Digital Gastronomy: Methods & Recipes for Hybrid Cooking

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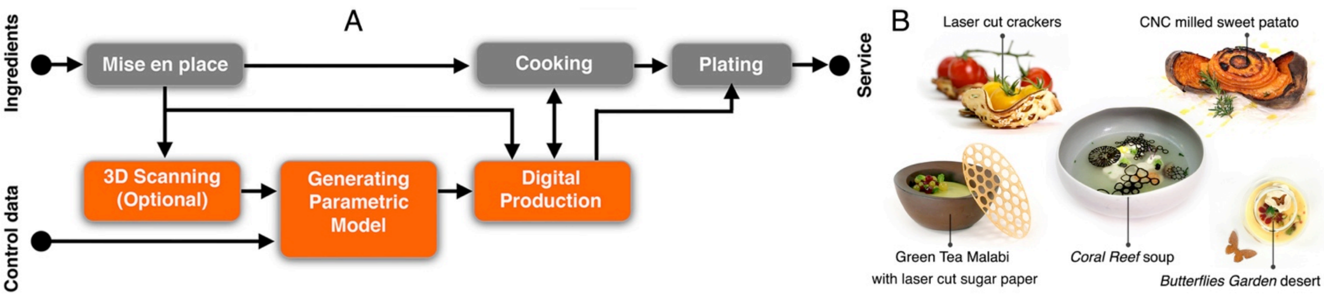

Figure 1: (A) A general scheme of a hybrid cooking procedure, using manual and digital techniques to allow personalization of a dish. Gray: traditional cooking. Orange: interaction with digital procedure. (B) Five examples of dishes made using hybrid cooking techniques.

ABSTRACT
Several recent projects have introduced digital machines to the kitchen, yet their impact on culinary culture is limited. We envision a culture of Digital Gastronomy that enhances traditional cooking with new HCI capabilities, rather than replacing the chef with an autonomous machine. Thus, we deploy existing digital fabrication instruments in traditional kitchen and integrate them into cooking via *hybrid recipes*. This concept merges manual and digital procedures, and imports parametric design tools into cooking, allowing the chef to personalize the tastes, flavors, structures and aesthetics of dishes. In this paper we present our hybrid kitchen and the new cooking methodology, illustrated by detailed recipes with degrees of freedom that can be set digitally prior to cooking. Lastly, we discuss future work and conclude with thoughts on the future of hybrid gastronomy.

Author Keywords
Food, kitchen, cooking, design, 3D printing, fabrication.

ACM Classification Keywords
H.5.2. User Interfaces: User-centered design.

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INTRODUCTION
Recently we have witnessed a growing number of projects importing digital technologies into the kitchen, in the form of food printers [18], robotic cooks [6,34,43], or theoretical research on the semantics and procedural relationship in culinary recipes [2,17,27,37]. Nevertheless, although the vision of Digital Gastronomy is not new [46], the potential of computers to enhance our culinary and cooking culture is still awaiting its bloom. Many of the new digital cooking developments present a high degree of technical sophistication, and are often biased towards quantitative reductionism of culinary culture. These projects suggest that cooking can be represented by a finite set of instructions, which can then be analytically manipulated to control fully autonomous machines.

The kitchen is more than a territory for digital augmentation seeking efficiency and control: it is a place where culture and meaning evolve [1], and creativity is celebrated [15]. Yet, although it holds major potential for interaction studies, within the HCI community the discourse on cooking is still limited, as recent research papers largely discuss eating habits, diet and the food media [5,12,43].

In our research, we aim to stimulate and enrich human creative practice, seeking integration between traditional cooking and digital tools. Thus, our work is a product of collaboration between professional cooks and computer scientists. We acknowledge the similarity between recipes (cooking procedures) and algorithms (problem-solving procedures), and believe that the integration of digital devices in the kitchen using designated procedures can give cooks new capabilities which will complement both classic and current trends in cooking (such as *molecular gastronomy*). Putting human cooking in the center of our exploration, we enable chefs to continue navigating culinary culture in the age of computers. At the same time, we value digital technology for its control and versatility, and we believe that the use of computers in the kitchen can ease and accelerate the exploration of new flavors, shapes and dining experiences that would be difficult to achieve through traditional cooking methods.

Thus, we propose a hybrid practice, envisioning a kitchen that features traditional and modern cooking tools side by side with computers and digitally controlled equipment, all part of the creative palette of the chef (see Fig. 2 & 3). Our kitchen features existing digital fabrication devices, such as 3D paste printers, laser cutters, CNC milling machines, and 3D scanners, together with custom parametric design procedures that merge into cooking recipes, allowing many versions for the same dish. Cooking with hybrid tools, the chef can leave some of the elements of the dish un-fixed; when diners order their meals, they can fix these elements based on their personal nutrition and taste preferences. A dedicated digital procedure applies these preferences to the preparation of the dish using computational tools, and thus suggests a new HCI cooking paradigm.

This vision of hybrid gastronomy presents many technical and interaction challenges, such as the collaborative and creative processes in a hybrid cooking team. Our work focuses on *cooking procedures*. We contribute the concept of hybrid recipes in which we merge manual and digital procedures, introducing a new generalized HCI scheme between the chef and the digital instruments (see Fig. 1A). The integration of computational tools into the traditional kitchen allows the chef to digitally control the taste, texture, structure and aesthetics of each dish.

In particular, this paper presents two methods for controlling the qualitative characteristics of taste and flavor: (1) by allowing control over the composition of ingredients in a dish, with various elements that will be mixed while eating, or by (2) changing the molecular structure of food as when chemical reactions occur in heating. While both methods are based on the same interaction scheme, each of them uses different parametric design procedure and digital fabrication tools. In addition to discussing the technical processes, we present complete recipes demonstrating how these methods can be used in preparing a dish (Figs. 6 & 9).

This paper is structured around a presentation of our concept of digital gastronomy, the hybrid recipes and the technology that enables them. In the next section, we review related work, before presenting our kitchen setting and hybrid recipe methodology. Then, in *Programmable Structure and Composition* and *Programmable Flavors by Selective Heating* we demonstrate our approach and suggest two hybrid recipes. We discuss implications for HCI before concluding the work in the last section.

RELATED WORK

Parametric design is the process through which generated patterns controlled by a small set of inputs achieve complex patterns and new aesthetics [32,36]. Together with the revolution in digital fabrication technology enabled by computer-controlled machines [13], today's designers can manipulate forms and aesthetics using digital control, while increasing capability in production. The potential of digital fabrication technology in cooking [24] has prompted researchers and cooks to explore the new creative territory of Digital Gastronomy [46].

Recent products have enabled digital applications of graphic patterns to food elements, such as digitally printing pancakes [30] or digitally dyeing cappuccino foams [39], paving the way for other digital instruments to move into the kitchen. Additionally, the use of laser cutting machines with food has been explored, mostly in adding decorative heated elements to toast and cutting vegetables, but also in cutting nori seaweed for sushi with delicate patterns [20]. Especially relevant to our approach is the work by Fukuchi and Jo, who have used laser cutting to selectively heat bacon, applying different treatments to the meat and fat [11].

3D food printing technologies hold promise for the future of digital food technologies, as suggested by the extensive investments researchers and engineers are making in this field [22]. In 2013, NASA announced it had started researching the implications of additive manufacturing to food in space, aiming to overcome the unique challenges of handling food for long-term space missions [29]. Closer to market, FOODINI [9] is a 3D domestic food printer using a paste extruder with fresh ingredients prepared before printing. Additionally, 3D Systems has developed the ChefJet Pro [48] 3D printer, which is based on solidification of edible powders such as sugar. Recently, the company opened the 3DS Culinary Lab in Los Angeles [3] to explore the potential of food printing, and presented several hybrid dishes made by top chefs with 3D printers.

