ChocoPen - Heated Desert Extruder

MMAE432 – Design of Mechanical Systems, Alpha Prototype Report

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***Abstract*— This report details the development of a handheld device used for heating and extruding food substances such as chocolate. A metal tube body with a nozzle, in the shape of a pen, is electrically heated to melt the food contents so that a plunger can move to extrude the now liquefied food. The user interacts with a force sensor for variable flow rate control as a DC motor actuates the plunger. Users indicate a desired temperature of the contents and a closed-loop control system ensures that the temperature is reached. The size and design of the device gives it functionality akin to writing with a pen, which can be useful for decorating deserts by drawing/writing with foods like chocolate.**

***Index Terms*—chocolate, desert, heated, food, extrusion**

I. Introduction

Artists of the culinary world have many mediums to work with and chocolate is a popular option for professionals and hobbyists. Chocolatiers, as they are called, work with chocolate to create elaborate decorations for deserts. In order to accomplish this the chocolate must be heated to work with, but caution must be made in how the chocolate is prepared. Chocolate is sensitive to the temperatures that it can experience as too high of a temperature can ruin the temper or even scorch the chocolate. Temper refers to how the chocolate is prepared for texture and stability with the crystallization of the fat content. Cocoa butter plays an important role in the texture and stability of the chocolate. Addition of milk fat for milk and white chocolates also factor into this. The ideal range to melt chocolate depends on the recipe. A milk chocolate and a dark chocolate have different fat and sugar contents, and for proper melting will need to reach different temperature ranges. In general, chocolate begins to soften above 85°F and melts above 90°F. Chocolates should generally not exceed 110°F or else they become lumpy and gritty as the moisture begins to evaporate [1].

Current methods to melt chocolate are somewhat crude and make temperature control difficult. The double-broiler method, where a bowl of chocolate is placed over a steaming pot of water for melting, is very common but offers little temperature control and has the risk of water entering the chocolate causing it to become unworkable. Microwaves are also common but give the user even less control over what temperature the chocolate reaches.

Once the chocolate is melted in order to effectively decorate with it, whether that be to draw or write, it will need to be transferred to another container/tool. A very common tool is a pastry piping bag. This gives the user great control over the piping of the chocolate, but has its fair share of flaws. If the user is working with a large batch of chocolate or if they need to leave the chocolate for any extended period of time, it will begin to cool and harden again. Reheating the chocolate once it is in the piping bag can be even more of a challenge. This method also requires the dirtying of additional kitchen items, or in the case of the piping bag it creates additional waste if the plastic bag is disposed of after use.

The ChocoPen is a proposed solution to make decorating with chocolate or other heated foods easier (see Fig. 1). Featuring controlled heating and extrusion in a single handheld device, the work of the professional and home chocolatier could improve greatly.

Figure 1 – Alpha prototype of the ChocoPen

II. Design process

For the purpose of marketability and scaling the product down for feasibility of design and construction by our team, the targeted audience for the ChocoPen was hobbyists and small businesses such as catering services. In order to be a device that improves the current processes for melting and working with chocolate we set out with a list of functional requirements that our design should meet.

- Must be able to heat contents up to 100°F
- Parts that come in contact with food must be food safe
- Can extrude as a volume flow rate of at least 1 cm^3/s
- Can hold at least 8oz of food by volume
- Must be operated by user's hand
- Parts that come in contact with food must be removable for cleaning
- Product size must be limited to under 1 ft^3
- Alpha prototype development budget of $800.00

We identified the critical functions that our device would need to prove feasibility of first. These were a mechanical system to extrude the food content and a controlled heating of the food. Without both of these aspects in the design, we felt that our product would not combat the difficulties associated with current chocolate decorating techniques.

Focus was first put on the extrusion system, and the development of a sketch model concentrated on this. Several methods for extrusion systems were considered. Mechanisms that included rollers to squeeze the food, a syringe style plunger, or even squeezing by hand were the mechanically simplest ideas. Others included using a pressurized air system for extrusion or a pump such as a peristaltic or progressive cavity pump. As we felt the product should be easily maintained and operated, the simpler mechanical systems were favored. For the first sketch model of the extrusion system a threaded rod held internally within a main tube body was used. The threaded rod was coupled to a motor that would spin to push a plunger piece down the tube, as it had its own threading to move down with.

