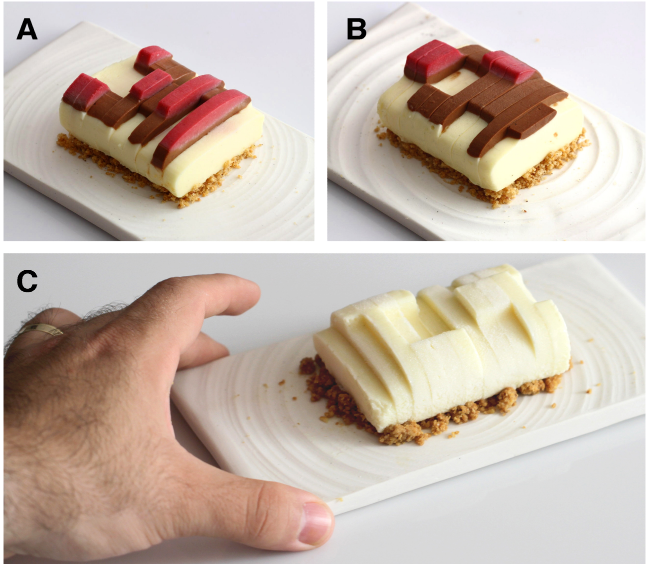

Figure 7 Three versions of our Three-Color Mousse Cake. (A) An alternating strawberry mousse structure (sour/sweet), vs (B) a grouped strawberry mousse structure. Both of the above desserts include a bitter dark chocolate structure (bitter/sweet) and a 72 mm-long white chocolate base (sweet). (C) A whole white chocolate dessert, 88 mm long.

Taste is composed of flavor, mouth-feel and aroma [6]. We define a *taste structure* as a spatial arrangement of edible material with unique taste characteristics in the dish. Assuming a dish having two or more taste structures, a chef can interact with the diners' experience and assemble taste patterns, i.e., control how taste structures comprise a dish, thus introducing an ability to control the change in taste while dinning. In Fig. 6C we suggest a graph formulation to represent taste patterns (Fig. 6D). In the dish, graph abstraction bits relate to nodes of a two-dimensional type (node volume and node taste). While we do not explore this formulation in depth here, we believe this representation can serve in future discussions of taste patterns, connectivity, the relationship between the length and width of taste structures, and more.

The potential of programmable taste structures still needs to be unfolded. We believe they can be a powerful tool in the hands of a cook who wishes to interact with recipes, personalize dishes, and create a number of different interpretations using the same raw materials. For instant, using a sour, bitter, and sweet flavor, a chef can assemble one dessert in which the bitter and sour flavors alternate with each other, another with one of the flavors grouped into a single cluster, and so on (see Fig. 7). These variations can result in an entirely different taste manifestation for each dessert, i.e., variety of dishes made from the same recipe via human-recipe interaction.

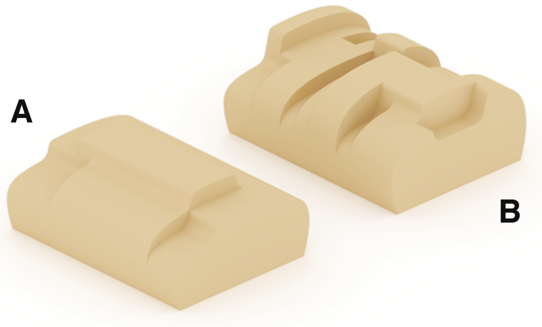

Figure 8 Two results from the same constraints, where (A) allows for rib repetitions, and (B) does not allow for repetitions. We can see that the limitations of the rib set size and rib repetitions result in significant design compromises. Rendering by V-Ray.