While 3D food printers can "manufacture food products with customization in shape, color, flavor, texture and even nutrition" [35], Sun et al. distinguish the world of additive manufacturing from robotics-based food manufacturing technologies that automate manual processes. A 2010 article in *The New York Times* reviews several cooking robots [6], including a 2006 AIC-AI Cookingrobot that cooks pre-programmed Chinese food [38], and a fully autonomous robot ramen restaurant in Nagoya, Japan [21]. Recently, Moley Robotics from Germany presented a machine featuring two robotic arms in a dedicated kitchen. Based on data retrieved from a human chef cooking a meal, this robot can imitate the movements of the chef and cook autonomously from scratch [14].

In our work, we apply hybrid design paradigms to recipes and cooking, reserving the place of chefs in the process while putting digital abilities into their hands as part of their creative toolkit. This interactive cooking project continues a

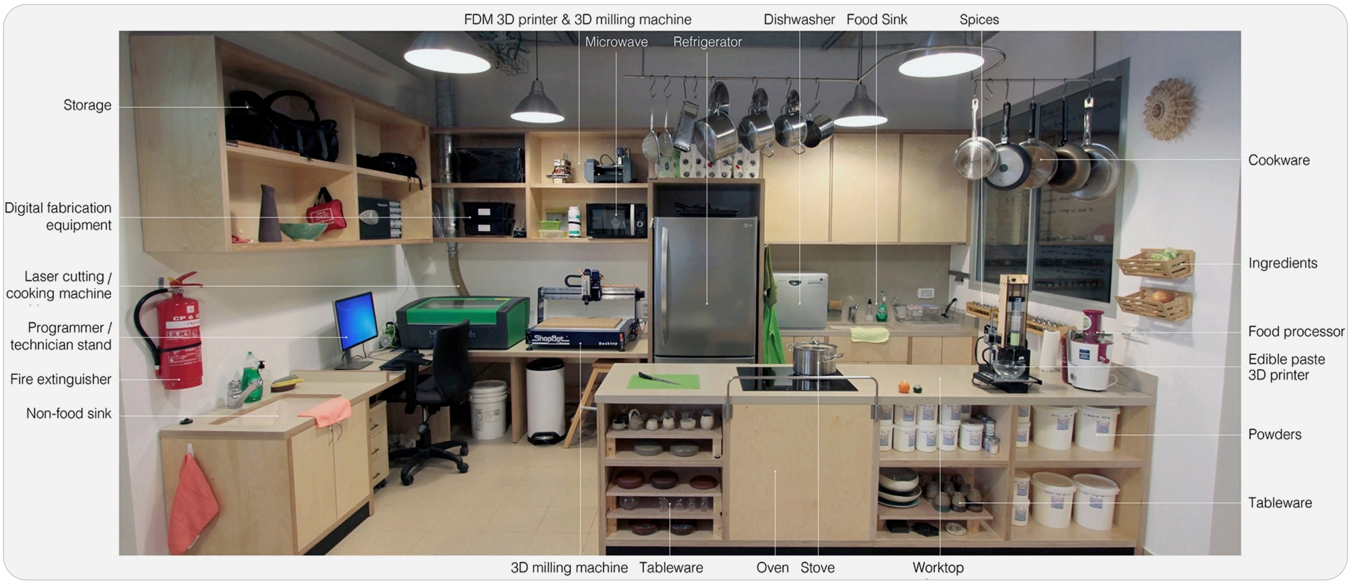

Figure 2: Our hybrid kitchen, featuring both manual kitchen and digital fabrication equipment.

line of research within the HCI and CG communities of hybrid tools, as presented in several projects on craft and digital fabrication and design [7,19,44-47].

THE HYBRID KITCHEN

In contemporary fine dining, chefs mix and hybridize a wide spectrum of techniques, presenting a culinary experience that goes beyond eating per se and demonstrates how traditional cooking mixes with modern scientific methods to achieve new tastes and aesthetics [28,40]. Digital tools can contribute more to this methodology than autonomous machines: the integration of computers with cooking allows cooks to individually address users' needs and desires. Moreover, digital information can allow us to easily calculate the nutritional content of ingredients or accurately affect cooking-related chemical reactions, and thus digitally fit recipes to personal preferences.

For this research, we constructed a hybrid kitchen featuring digital and analog cooking instruments. As many of these devices are either too expensive for domestic kitchens or require a high level of skill in order to operate them, within the context of this paper our target kitchens are professional facilities, which require efficiency and massive cooking capacities. Yet, we would like to note that in order to scale our cooking paradigm, a farther research may be needed to modify and adjust the presented techniques.

Cooking with Digital Fabrication Technologies

We equipped our kitchen with several digital instruments used for various fabrication tasks (see Figs. 2 & 3), and with a 3D scanner. Some of these devices need special adjustments in order to be used for food preparation. Below is a list of the devices and the unique settings we used.

3D Printer We used a Printrbot Simple Metal machine with a dedicated heating bed and Paste & Food Extruder for 3D printing a tofu coral structure (see Programmable Structure and Composition section for details). Due to the changes in the extruder structure and the printing matter, several adjustments were made in the slicing and printing settings/process. Replacing the original Simple Metal extruder with the paste extruder resulted in a reduction of the Build Volume by 3 cm and 3 mm on the Y and Z axes respectively. To allow the original build volume, one can extend the printing bed on the Y axis by 3 cm and shorten the needle by 3 mm. No further setting changes are required. The paste extruder is a non-heated extruder; therefore, a cold extrusion has to be enabled. The paste consistency and texture in combination with the needle diameter requires several changes: (1) relatively slow head traveling and faster extrusion; (2) bigger/higher layer height; (3) faster and longer retraction. In the *Programmable Structure and Composition* section, we discuss printer setting for an instant tofu-methylcellulose paste.

2.5D Milling Machines We used a ShopBot Desktop 2.5D milling machine, with 1/4-inch flat-top and ball-nose milling bits, and a Roland Modela MDX-15 2.5D milling machine, with a 1/32-inch flat-top milling bit. Because we use these machines to mill root vegetables, the setting for spindle speed and feed-rate were similar to soft wood. As root vegetables can wet the milling environment during machining, we protected exposed surfaces with plastic sheets. For the ShopBot Desktop we designed a special clamp that we 3D printed with Shapeways (www.shapeways.com) using Nylon 12 track, as well as steel and bronze clamps, and a sharp bronze holder, to fit vegetables of varying shapes.

Laser Cutter We used a Universal VLS3.50 Laser Platform (40W), with both its regular optics (lens) for surface heating task and the High Power Density Focusing Optics

(HPDFO™) cutting tasks. We kept the machine in focus for all tasks, and used an Acktar Spectral Black™ coated foil, which absorbed most of the energy from the 10.6 micron wavelength laser. The foil efficiently prevents the laser's tray from heating and is made of food-safe materials (though not certified as food grade). The foil can be replaced as needed. To fine-tune the proper laser setting and eliminate the bitter/burnt taste that may occur when using such a strong laser on food, we ran numerous experiments and tests. The final laser settings differ between tasks, as discussed within the relevant sections below.

3D Scanner We used a NextEngine 3D Scanner with PartGripper and AutoDrive to clamp objects. We 3D scanned a sweet potato and a meringue structure. No special modification was needed for the scanner.

The integration of these digital devices with cooking procedures as presented in the rest of this paper, enables a hybrid cooking process and allows the application of new digital capabilities to the construction of recipes and dishes.

The Hybrid Cooking Methodology

While manual cooking centers on human involvement, computers contribute a new level of control and flexibility that is otherwise hard to introduce to a professional kitchen. Digital fabrication tools enable the application of these computational additions to the manually cooked dish. Therefore, a hybrid cooking team with varying skillsets is necessary to fully realize the potential of this new approach.

Our team included a professional chef, a chemist who is also a professionally trained cook, designers, and computer scientists. In the design process, the chef's role is to define a recipe with certain degrees of freedom in its flavor and presentation, and later to define the constraints to be taken into consideration while developing a parametric procedure. Through teamwork we carefully infuse computational tools into the cooking process via our interactive scheme (Fig. 1A). This results in a complete dishes and hybrid recipes that combine the advantages of manual and digital cooking.