Figure 2 – Sketch model featuring the threaded rod extrusion

The sketch model did not yet have a heating system so tests with foods like chocolate that would melt and harden again upon cooling were not tested. However, it did successfully extrude already liquid foods such as ketchup (see Fig. 2).

Another feature of the sketch model included the removable pastry tip operation. Pastry tips that are already commonly available in a number of hole sizes and designs were interchangeable, and many home cooks or professionals would already have a set that they could use to their liking.

The sketch model design process also allowed us an opportunity to better understand what the scale of our device could be. We already had the functional requirement of being able to hold 8oz of food in place, and being able to have the user operate the device by hand might have become an issue. Working with cheap materials like the PVC pipe for the tube body made it much easier to see and understand the scale we were actually working with, instead of relying on numbers on paper. While the sketch model did not include a full electronics system, other than batteries to power the DC motor for extrusion, it made us address the challenge of how to package the electronic components. Thought was given to have them all packaged onto the body of the handheld section of the device, but for the functionality that we wanted it quickly became apparent that it would not be feasible. The handheld size and weight of the sketch model handheld portion was deemed desirable and we did not want the inclusion of electronics to degrade the handheld functionality.

While the threaded rod extrusion worked for ketchup, in anticipation that hardened chocolate within the threads of the rod would prevent operation, we opted for a rack and pinion extrusion method for the next design iteration. The rack design has the advantage of never having the gear pieces come in contact with the food, but the rack on full retraction of the device does protrude from the back end. A motor is held in place in a plastic housing piece that guides the rack to remain straight (see Fig. 3).

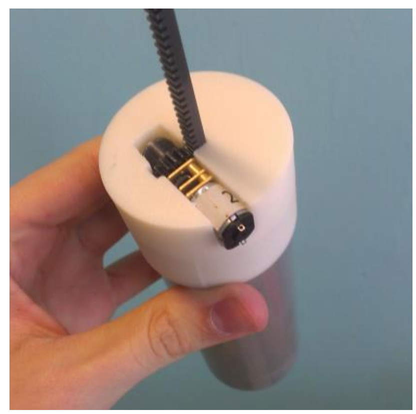

Figure 3 – Early iteration of motor housing design

An aluminum body was chosen because of the need for heat conduction, machinability, weight and durability. Aluminum was readily available to us for construction and came in raw material sizes/shapes suitable for easy machining. The plastic motor housing was 3D printed with acrylonitrite butadiene styrene (ABS) plastic since it is a common material for 3D printing and has a higher melting temperature than the other commonly used polylactic acid (PLA) plastic. Since the motor housing would be in contact with the warm body tube and would undergo stresses from the motor, we wanted the plastic to remain strong even when heated. Heating options that were considered included off-the-shelf electric heating pads, customized configurations of heating wire, ceramic heating cartridges, or separated heating elements that heated fluid such as a fan blowing warm air over the food or heated water flowing through tubes. Again, for the sake of easy operation and maintenance the simplest option of off-the-shelf heating pads were implemented. To generate heat a voltage is applied to the heating pads and the high resistance of the internal wires generate heat. Their flexibility allowed them to be wrapped around the outside of the tube for good surface contact. Two heating pads with dimensions of roughly 5cm by 10cm were used in parallel and wrapped lengthwise with the tube body [3].

To actuate the motor when the user commanded it, a force sensor was used in the electrical control. The user pushes on the location of the force sensor with varying pressure to change the rotational speed of the motor, thus controlling the flow rate of the food extrusion.

A temperature sensor is held against the outside surface of the tube body in an attempt to read the temperature of the device and the food content. This allows the user to know what temperature their food reaches and is critical into the design of the thermal control system to prevent overheating.

A 12V DC transformer power supply was chosen for the sake of having an operating voltage for the heating pads to reach a high temperature and for the DC motor to have high torque. The control of the electronics is done with an Arduino Uno microcontroller which can operate off of 12V and also provides 5V lines to the other electronic components (see Fig. 4). The microcontroller is programmed to read an analog signal from the force sensor and convert that into an appropriate pulse-width modulated (PWM) signal of a metal–oxide–semiconductor field-effect transistor (MOSFET) that we have connected to act as a switch to connect the motor to ground. The higher the user presses the force sensor, the higher the duty-cycle (DTC) the motor experiences of 12V thus increasing the rotational speed and peak torque. A current sensor was installed to read the current that the motor draws. If the chocolate is not yet melted and the user tries to extrude the chocolate the motor will stall because it cannot provide enough force to extrude still solid food. A stalled DC motor that is provided a continual high voltage has the potential to overheat and become damaged. A current sensor is used to read when the current of the motor peaks during stall and shuts it off to prevent burnout.