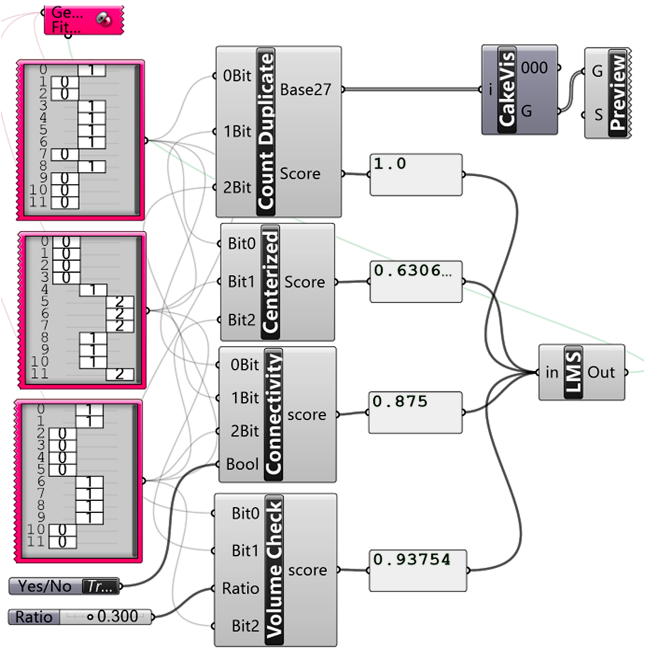

Figure 9 Grasshopper Galapagos GUI of the rib-mold arrangement problem solver. The genomes are listed in the left.

THE MOLD-RIB ARRANGEMENT PROBLEM

Arranging the mold-ribs to satisfy specific dish requirements requires the chef to solve an optimization problem. With a given set of 27 mold-ribs, we are looking for a subset of *n* mold-ribs arranged to satisfy the following cooking requirements: (1) *dish volume* (an important and initial factor in personalizing dishes); (2) *no repeated ribs* (a logistical constraint as we had only one rib of each kind – additionally, in a practical restaurant setting the number of ribs may be different yet still limited, thus the SW will still need to take this into account); (3) *centralized dish mass* (for stability, we prefer to populate central bits prior to side bits if possible); and (4) *bits distribution preference*, i.e., whether we want the bits to form connected groups or demonstrate alternating height levels (the first order parameters to control taste pattern). The requirements are responsible for variations in the bits topology, enabling chefs to manually cast the different edible materials in the preferred arrangement, as demonstrated in Fig. 7A & 7B. In our design, *n* must be smaller than 18, when the first and last ribs are mold borders (see Fig. 5B).

To solve our optimization problem, we implemented a parametric design model of rib arrangement in Grasshopper (a parametric plugin to Rhino). Within the Grasshopper environment we use the Galapagos tool, which is an evolutionary algorithm solver. Within the parametric search space, the genomes for the evolutionary algorithm are the DSR bits value (0,1,2), assuming 12 ribs (a cake in the length of 12x8 = 96 mm). The GUI is presented in Fig. 8 and the Grasshopper code can be downloaded from the project website (http://digitalgastronomy.co/).

The fitness landscape consists of four functions (*Count_Duplicate; Centralized*; *Connectivity*; and *Volume Check*), each given a score in the range {0,1}. Count_Duplicate lowers its score if find duplicates, and thus is responsible for the unique mod-rib requirement. Centralized lowers its score if bits are far from the dessert center, centralizing the mass. Connectivity depends on user input parameter, and can lower or raise the score with respect to the standard deviation of the derivatives between rib-molds ($\|DSR^n - DSR^{n-1}\|$). Lastly, Volume calculates the difference between the requested volume and the current one. A least mean square (LMS) calculation of the scores is the fitness function of the solver, aiming at maximizing its value until converging to approximately global optimum.

In this case, we prepared only 27 unique mold-ribs, so we cannot allow for repetitions. This is a severe limitation on the search space and limits both the quality of the result and the design flexibility. Fig. 9 compares two results using the same constraints, with and without rib repetitions. While theoretically we can easily allow rib repetitions, in a setting where several desserts are being made at the same time, we will always need to take into account the number of mold-ribs we have from each DSR, while searching for the optimal[1] solution for our given equipment.

Fig. 10 demonstrates the use of the evolutionary solver to determine which mold-rib arrangement plans will satisfy varying conditions. After the chef decides on the preferred volume and connectivity pattern of the dessert, the solver

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[1] We would like to clarify that "optimal" is only with respect to constraints and preliminary condition—we are merely solving a mathematical optimization problem. By no means do we aim to create an optimal dessert, or claim that this is the best cake possible. We simply mean that the SW considers the conditions and generates the best solution possible.