Many chefs present customers with a set menu, limiting guests' choices for practical reasons [31]. Others prefer to personalize the menu, and even track returning customers and plan their meals based on their preferences and past experiences. However, this result is rarely achieved by modifying the dish itself, but by customizing the set of dishes presented to the customer [10]. The tension between these approaches motivates our construction of hybrid recipes: recipes defined by the chef, with certain degrees of freedom to be set by a parametric design procedure prior to cooking and constructing a unique variation of the dish.

For example, the volume of ramen soup broth with varying quantities of dashi, chicken stock and soy sauce can be represented as a sum of liquid volumes: $V_{ramen} = V_{dashi} + V_{chicken} + V_{soy}$ for which a chef can define simple constraints such as $V_{dashi} \in [0, v/2]$, $V_{soy} \in [v/30, v/15]$. According to these constraints and personal preferences from the consumers (how much do they like dashi and soy?), a simple procedural process finds the correct amounts of chicken stock, soy sauce and dashi stock in order to satisfy volume constraints and consumer preferences. Nevertheless, while the stocks are made manually, and toppings can be added to the soup, our ramen still relies on a traditional recipe, side by side with computational procedures.

The digital methods (1) to selectively apply or remove ingredients[1] using 3D printing and milling, or (2) to selectively heat food surfaces with a laser, share similar concepts. Both methods deal with division of quantities, which links them to an additional challenge: *how* should we construct a dish from its separate parts? While a computer can help set the quantities of different ingredients to construct a food element as part of a dish, it can also go beyond and define how this application can be implemented: i.e., how can we design food constrained by the volume (or surface) of its ingredients, and what is the best way to distribute them? This distribution and design problem depends on aesthetic, textural, and flavor preferences, as defined by the chef.

As texture affects taste, we see a future potential to explore the flavors of digitally applied selective patterns on food. Here, however, our distribution function is mainly aesthetic criteria, while the volume problem can satisfy individual preferences for ingredients as a function of taste and health.

We seek a culinary and cooking experience where a parametric design engine solves the problem of balancing two dependent criteria in the preparation of a dish or part of it: (1) determining the quantity of ingredients in the dish, and (2) determining the distribution of these ingredients and

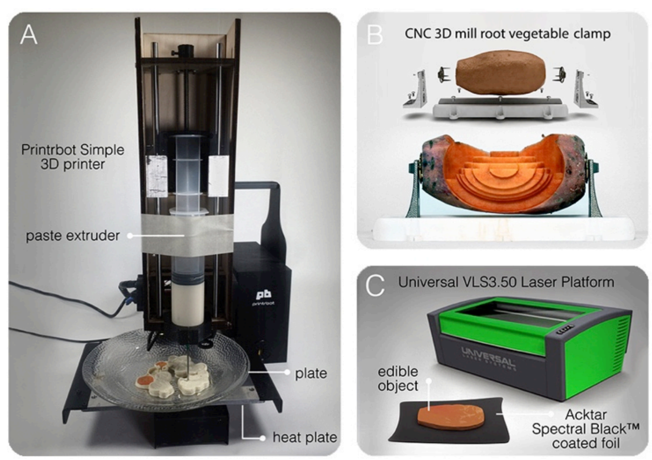

Figure 3: Digital fabrication devices used in our hybrid kitchen: (A) a 3D paste printer; (B) a custom root vegetable clamp for our 2.5D CNC milling machines; and (C) a laser cutting machine.

[1] We treat part of an ingredient that was selectively modified (such as with laser heating) as a new, separate ingredient.

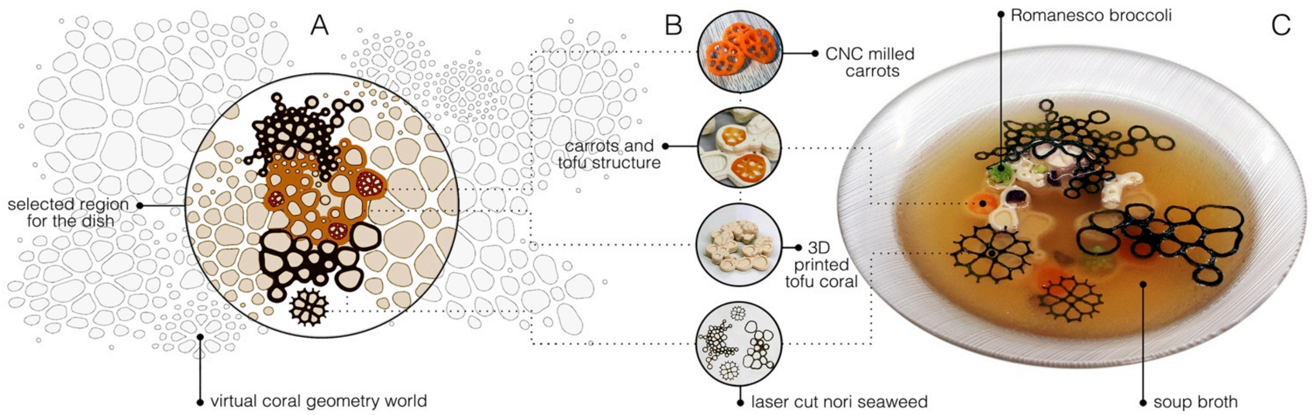

Figure 4: Implementation of a coral reef style on a soup. (A) A virtual pattern defines the required style. (B) Various soup toppings can be digitally produced. (C) The final dish is assembled from the digitally created toppings and manually produced soup.

how it impacts the texture, construction and aesthetics of the food. In this model, the ingredients are still planned by the human cook who positions the elements in the dish. To demonstrate how such procedures and recipes may look, we now turn to an outline of the hybrid cooking of two dishes: a soup with a 3D printed noodle structure that holds varying liquids while following predefined aesthetics and volume restraints, and a dessert selectively heated with a laser cutter to promote a chemical reaction on a given surface.

PROGRAMMABLE STRUCTURE AND COMPOSITION

Many common dishes allow for some level of flexibility in the quantity of their ingredients, spanning a wide range of nutrition and flavor under very similar recipes. Some of these dishes are seasoned while they are eaten (such as dipping sushi in soy sauce) rather than having the seasoning ingredient distributed evenly over the whole dish, allowing the diners to personally construct their favorite versions of the dish just before eating it.

Here we explore the idea that a parametric procedure can fine-tune the quantity of ingredients under predefined boundaries set by a chef. As the ingredients are not cooked together, but organized in a digitally determined structure prior to serving, they are mixed and affect the taste as part of the eating experience. We explore how digital tools can help determine the distribution of ingredients, impacting the dish's aesthetics and the process of eating it. We suggest a recipe for a *Coral Reef Soup*, in which various liquids are segregated to allow digital control of the liquids/noodle ratio and seasoning per each diner's preference.

The integration of parametric procedure into 3D design structures under given constraints is common in contemporary architecture [36]. Relying on a similar procedure, we investigated a method to construct a dish by developing a recipe with degrees of freedom in the quantities of its ingredients, and also developed a virtual model to determine the aesthetic style of the dish. Prior to constructing the dish, diners list their preferences and set the free parameters of the recipe, then a parametric design procedure generates a 3D food model to satisfy the requirements and constraints and define how ingredients will be distributed in the 3D space of the dish. To demonstrate that concept, we present our case study in detail.

A Case Study: Segregation of Liquids in Soup

Soup creates an opportunity for programmable structures and composition. While it allows easy modification of flavor by mixing liquids, such as seasoning ramen soup with soy sauce, these liquids require containers to keep them apart prior to serving. We suggest rethinking soup by keeping some of its ingredients apart. For example, our Coral Reef Soup is built on a hot and sour soup liquid, which needs a base to balance its strong flavors (see Fig. 6). Possible bases include tofu noodles or turkey stock, depending on personal preferences. Soy sauce can be added for seasoning. Instead of setting the exact quantities in advance, the recipe allows for some freedom in the ratio of ingredients.