A PWM controlled DTC is also implemented for the heating pads. The user sets a desired temperature that they want the system to reach by adjusting a potentiometer knob, this is dependent on the type of chocolate that they are using. An LCD is used to display the temperature that they are setting as well as the current temperature of the system that is measured by the temperature sensor. We have implemented a closed-loop proportional-integral-derivative (PID) controller to manage the temperature of the device. We have the PID gains set to 5, 0.1, 0.1, respectively. The control system changes the DTC of the heater's PWM signal that is used with a MOSFET as a switch to connect the heating pads to ground. The higher the DTC the higher temperature the heating pads will eventually reach. The heating pads supplied with constant +12V power supply can reach temperatures exceeding 200°F, and the PWM control implemented in the design provides temperature control to limit their operating range from 70°F to 110°F.

Packaging of the components proved to be one of the biggest obstacles in putting together the alpha prototype of the ChocoPen. The challenge presented itself in needing to make the design allow quick and easy disassembly for cleaning.

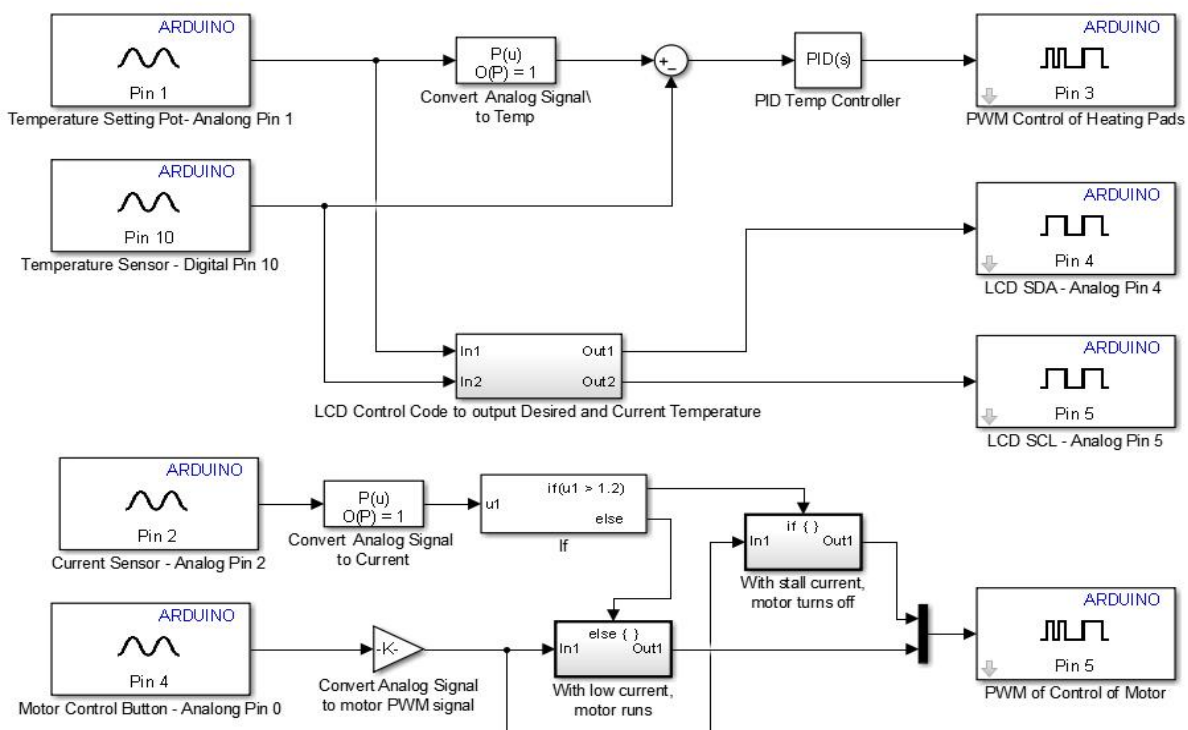

Figure 4 – MATLAB Simulink model of the Arduino control system

Three main section of electronics were identified: the electronics control box, motor housing, and components attached to the tube body. The electronics control box housed the power supply, microcontroller, and user interactive components like the LCD display of temperature settings and the temperature setting knob. The motor housing contains the motor, guides the rack gear, and is also the end cap of the tube. The electronic components on the tube include the heating pads, force sensor, and temperature sensor. Since there needs to be wired connections from each component back to the electronics control box and the motor housing should be removable for cleaning, a connection port needed to be designed for the components on the tube body. A wire connection from the tube to the motor housing was implemented, and then the wires connected to the motor were consolidated together into one bundle of wires sent back to the electronics control box.

The final design of the tube body features a silicone coating that serves multiple purposes. First it holds all of the electric components in place, protects them from damage, and waterproofs them during washing. Before coating in silicone all of the electronic components of the tube body were held in place with Kapton tape (see Fig. 5). Second it offers a comfortable material for the user to hold onto. And with silicone being an excellent insulator, this layer protects the user's hand from the high heating pads temperatures and keeps the tube and food warm for longer periods of time.

Figure 5 – Tube body with electric components taped in place before silicone coating

III. Analysis

While a lot of the design choices were implemented because they were quickly identified as the best option other elements were analyzed or changes were made by trial and error.