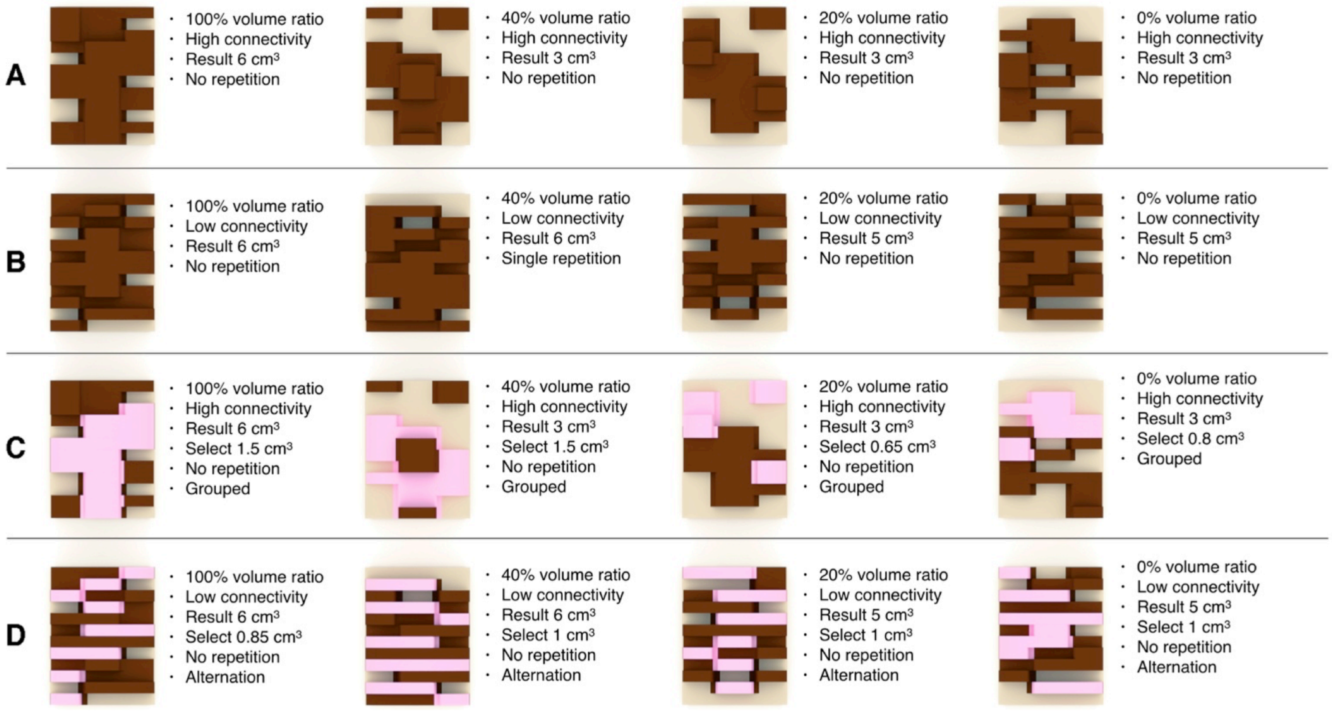

Figure 10 Outputs from the evolutionary solver (Grasshopper Galapagos) for the Rib-Mold Arrangement problem. (A) Four high-connectivity solutions for varying volume requirements; (B) and four low-connectivity results for the same volume requirements. In (C-D) we illustrate possible taste distributions that can be applied manually by the chef. Rendering by Octane Render.

executes at least 100 breeding iterations before stopping. The algorithm does not specify how and where to locate each of the edible materials; it only creates the preferred topology with respect to volume and connectivity. The chef manually casts those substances and lets them stabilize before serving to the diner, as explained in more detail in the following section.

DEMONSTRATION: THREE-COLOR MOUSSE CAKE

In order to realize our concept, we offer here a specific recipe for a *Three-Color Mousse Cake*, based on a sweet/acidic (sour) flavor substance (strawberry mousse); a sweet/bitter flavor substance (dark chocolate mousse); and a sweet substance (white chocolate mousse).

After the chef chooses the requirements and receives the DSR arrangement from the algorithm (as in Fig. 10), she or he assembles the mold (Figs. 3 and 4), then prepares the mousse. The chef applies the three-color mousses and controls their quantities manually, based on the given topology (as in Fig. 1 and Fig. 6).

The topology allows for the preferred taste structures to evolve, such as continuous bitter flavor with grouped spots of acidic flavor, or a continuous pattern of bitter and acidic flavor, all atop a sweet white-chocolate structure (as in Fig. 7). Thus, the Three-Color Mousse Cake demonstrates a dessert with the potential to render a high number of taste patterns and dining experiences.

Almond Streusel

Ingredients:

- 50 g flour
- 50 g sugar
- 50 g ground almonds
- 50 g butter

Instructions: mix everything together in a mixer fitted with a paddle until small grains form. Bake at 170°C for 15 minutes. Let it cool.