Using a contemporary cooking technique, we created a tofu-methylcellulose paste that changes its viscosity as a function of temperature. At room temperature, the paste is very soft and can be easily printed using a paste dispenser, though it can still hold a 3D shape. When the tofu-methylcellulose structure meets 80˚C liquid (the soup), it changes its viscosity, hardens and resembles regular noodles in its mechanical performance. The noodle is designed in such a way to allow for the segregation of these liquids in the soup, using a predesigned parametric style.

Virtual Coral Reef Concept

As a demonstration, we developed a concept design for a virtual coral reef pattern. Working from the pattern, the chef can select a region to generate various elements of the dish, such as laser cut seaweed, CNC milled carrots, or a 3D printed tofu noodle. In defining the coral reef style we rely on examples from [16], and define abstract notion of a reef (variable and continuous sizes and heights of oval pools, distributed in a graph-like pattern with points of symmetry). This virtual concept design can be either digitally drawn (see Fig. 4) or automatically generated, to resolve the problem of ingredient volume and distribution (see Fig. 5). Obviously, the coral reef concept we developed here is only one illustration of the potential for digitally determining dish aesthetics and distribution of ingredients.

The digital allowance in designing and fabricating various elements of the dish in a given style leads to the more advanced concept, where the chef uses a parametric design procedure to set free parameters in the recipe per the consumer's preferences: i.e., programs the structure and construction of the dish. Thus, to highlight the potential contribution of digital tools in hybrid cooking, we developed an algorithm to design a CAD model for the 3D printed tofu noodle. This model satisfies the requested amount of independent ingredients (tofu and soup liquids such as seasoning sauce and stocks), while obeying the predefined concept design of our coral style.

Our generative algorithm designs an edible tofu noodle reef, which serves as a liquid segregation container. The algorithm helps to personalize the dish, bounded by the chef's definition of parameter boundaries and aesthetic constraints. The data and parameters that are provided to the algorithm by the chef are as follows:

1. A curve $f_{plate}: [0, R] \rightarrow \mathbb{R}^2$ describing the profile of the serving bowl (the rotation of this curve around the z-axis will result in a bowl with radius R).
2. A number $V \in R$ represents the total volume of the soup ($V = V_{soup} + V_{tofu} + V_{sauces}$).
3. A number $a \in [0,1]$ represents the desired ratio between the surrounding soup and the total volume of ingredients $a = V_{soup}/V$.
4. A set of numbers $s_1, s_2, \dots, s_k \in \mathbb{N}$, such that for every i, s_i represents the customers preference for the i-th liquid on a scale between 1 and 5.
5. A set of $q_1, q_2, \dots, q_k \in \mathbb{R}$, such that for every i, q_i represents the amount of a single serving of the i-th liquid.

The tofu structure has to fulfill several constraints: (a) the total volume of the coral is V_{tofu}; (b) in order to serve as a container, the structure includes cavities of appropriate volume to hold the liquids; (c) because the liquids do not mix with the soup, the cavities' heights must exceed the soup's height. The aesthetic style resembles the pattern as defined earlier. We use a graph of pools with distorted circle contours, limiting the variance in heights and base areas between every two neighboring pools.

The implementation of the generative algorithm

Here we describe our generative algorithm, which fulfills the constraints as implemented in Grasshopper (a parametric plugin for Rhino's CAD environment).

Satisfying aesthetic constraints: small variance in pool base areas. As the aesthetic constraints resemble the morphology obtained from a Voronoi tessellation, we base our pools pattern on Voronoi cells. Given a group of randomly selected points $P = \{p_1,\dots,p_n\}$ on a plane, the Voronoi cell

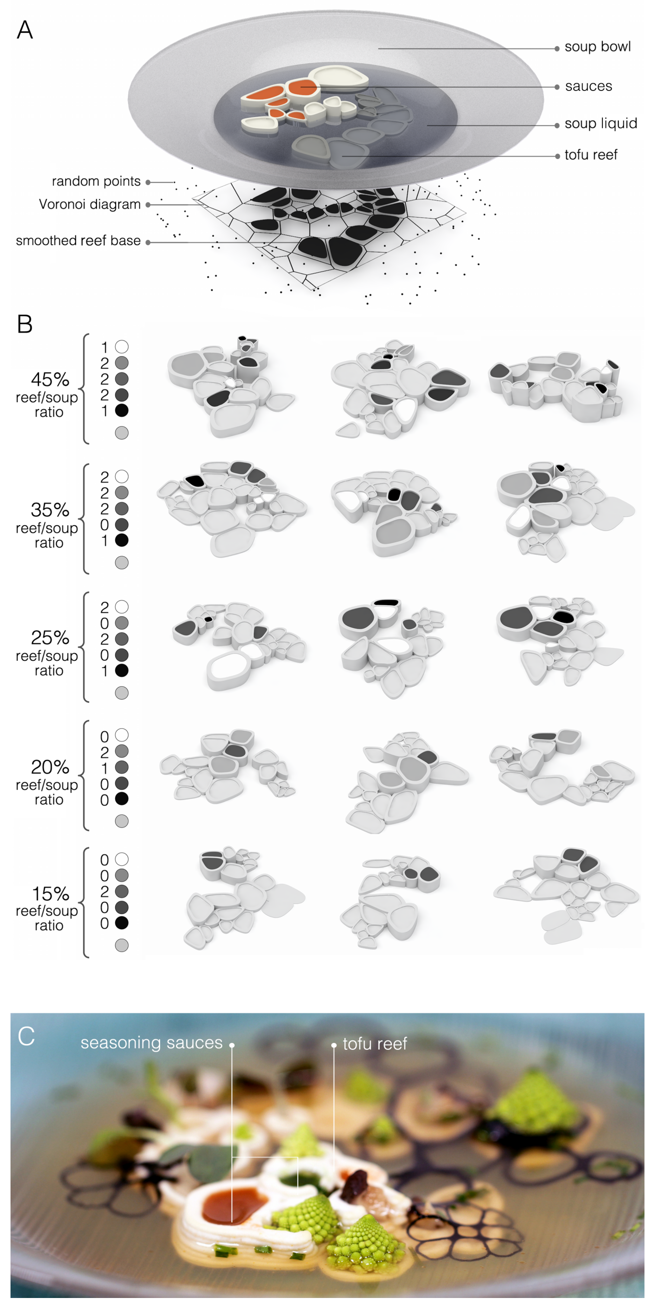

Figure 5: A generative algorithm to resolve the ingredient volume and distribution problem in a segregated-liquids soup. (A) The 3D reef structure depends on the profile of the serving bowl and the volume contraints, while its 2D base pattern is determinded by a randomly generated Voronoi tessellation. (B) Examples of various outputs per various constraints (reef/soup ratio and number of pools per liquid). (C) A photo of a 3D printed tofu reef with two segregated sauces.

$V(p_i)$ of a point is the area around p_i for which each additional point on the plane would be closer to p_i than to any other point of the given set P. We satisfy the constraint of small variance in pool base areas between two neighbors

Tofu Instant Noodles Paste 1

200ml water at room temperature
340g soft tofu
12g methylcellulose
Pinch of salt
Dash of sesame oil

Mix methylcellulose with water in a saucepan and bring it to a boil. After one minute, move it to a food processor, add tofu, salt, and oil, and process at high speed until it has a consistent, uniform texture. Chill.

Hot and Sour Soup 3

10g dry kombu seaweed
5 dry shiitake mushrooms
1.5 liter water
3 tablespoons rice vinegar
Dash hot chili pepper
4 black peppercorns
A few coriander seeds
50ml soy sauce
1 bunch spearmint
10g lemongrass
10g scallion
1 star anise
5g ginger
30ml lemon or lime

Boil all ingredients in a pot, simmer for 30min and filter.

Tofu Reef Noodles 2

Tofu instant noodles paste
Personal preferences of turkey stock [none – 20% of total liquids]
Personal preferences of tofu structure with respect to soup volume
Virtual Model of serving bowl

Fill the 3D printer paste extruder with the tofu instant noodles paste. Generate a 3D reef model using the parametric procedure, your personal preferences for ratio of stock to reef, and your model of the serving bowl. If you are not satisfied with the model, generate an alternative one. Upload the model to the 3D printer's control SW. Position your serving bowl on the printer's tray. On the first layer, extrude more paste and generate a slightly shorter layer to allow better adhesion to the printing surface, and follow the unique printing instructions for tofu noodles.