The original dimension of the sketch model had a 2in outer diameter which held enough chocolate for our 8oz functional requirement but was uncomfortable for some to hold and took an extensive amount of time to heat all of the chocolate. If children would be using this device alongside adults, the form factor needed to be shrunken a little. An even greater concern with a large diameter tube is the time it took for the chocolate to warm up. The issue is not with getting the tube itself to heat up as the metal body conducts heat from the pads very easily, the issue is with how long it takes for the entirety of the internals to heat up. The chocolate in contact with the walls heats ups nearly as fast as the tube itself, but the chocolate in the middle relies on conduction from the rest of the chocolate. We ordered a number of aluminum tubes with different outer diameters to experimentally determine how the size affects the time to melt with the theory that a smaller diameter would heat chocolate at a higher volumetric rate since the distance from the chocolate in the center to the walls is smaller. Table I shows the results from testing 4 6in long tubes with different outer diameters and measuring how long it took for the chocolate inside to reach a soft, workable state.

TABLE I – Testing chocolate melting times with different Al tube diameters

Aluminum tube sizing changes on time to melt chocolate				
Outer Diameter (in)	Inner Diameter (in)	Inner Cylinder Volume (fluid oz)	Time to melt (min)	Time/Volume (min/oz)
1.25	1.12	3.27	4	1.22
1.5	1.37	4.90	6	1.23
1.75	1.62	6.85	10	1.45
2	1.87	9.13	15	1.64
Heating done with 70% DTC of heating pads 12V power				

From these results we decided to go with the 1.5in outer diameter tube. There was no noticeable performance change dropping down to 1.25in diameter and 1.5in along with the extra thickness we will have with the electronics and silicone will result in a more comfortable size for holding. This came with a drop in capacity but still had an improved time/oz heating capability. Even if someone wanted to heat 9oz of chocolate, two batches in a 1.5in diameter tube would heat faster than 1 batch in a 2in tube. We also made sure that our plunger concept would move all of the chocolate inside of the tube. A plastic disc covered in a rubber cap piece was used as a plunger and proved effective enough to move all of the chocolate through the tube except for what was caught in the tube's imperfections (see Fig. 6).

Figure 6 – Internal view of tube after chocolate extrusion

From our experiences with testing extrusion through an un-machined tube, with the end caps just be attached through a snug friction fit we figured out that the end caps of the tube would need to be threaded into place. This is to securely attach them and to prevent leaks. The motor provided enough force against the chocolate, especially when not melted, to push the motor housing piece off the back. Having the housing attached with threading prevents this.

The interchangeable pastry tip design that was implemented with our sketch model was not continued into the alpha prototype. The reason for this was due to the tip not heating well enough for the chocolate sitting in the tip to melt. Pastry tips are rather long and in our design the farther away a component is from the main tube body, the longer it would take to heat up since it would rely on conduction from the tube body. The long pastry tip would not warm up through conduction as is needed for our design. The proprietary threaded nozzle design was done to ensure no leaking and to provide a larger thermal mass to the nozzle so the exposed metal would not cool as fast.