Strawberry Mousse

Ingredients:

- 100 g strawberry puree
- 20 g sugar
- 3 g powdered gelatin
- 18 g cold water
- 100 g cream

Instructions: soak the gelatin in the water for 10 minutes. Warm the strawberry with the sugar until dissolved. Mix the strawberry with the gelatin. Lightly whip the cream and fold into the strawberry. Put one layer in the mold and freeze for 30 minutes.

Dark Chocolate Mousse

Ingredients:

- 100 g milk
- 65 g sugar
- 50 g egg yolks
- 4 g powdered gelatin
- 24 g cold water
- 120 g dark chocolate
- 240 g cream

Instructions: soak the gelatin in the water for 10 minutes. Warm the milk, sugar and egg yolk on low heat until the mixture thickens (85°C). Remove from heat and mix with the gelatin and chocolate. Lightly whip the cream and fold into the chocolate mixture. Pour a layer into the mold and freeze for 30 minutes.

White Chocolate Mousse

Ingredients:

- 100 g milk
- 65 g sugar
- 50 g egg yolks
- 4 g powdered gelatin
- 24 g cold water
- 120 g white chocolate
- 240 g cream

Instructions: soak the gelatin in the water for 10 minutes. Warm the milk, sugar and egg yolk on low heat until the mixture thickens (85°C). Remove from heat and mix with the gelatin and chocolate. Lightly whip the cream and fold into the chocolate mixture. Pour a layer into the mold and freeze completely before unmolding.

Finishing the Dessert

Put a layer of streusel on a plate. Unmold the cake and put it on the streusel layer.

DISCUSSION AND CONCLUSIONS

In this work we contribute a new procedure to the growing body of DG research and developments, to allow chefs to program the taste of food, enabling for local computational control of taste. We propose to use a modular mold to cast edible substances. By using a mold with a large number of shape permutations, we accelerate the 3D forming stage compared to food printing: while it can take hours to print a shape with an edible paste, casting the same shape is immediate. Yet we are aware that after casting we still need to stabilize the liquid substance, which may take significant time, depending on the method. For example, we demonstrate the use of a modular mold with a mousse recipe, which needs to be fully frozen to stabilize and solidify it. Although this takes time, there are methods to accelerate the process, such as using liquid nitrogen that we did not explore in detail.

Nevertheless, the limitations of 3D printing for cooking go beyond the time it takes to produce 3D edible shapes. It is difficult to parallelize multiple printing tasks. In most cases, the print time of several objects will be similar to the print time of a single object—the printing task itself is the bottleneck of the process. Since the machines are relatively expensive, it is cost-prohibitive to buy multiple machines. However, molds are relatively cheap and we can cast in parallel with no significant extra cost. Moreover, one of the main limitations of 3D food printing is the low variety of raw food materials and flavors. Casting, on the other hand, is much more flexible in materials and flavors and can be used for cold desserts as well as baking.

Furthermore, our work aims at a more fundamental contribution than accelerating production time per-se. We wish to enable digital control of *taste structures*, initiating a new interactive capability for recipes. Several taste structures can form a taste pattern, bringing DG to the realm of taste bits, pixels and voxels. Chefs will be able to control the taste experience as a function of each edible material's location within the dish, and add a new level of interaction to the user experience. To explore this new cooking and interaction horizon, we suggest adopting graph topology representation to express and design taste structures and patterns, relying on the vast body of work using graphs and presenting patterns in CG.

In this paper, we do not aim at directly impacting diners' experiences yet. There is still a vast amount of technical and conceptual research work to accomplish before the DG vision will be ready for the dining table—we need to improve resolutions, develop digital recipes and design tools, ground technologies and cooking methods, and more.

Hence, when considering future work, we would like to extend our linear modular mold to higher dimensions, allowing modularity in more than a single axis and improving local resolution. In addition, an improved algorithm could optimize the topology to assist in planning the taste patterns themselves, as well as their placement in the mold. For example, when a chef casts an edible substance in a liquid form, the topology will guarantee that the material fills all of the relevant depressions and channels. Layer by layer, the casting process will form a complex taste structure designed and simulated using the genetic algorithm. Further research is required to explore how diners and chefs can interact with taste structures and taste patterns, and how we should express eating preferences, experiences, and nutritional needs via computational tools.

Going beyond DG, and with respect to digital fabrication, our modular mold concept suggests an alternative mode of production. While researchers already advocate for discrete control of material characteristics [12], all current methods aim to produce food via a digital process—i.e., they have localized control of every drop or 3D voxel of material. Our concept utilizes the modular mold and mold design paradigm to control inner material structures within an object produced with analog casting, accelerating the production time of a 3D shape.

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