Turkey Stock 4

500g turkey parts such as wings, drumsticks, and thighs
1000ml water + running water

Put turkey parts in a soup pot, cover with water. Bring water to boil and remove from heat. Discard the water and wash the turkey with cold water. Put the turkey into 1000ml of fresh water, bring to boil and simmer for 50 minutes.

Nori Seaweed add-ons (optional) 5

1 sheet nori seaweed per serving
2D virtual pattern (can be generated with the reef generator)

Put the nori in Universal VLS3.50 40W laser cutting machine, and cut the shape with the following setting: power 5, speed 7, ppi 500.

Dish Construction (per serving) 6

1-3 nori seaweed pieces
Handful of broccoli or other sprouts
1 tofu reef noodle in a serving bowl
1.5 cups of boiling hot and sour soup
A few small pieces of Romanesco broccoli
Turkey stock as necessary Shiitake, king oyster and morchella mushrooms, cut into small pieces
1 small carrot, cut into small disks

Use the mushrooms, sprouts, Romanesco broccoli and carrots to decorate the tofu. Pour hot and sour soup onto the bowl. Do not cover the pools in the reef. The hot liquid will strengthen the reef. Add the stock to the open pools. Place the seaweed on top, and serve hot.

Figure 6: The Coral Reef Soup recipe (6 servings). Gray: traditional cooking. Orange: interaction with digital procedure.

by ensuring there is a uniform or gradually changing distribution of the points that define the cells, and select cells only inside the plate boundaries. In addition, we remove a random number of the remaining cells (15%-30%) to gain a sparse structure.

Satisfying aesthetic constraints: pool contours. While the Voronoi tessellation results in a continuous cells structure, the cells' contours are polygons and not fully smooth. To overcome this limitation, we use a group of closed NURBS (non-uniform rational B-spline) curves $N_1(u),\dots,N_n(u)$. The control points for each curve $N_i(u)$ are selected to be the i-th cell $V(p_i)$ vertices combined with points on its edges, and a high degree for its basis functions. The obtained curves serve as our pool bases.

Satisfying physical constraints: enough pools above the soup height. After obtaining the pool bases, we extrude them in 3D. Yet prior to applying the heights to all pools, we ensure that enough pools exceed the maximal soup height h_{max}. Notice that $h_{max} = f_{plate}(r)$ for $r \in R$ solves the equation of volume of a solid of revolution:

$$V = 2\pi \int_0^r x \cdot \left|f(r) - f_{plate}(x)\right| dx \qquad [1]$$

To guarantee a small variance in heights, all the liquid-containing pools were selected with low spatial proximity, picking a random point inside the plate $p = (x_0,y_0)$, and sorting all curves according to the distance between their centers of gravity $c_1,\dots,c_n$ and p. Satisfying our requirements, if we need t containers, the first sorted t curves that can hold the sauces are selected as the bases of these containers. Let $N_{\sigma(1)},\dots,N_{\sigma(t)}$ be these curves ($\sigma \in S_n$). Then, for every $N_{\sigma(i)}$ such that $i \in [t]$ we apply a random height $h_{max} \le h_{\sigma(i)} \le 2h_{max}$ and a zero depth. Define V' to be the total volume of the forced pools, then:

$$V' = \sum_{i=1}^{t} h_{\sigma(i)} \cdot \mathrm{Area}\left(N_{\sigma(i)}\right) \qquad [2]$$

Satisfying aesthetic and physical constraints: small variance in heights and volume constraint. Finally, we apply heights to the rest of the pools using the following Gaussian g(x,y) around point p:

$$g(x,y) = 2h_{max} \cdot e^{-\left(\frac{(x-x_0)^2}{2R^2} + \frac{(y-y_0)^2}{2R^2}\right)} \qquad [3]$$

Heights of the remaining curves $N_{\sigma(t+1)},\dots,N_{\sigma(n)}$ are applied according to g on their centers of gravity. To prevent the resulting volume from violating the total volume constraint, we factor the remaining heights with c:

$$c = \frac{V - V'}{\sum_{j=t+1}^{n} h_{\sigma(j)} \cdot \mathrm{Area}(N_{\sigma(j)})} \qquad [4]$$

Finally, we randomly select t pools from all pools with height $\ge h_{max}$ that satisfy a defined area constraint (i.e., can hold the sauces), and apply them a depth depends on the sauces they are supposed to hold, and fix their heights accordingly. To obtain style consistency, minimal shallow depths are applied to the remaining pools. As the model is ready, the chef can 3D print it, and constructs the dish as suggested in Fig. 6.

PROGRAMMABLE FLAVORS BY SELECTIVE HEATING

One of the most powerful applications of digital control to design and fabrication is the ability to selectively apply different treatments to different areas. This link between information units (bits) and material units (atom) is at the center of many research institutions, such as the Center for Bits and Atoms at MIT (www.cba.mit.edu). In this section we explore initial directions in applying digital control to thermal reactions on the surface of food elements, using a commercial IR CO_2 laser for precise control of surface heating, resulting in the Maillard reaction.

Generally speaking, many chemical reactions and physical transformations occur while heating food. These include processes like protein denaturation, volume and phase changes, reduction of water content or drying, caramelization and other changes in color, volume, texture and nutrition value [8]. One important example is the Maillard reaction between amino acids and reducing sugars, which is responsible for many desirable flavors and aromas.

However, under some conditions, the Maillard reaction can generate carcinogens, as when potatoes are overheated [25]. Thus, there is a need to precisely and selectively control the heat evolution on the surface of cooked ingredients to control the reaction products and their spatial distribution in the food (i.e., the surface concentration of flavor and aroma molecules), in order to properly balance taste, color and potential negative effects. Moreover, as an early study we ran in the lab shows (see below), there can be a wide variation of personal preferences when it comes to flavors associated with the Maillard reaction. These findings pose a strong motivation to further explore the selective precise application of surface heating.

The Maillard reaction is of great interest to modernist cooks, as cooking foodstuffs sous-vide followed by surface browning (using a torch or cryofrying) is increasingly popular in professional kitchens. One application for the Maillard reaction is in the browning of meringues. Unlike meat or vegetables, meringues can be made with a controlled process, guaranteeing repeatable density and a constant ratio between ingredients. This makes the meringue ideal for our experiments with selective application of the Maillard reaction.

A Case Study: Laser-Induced Reactions in Meringue

A meringue is made of egg white proteins, table sugar and water. As egg whites contain 18 different amino acids [26], and table sugar is made of sucrose, upon heating the mixture, numerous chemical reactions take place, mainly the Maillard and caramelization reactions. These two reactions are responsible for the rich, deep flavors of cooked foods and their brown, appetizing appearance. The Maillard reaction is a complex, multistep reaction between a reducing sugar (a carbonyl group) and an amino acid, resulting in brown, poorly characterized, high molecular weight products called melanoidins [33] and dozens of small aroma molecules responsible for a large range of aromas and flavors, such as baked (furfural and hydrofurfurals), nutty (alkylpyrazines and oxazoles), buttery (diacetyls and acetoins), meaty (thiofenes), and many more flavors and scents. The final flavor or aroma associated with the Maillard reaction is highly dependent on the identity of the amino acids and sugars involved, as well as the reaction conditions, such as temperature, pH, reaction time and water content [42]. The caramelization reaction, in the case of sucrose, is the result of decomposition of sucrose to the monosaccharides glucose and fructose, which are in turn further dehydrated, undergo intramolecular rearrangements and decompose to form volatile aroma molecules and oligomerize to form the poorly characterized colloidal compounds named caramelan ($C_{12}H_{12}O_9$), caramelen ($C_{36}H_{18}O_{24}$) and carameline ($C_{24}H_{26}O_{13}$), all of which are associated with the bitter-sweet character of caramel [41]. Caramelization occurs at relatively high temperatures of >120°C, while the Maillard reaction starts at around 50°C. The Maillard reaction is believed to be more dominant when there is a source of protein in the reaction [23].