Some tuning of the PID control system was done, but not to the full extent that it could have been. Since the tube takes some time to heat up in testing and to do numerous trials also requires cooling down, fine tuning of the PID was not completed. We did reach the state of our current system which does not overshoot the temperature but tends to have an offset error a couple of degrees below the desired temperature.

IV. RESULT

In the end, a device was made that successfully heats its contents, can extrude chocolate that is fully melted, and it easy to operate and clean. The setting limits that the user can set the heating pads for are from 70°F to 110°F, preventing the possibility of scorching. Overheating the chocolate to the point of ruining the temper would result only from user error of setting the temperature too high for the specific chocolate they are using. Variables of the amount of food, size of the food pieces, and desired temperature affect the time it takes for the food to melt for extrusion. For store bought semi-sweet chocolate chips that were used for testing purposes, at full capacity the time it took for heating was between 15-20 minutes. The extrusion with a rack and pinion design featuring a geared hobby DC motor for high torque successfully extrudes chocolate at a flow rate higher than 1 cm^3/s and the force sensor PWM control gives the user full control over the flow rate. This control of the extrusion allows for great control to draw or write designs in chocolate or other extruded foods (see Fig. 7).

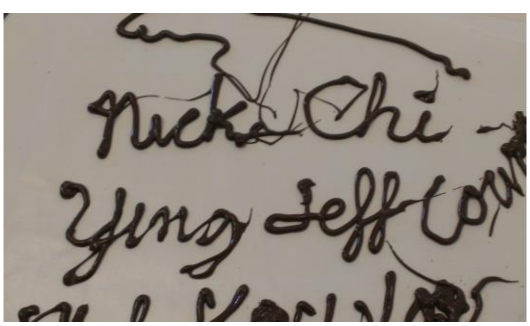

Figure 7 –Writing examples with chocolate

The design can be fully disassembled to clean the parts that come in contact with the food content, and all of these parts are food safe (see Fig. 8). The ChocoPen is also designed so the user can operate with one hand safely and comfortably.

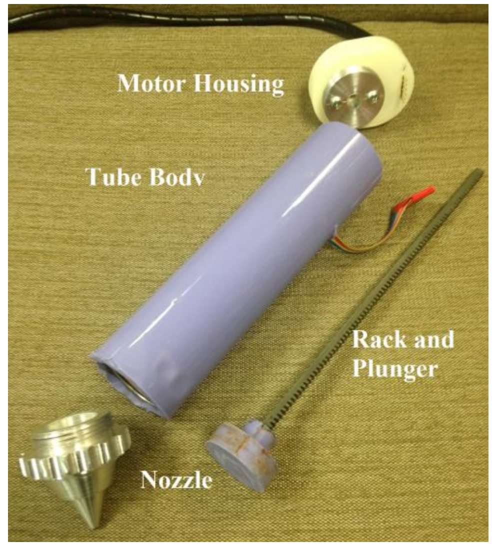

Figure 8 – Disassembled handheld ChocoPen section

V. DISCUSSION

There are a lot of great successes from the development of this heated food extruder design but has its fair bit of issues that have still not been addressed.

The extrusion of the food works well as the motor we have chosen can provide torque up to 70oz-in when operating at 12V [3]. This seems to be more than enough torque to extrude the chocolate in a uniformly heated and melted state, but not enough to push semi-solid pieces through the nozzle. The caveat with this being that the motor will stall when the food is still not liquid enough for extrusion. The current sensor that is installed in the system to stop the motor when it stalls is just a quick fix to the issue. The code implemented with the microcontroller stops the motor and will only start it again after the user has released their finger from the force sensor. This does protect the motor, but due to strange behaviors in the current signal even a very quick peak in the current reading will stop the motor and force the user to release the button. In doing detailed drawing work this could become a nuisance. Installing a different motor like a stepper motor may prove useful as they can provide higher startup torques than a DC motor.

Heating of the system still takes much too long for this to be a truly viable product for a chocolatier of any level. At 15-20 minutes of heating time, the double broiler method of heating and a piping bag still provides a faster method to begin drawing with chocolate. It is the chocolate in the center of the tube that does not heat quick enough, as the chocolate in contact with the sides heats nearly as quickly as the tube itself. Having a mechanism to stir the chocolate on the inside while heating may improve heating times. The heat cannot simply be turned up to max for the chocolate in the middle as the chocolate on the sides would experience those elevated temperatures directly, possibly scorching it. The space between the chocolate is the main issue with having the heat conduct throughout. The smaller the chocolate pieces are, the more contact there is between them, and the faster it would all reach a point of melting. Something that was discussed, but never tested was having a pre-molded solid chocolate cylinder that is inserted into the tube for extruding. With a single solid piece the heat would conduct through the entire piece and in theory could be faster than many pieces of chocolate like the chips that we have been using in all of our tests.

This issue of heating is also problematic in how the user interacts with the system. Currently the user can read the current temperature reading on the LCD, but this is the temperature of the metal tube body and not of the chocolate itself. Without trying to run the motor, the user cannot know whether or not the chocolate is ready for extrusion. We considered an indicator light that would go off after a preset time that we could figure out empirically but there are too many factors involved to determine a reliable timeframe. The amount of chocolate, type of chocolate, size of the pieces, and the desired temperature would all be variables in determining the time it takes for the chocolate to be soft enough for extrusion so trying to figure out a time for the chocolate to be homogenously heated would prove futile. The only part that reaches the center of the tube at this time is the plunger, perhaps a temperature sensor can be implemented in some way on the chocolate facing side of the plunger in an attempt to read the chocolate's temperature.

There is a lot to be desired for the aesthetics of the product as well. The wires from the tube body to the motor housing are gaudy and not user friendly since there is potential to plug it in backwards. A keyed port connection such as a USB would be ideal, but due to the high electric currents needed by the heating pads larger wires are needed than found in conventional cables. In searching for readily available components, no wire connectors for our needs came up so we improvised with prototyping jumper wires. The silicone was the only one available to us at the time and comes as a lavender purple color, but dyes could be added or a different brand of silicone used to change the color. Due to our limited knowledge in working with electronics we opted to use off-the-shelf products like an Arduino Uno and a full power supply so the electronics control box could be downsized greatly.

In order for this device to be a viable product for a chocolatier the cost also has to be considered. The cost for producing this one prototype is around $150 without labor costs. If brought to a production scale for mass manufacturing there are a lot of areas for cost savings compared to producing a one-off product. Buying electronics in bulk and as individual components to be assembled on custom circuit boards would save money. The plastic components could be injected molded for large quantity production. The rack and pinion pieces were expensive as they are made from metal, but plastic components should be suitable for the loads that they experience. Machining of the aluminum components could be automated on CNC equipment to minimize labor costs as well. We believe that the selling price point of this product can be brought some point below $100 when on the market at large scale production.

VI. Conclusion

The final deliverable product that is featured in this report is a functioning pen style extruding device suitable for food applications. The heating control system is designed to heat chocolate within the desired temperature range for melting without overheating, but other foods can certainly be used as well. Other foods that would need heating such as butterscotch chips would work, and other foods like frosting that do not require heating may be extruded with this device too.

There are many improvements that can still be made to the design in order for it to be a viable replacement to current chocolate working methods. Taking up to 20 minutes for chocolate to become heated for extrusion does not save time, especially with the volume sacrifice that was made in the design for the sake of ergonomics. The main benefits of this product are the ability to set it up to start heating and being able to leave it alone and that it limits the number of items being dirtied for the chocolate work. The user can go on and do other things while they wait for the chocolate to melt without needing to worry about overheating thanks to the thermal control system. Since the heating and extrusion systems are contained in this one product packages, no additional kitchenware items are needed for something like desert decorating. Many aesthetic improvements can be made and would be completed when preparing the design for the sake of manufacturability. Electronics packaging, especially in the electronics control box, can be revised with smaller components and more efficient space management.

The alpha prototype of the ChocoPen features several innovative designs to challenge the conventional methods of heated food extrusions, like chocolate desert decorating. While the current iteration solves some of the issues with conventional methods such as overheating of the food or having the food cool down while working with it, the prototype presents some of its own issues like the amount of time it takes to heat chocolate to the point of melting.

Acknowledgment

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