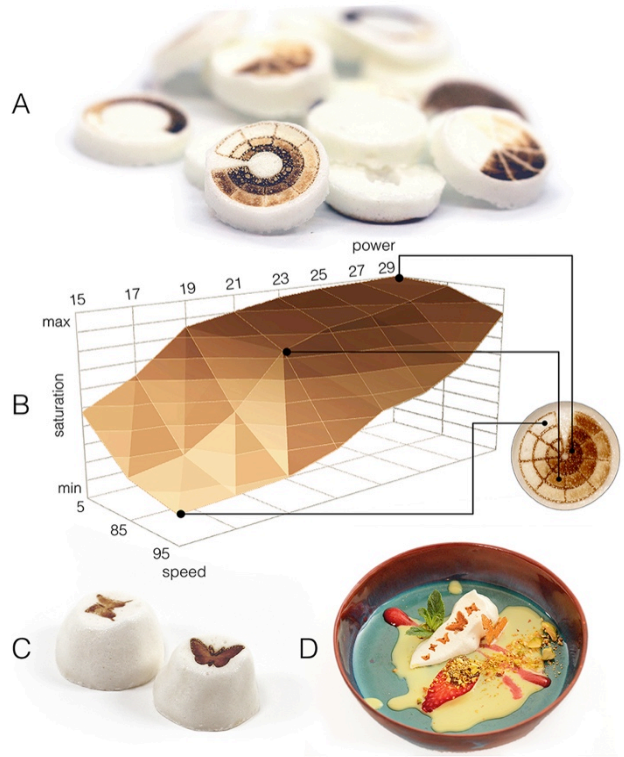

Figure 7: Laser-induced Maillard reaction in meringue: (A) Meringue disks used to tune the laser setting and run taste tests; (B) a laser-induced Maillard saturation plot in meringue as a function of laser setting; and (C-D) examples of implementation of laser-induced Maillard reaction in meringue.

When heating meringue with a laser, food in direct contact with the laser is vaporized. The area around the beam's focal point is heated and provides the necessary energy of activation for the various chemical reactions. As the heat transferred to the meringue is highly controlled and depends on the intensity and speed of the laser, this heating method allows more accurate control over reaction conditions (temperature, water content of the medium, reaction time etc.) and thus possibly allows better control over reaction products. Heating with a laser may also reduce charring (pyrolysis caused by heating to very high temperatures of above 250°C) of the food, which is highly desirable in terms of taste, health and appearance. This kind of heating provides a highly controllable alternative to conventional heating techniques and may also allow control over aroma, flavor and color formation.

In an early experiment we used a laser to heat the surface of meringue disks, achieving continuous grades of browning reaction on the disks as function of the laser settings (see Fig. 7). The maximum heat setting was selected to achieve a dark brown color (i.e. maximum saturation), with no burnt smell or flavor. Based on that grade, we prepared three disk groups (natural color with no heat, half saturation, and maximum saturation). Five people were asked to qualitatively describe the flavor of each color in a blind, random-order taste test.

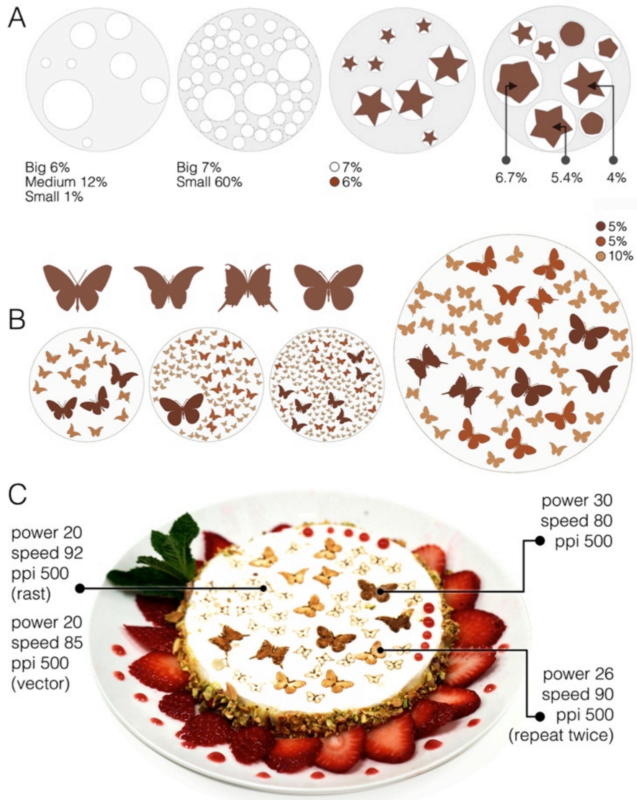

Figure 8: A circle packing algorithm can be used to control the area coverage of the laser induced Maillard reaction. (A) Circle packing allows us to control the amount of surface coverage, and can be modified by replacing the circles with circle-bounded shapes, which can then be deformed to enable control of their relative coverage (right). Numbers refer to ratio between area coverage and general area. (B) We used butterflies in various user-controlled sizes to render 3D depth (big and saturated butterflies are near, small and light are far). (C) Laser-induced Maillard in meringue applied to a Pavlova desert (with laser settings attached).

Our preliminary observation shows that personal preferences clearly differ from one person to the next. For example, some people stated that the natural disks tasted bitter or artificial, while others called them tasty. The maximally saturated disk was described as sugary, caramelized, bitter in a good way, and cooked. Finally, two people chose the half saturated disks as their preferred option, while three chose the maximally saturated disk.

While this initial study is not sufficient to claim or generalize deep conclusions about personal preferences related to Maillard reaction conditions and aroma products in a meringue, it contributes one important conclusion: People differ in their response to laser-induced reaction products in meringue, reinforcing the need for subjective tuning of flavors. Thus, we now turn to presenting a simple procedure to selectively apply varying reaction conditions to meringue surfaces, affecting the final appearance, flavor and spatial distribution.

Area Coverage Algorithm

As laser-induced Maillard reactions in meringue occur on its top surface, a relatively wide and flat meringue will allow for a higher ratio of reaction per volume. Yet, this top surface still needs to be digitally analyzed and processed prior to the application of selective heating. We assume the shape of this surface is known: as the digital process begins after the meringue has been made, a procedure to digitally acquire a representation of the meringue shape is needed, either by 3D scanning the meringue piece or by using a well-known mold to shape the meringue. In order to allow for personalization of the Maillard reaction profile in meringue, one needs to know the consumer's preferences and hold a parametric model to selectively control the distribution of various saturation levels on the surface using the laser. We demonstrate this approach using a circle-packing algorithm while relying on the saturation model we presented earlier.

We based our area coverage procedure on a circle-packing parametric model, where variably sized circles are packed into a given boundary without overlapping (see Fig. 8). Our circle-packing procedure relies on open source code [4] in Grasshopper which we modified so that we could position a given model inside the circles. In our procedure, we select one of four butterfly models. As the size of the circle is controlled parametrically, smaller circles are treated as "background" butterflies rendering an illusion of 3D depth, thus getting less heat, with respect to the saturation model. Hence, the user can select the set of sizes for primitive circles, and the total number of circles (density), while the computer will suggest a butterfly pattern to be executed with the laser.

A circle-packing algorithm allows to easily replace circles with any given symbol (such as a butterfly) with no need for further processing. In Fig. 9 we suggest our Butterfly Garden dessert recipe: a fusion between a Pavlova and a floating island. Our hybrid recipe allows for personal tuning of the meringue flavor, as the diner can determine the amount of meringue surface to be affected by the Maillard reaction (and to what level), satisfying personal taste.

Circle packing is only one example of an algorithm that can solve the problem of area coverage. Many alternative methods are available. For example, we could use a parametric procedure with a force field to implement a constraints map, then tile the area we want to cover and scale each tile's area to fit these constraints locally. A different option is to break the surface into small segments and randomly pick segments for selective heating, until we have covered the total area. Here, we suggest methods to tweak the parameters of a pattern design procedure, but we could also use a process to distribute the surface or volume ratio of the various reactions or ingredients in the desired pattern, as presented in the following section.

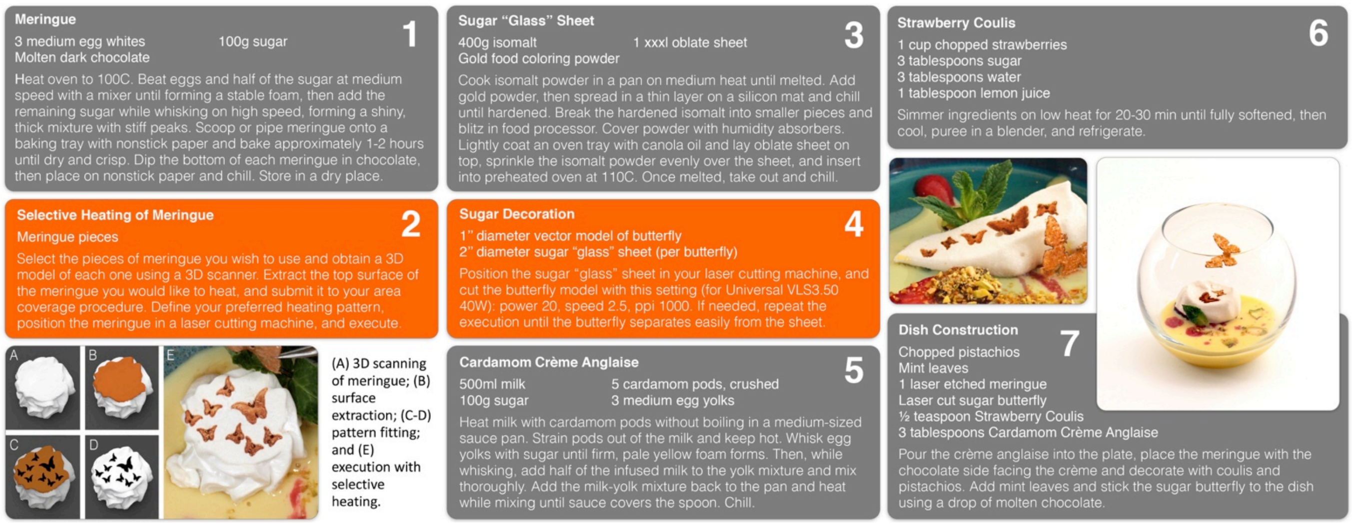

Figure 9: The Butterfly Garden recipe (6 servings). Gray: traditional cooking. Orange: interaction with digital procedure.

DISCUSSIONS AND CONCLUSIONS

The methods and recipes presented here are the product of a year-long project by a team of computer researchers, designers, chemist and cooks. We constructed a special kitchen to run our experiments and develop new processes, and present in this paper only a small part of this work. Many of the interactive methods we used evolved during the study, supporting our hypothesis that manual involvement and hybrid practice are important to allow a wide spectrum of creative outcomes, fusing the traditional manual practice with analytic methods.

Unlike many new digital cooking developments that seek a fully autonomous practice, we aim at finding territories where the computer can enhance the traditional kitchen with new capabilities, to expand the chef’s creative palette, building upon prior HCI research on hybrid design and fabrication. Since we use digital fabrication tools to produce some elements of the dish, we rely on a CAD model to control this process. This gives the potential for deep integration of digital procedures in planning and constructing a dish. We suggest not only rethinking recipes but building them with certain degrees of freedom, such as variations in the amount of some ingredients and in the conditions for chemical reactions associated with cooking. Using parametric design tools, we can achieve a variety of results from the same recipe, and never repeat the exact serving, even with the same constraints. Our parametrically generated CAD model will determine the exact distribution of the ingredients to fulfill personal preferences as well as a distribution model, both mathematically determined by the chefs while they plan the dish and its hybrid recipe.

In the paper we proposed the new concept of hybrid recipes, gave a generalized hybrid-recipe scheme to illustrate an interactive cooking scenario, and presented two detailed hybrid recipes. The Coral Reef Soup recipe allows personalization of the volume of various liquids (with different tastes) in a desirable shape by creating a 3D structure of pools, and presenting a generative algorithm to solve such a challenge. Here, the digital design process determines the quantity of ingredients that the diner will mix while eating the dish. The Butterfly Garden recipe employs a simple, 2D ingredient distribution procedure, while introducing a new concept of selective heating to control flavor formation (specific chemistry) and its character. This laser-induced heating allows computational control over flavor, as personal preference can determine the distribution pattern of various reaction products and their identity. While these two examples significantly differ in their recipes and cooking techniques, they both realize our general hybrid cooking scheme (Fig. 1A). In addition to these two recipes, we experimented with 3D scanning and milling root vegetables, to digitally control the volume of a stuffed sweet potato; we laser cut sugar crust for a dessert and developed laser cut crackers; and more.

Envisioning future work and the possible implications of our hybrid cooking methodology, we wish to (1) continue investigating hybrid recipes with existing cooking and fabrication methods, aiming toward a new hybrid digital gastronomy cookbook; (2) develop new technology to allow for more selective and localized tools in the hand of the chef, and better interaction and design tools; (3) study the diner/chef interaction in a real dinning experience, and (4) deploy these developments into a professional kitchen to evaluate them in real cooking conditions with wide range of cooks and consumers. Nevertheless, our main hope is that our current Digital Gastronomy cooking portfolio will encourage hybrid development in the kitchen, complement modernist cooking and sustain traditional food culture side by side with new developments and opportunities, and present a diverse territory for ideas and cultures to evolve.

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REFERENCES

1. Bell, G. and Kaye, J.J. Designing Technology For Domestic Spaces: A Kitchen Manifesto. Gastronomica, 2, 2 (2002), 42-62.
2. Bollini, M., Tellex, S., Thompson, T., Roy, N., and Rus, D. 2013. Interpreting and executing recipes with a cooking robot. In Experimental Robotics, pages 481–495. Springer.
3. Carter, Noelle. 2015. The future of printed food: 3DS Culinary Lab opens in Los Angeles. Los Angeles Times. (October 2015). Retrieved March 20, 2016. http://www.latimes.com/food/dailydish/la-dd-3d-culinary-printer-20151028-story.html
4. Circle Packing. 2011. grasshopper3d discussion forum. (May 18, 2011). Retrieved March 27, 2016. http://www.grasshopper3d.com/forum/topics/circle-packing-1
5. Cordeiro, F., Epstein, D. A., Thomaz, E., Bales, E., Jagannathan, A. K., Abowd, G. D., and Fogarty, J. 2015. Barriers and Negative Nudges: Exploring Challenges in Food Journaling. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15). ACM, New York, NY, USA, 1159-1162.
6. Daly, Ian. 2010. Just Like Mombot Used to Make. The NYTimes, Dining & Wine. (February 23, 2010). Retrieved March 20, 2016. http://www.nytimes.com/2010/02/24/dining/24robots.html?8dpc=&pagewanted=all&_r=0
7. Efrat, T. A., Mizrahi, M., and Zoran, A. 2016. "The Hybrid Bricolage - Bridging Parametric Design with Craft through Algorithmic Modularity." The 34th international conference on Human factors in computing systems (CHI '16). ACM, New York, NY, USA.
8. Field, S. Q. 2011. Culinary Reactions: The Everyday Chemistry of Cooking. Chicago Review Press (November 1, 2011).
9. FOODINI, A 3D FOOD PRINTER. 2016. Natural Machines website. Retrieved March 20, 2016. https://www.naturalmachines.com/
10. Fried, A. (2015). Chef's Table session 1 episode 4 - Niki Nakayama. 26 April 2015 (USA). Netflix.
11. Fukuchi, K. and Jo, K. 2011. Laser Cooking: An Automated Cooking Technique Using Laser Cutter. Proc. 5th Int'l Conf. Tangible Embedded, and Embodied Interaction (TEI 11), ACM Press, 2011, pp. 163–168.
12. Ganglbauer, Eva, Fitzpatrick, Geraldine and Güldenpfennig, Florian. 2015. Why and what did we throw out?: Probing on Reflection through the Food Waste Diary. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15). ACM, New York, NY, USA, 1105-1114.
13. Gershenfeld, Neil. 2007. FAB: The Coming Revolution on Your Desktop—From Personal Computers to Personal Fabrication (New York: Basic Books, 2007) 3–27.
14. Gibson, Megan. 2015. Meet The Robot Chef That Can Prepare Your Dinner. TIME Tech Innovation (April 14, 2015). Retrieved March 20, 2016. http://time.com/3819525/robot-chef-moley-robotics/
15. Grimes, A. and Harper, R. 2008. Celebratory technology: new directions for food research in HCI. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '08). ACM, New York, NY, USA, 467-476.
16. Haeckel, E. 2008. Art Forms in Nature: The Prints of Ernst Haeckel. Prestel (August 25, 2008)
17. IBM Cognitive Cooking. 2014. IBM website. Retrieved March 30, 2016. http://www.ibm.com/smarterplanet/us/en/cognitivecooking/index.html
18. Jacobs, A. J. 2013. Dinner Is Printed. The NYTimes, Sunday Review. (Sept. 21, 2013). Retrieved March 21, 2016. http://www.nytimes.com/2013/09/22/opinion/sunday/dinner-is-printed.html
19. Jacobs, J., and Zoran, A. 2015. "Hybrid Practice in the Kalahari: Design Collaboration Through Digital Tools and Hunter Gatherer Craft." The 33th international conference on Human factors in computing systems (CHI '15). ACM, New York, NY, USA.
20. Jeannie. 2012. Designer Nori: Delicate Laser Cut Seaweed Patterns. JEANNIE JEANNIE blog. (Apr 13, 2012). Retrieved March 20, 2016. http://www.jeanniejeannie.com/2012/04/designer-nori-delicate-laser-cut-seaweed-patterns/
21. JPNews. 2009. Nagoya Robot Ramen. (July 31, 2009). Retrieved March 20, 2016. https://www.youtube.com/watch?v=5sVOSlUn7e0
22. Kira. 2015. 3Ders Monday Warm-up: The Top 3D Food Printers that will Feed the Future. 3ders website. (Nov 2, 2015). Retrieved March 20, 2016. http://www.3ders.org/articles/20151102-3ders-monday-warm-up-the-top-3d-food-printers-that-will-feed-the-future.html
23. Kroh, L. W. 1994. Caramelisation in Food and Beverages. Food Chem. 1994, 51, 373-379.

24. Lipson, Hod and Melba Kurman. 2013. Fabricated: The New World of 3D Printing. Chapter 8: Digital cuisine, P. 129 Wiley publications. 2013.
25. Losso, Jack N. 2015. The Maillard Reaction Reconsidered: Cooking and Eating for Health. CRC Press (December 4, 2015)
26. Lunven, P., Le Clement De St Marcq, C. 1973. Amino acid composition of hen's egg. Br. Jr. Nutr., 30, 189-194
27. Malmaud, J., Wagner, E., Chang, N., and Murphy, K. 2014. Cooking with semantics. In the ACL 2014 Workshop on Semantic Parsing, pages 33–38.
28. Myhrvold, N., Young, C., Bilet, M. 2011. Modernist Cuisine: The Art and Science of Cooking. The Cooking Lab; Spi Har/Pa edition (March 7, 2011).
29. NASA website. 2013. 3D Printing: Food in Space. (May 23, 2013). Retrieved March 20, 2016. http://www.nasa.gov/directorates/spacetech/home/feature_3d_food_prt.htm
30. PancakeBot. 2015. By StoreBound. Retrieved March 20, 2016. http://www.pancakebot.com/
31. Reaney, J. 2012. The Rise of the No-Choice Restaurant. Forbes Travel Guide. (SEP 26, 2012). Retrieved March 26, 2016. http://www.forbes.com/sites/forbestravelguide/2012/09/26/the-rise-of-the-no-choice-restaurant/#4c0308f25f0a
32. Reas, C., McWilliams, C., and LUST. 2010. Form and Code: In Design, Art and Architecture, A Guide to Computational Aesthetics. Princeton Architectural Press.
33. Rizzi, P. G. 1997. Chemical Structure of Colored Maillard Reaction Products. Food Rev. Int. 1997, 13(1), 1-28.
34. Sugiura, Y., Sakamoto, D., Withana, A., Inami, M. and Igarashi, T. 2010. Cooking with robots: designing a household system working in open environments. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10). ACM, New York, NY, USA, 2427-2430.
35. Sun, J., Peng, Z., Zhou, W., Fuh, J.Y.H., Hong, G. S., Chiu, A. 2015. A Review on 3D Printing for Customized Food Fabrication. Procedia Manufacturing, Volume 1, 2015, Pages 308-319.
36. Tang, Ming. 2014. Parametric Building Design Using Autodesk Maya. Routledge; 1 edition (February 15, 2014).
37. Tasse, D., and Smith, N. A. 2008. SOUR CREAM: Toward semantic processing of recipes. Technical report, Technical Report CMU-LTI-08-005, Carnegie Mellon University, Pittsburgh, PA.
38. Technovelgy website. 2006. AIC-CI Cookingrobot Chinese Robotic Chef. (October 16, 2006). Retrieved March 20, 2016. http://www.technovelgy.com/ct/Science-Fiction-News.asp?NewsNum=770
39. The Ripple Effect. 2016. Coffee Ripples website. Retrieved March 20, 2016. http://www.coffeeripples.com/
40. This, H., DeBevoise, M. 2008. Molecular Gastronomy: Exploring the Science of Flavor (Arts and Traditions of the Table: Perspectives on Culinary History). Columbia University Press (August 18, 2008)
41. Tomasik, P., Palasinski, M. and Wiejak, S. 1989. The Thermal Decomposition of Carbohydrates. Part 1: The Decomposition of Mono-, Di- and Oligo-Saccharides. Adv. Carbohydr. Chem. Biochem. 1989, 47, 203–270.
42. Van Boekel, M.A.J.S. 2006. Formation of flavour compounds in the Maillard reaction. Biotechnol. Adv. 2006, 24 230–233.
43. Vildjiounaite, E., Kantorovitch, J., Kyllönen, V., Niskanen, I., Hillukkala, M., Virtanen, K., Vuorinen, O., Mäkelä, S.M, Keränen, T., Peltola, J., Mäntyjärvi, J. and Tokmakoff A. 2011. Designing socially acceptable multimodal interaction in cooking assistants. In Proceedings of the 16th international conference on Intelligent User Interfaces (IUI '11). ACM, New York, NY, USA, 415-418.
44. Zoran, A. 2013. Hybrid Basketry: Interweaving digital practice within contemporary craft. In ACM SIGGRAPH 2013 Art Gallery (SIGGRAPH '13). ACM, New York, NY, USA.
45. Zoran, A. and L. Buechley. 2013. Hybrid reAssemblage: An Exploration of Craft, Digital Fabrication and Artifact Uniqueness, Leonardo, Journal of Arts, Sciences and Technology, Vol. 46, No. 1, 4–10 (2013).
46. Zoran, A. and Coelho, M. 2011. Cornucopia: The Concept of Digital Gastronomy. Leonardo, Journal of Arts, Sciences and Technology, volume 44, issue 5, October 2011, pages 425–431.
47. Zoran, A., Shilkrot, R., Nanyakkara, S., and Paradiso, J. A. 2014. "The Hybrid Artisans: A Case Study in Smart Tools." ACM Trans. Comput.-Hum. Interact. (ToCHI) 21, 3, Article 15. June 2014.
48. 3DS Culinary. 2014. 3DSystems website. Retrieved March 20, 2016. http://www.3dsystems.com/culinary