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M&T Integration Lab
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Executive Summary

Overview
Orble is a customer-facing automatic bubble tea machine that offers establishments the chance to offer dozens of boba beverage options with the tap of a finger and the footprint of a soda fountain.

The Product
Orble is a free-standing beverage dispenser for large institutions and independent retailers to increase accessibility to a highly-demanded product currently only offered at limited locations. This machine enables a custom “grab-and-go” boba experience for consumers while our merchants are able to easily monitor real-time drink inventory levels, machine health, and track top sellers from our high-tech diagnostic dashboard. The machine has the capability to store and cook boba pearls, craft drinks with personalized sugar, creamer, and tea levels, and seal the cup right in front of the customer.

Orble challenges all of the assumptions bubble tea machine manufacturers make when designing their products. Store-bought bubble tea currently requires an amalgamation of machines for drinks to be made at a consistently high quality, and the stovetops, mixers, and sealers each require their maintenance, repair, and care. Shops employ a conveyor belt model, where an employee performs a series of sequential tasks while moving from one machine to another, and machines are optimized to be easily operated by employees and perform one step of the bubble tea making process. Orble’s compactness increases efficiency as processes would be able to work concurrently. Components would be fixed and require little movement, resulting in fewer chances of spillage and errors, and restocking of raw ingredient inputs and cleaning would be more streamlined, as they are all input into one unit. However, automation is secondary to the true value add, which is increasing accessibility to a popular food product by increasing affordability and expanding to areas where fresh and good-quality bubble tea cannot be reliably bought. Orble will ensure that bubble tea production will no longer be limited to stores that have invested in ample real estate, high labor costs, and unique, expensive equipment.

The Team
The team is composed of Esther Amao, Sophia Anzai Takahashi, Lada Korotaeva, Nastassja Kuznetsova, and Sarah Tadlock and is advised by Professor Mark Yim. On the technical side, this solution consists of mechanical components integrated with sensors, actuators and microcontrollers to control and execute the flow of action. The founding team consists of three mechanical engineers with experience in fluids, thermodynamics, material selection, CAD, rapid prototyping, and precision-machining, and two computer engineers with experience in hardware/software integration, power and space management, circuit analysis and testing, embedded systems and software development. From a business perspective, one of the Co-Founders is currently in the Jerome Fisher Management and Technology Program, housed in the Wharton School and School of Engineering, and brings business acumen, knowledge of market-driven approaches to selecting target audiences, and business strategy knowledge.

The larger Orble team also has four other team members focused on 1) web development, rendering and marketing, 2) market research and customer validation, and 3, 4) UI/UX and customer experience.
The team is primarily advised by Professor Mark Yim, who leads the GRASP Lab at the University of Pennsylvania, focusing on robotics, sensing and automation, and Professor Jacqueline Kirtley, a researcher at the Wharton School whose research focuses on the ways strategy and technology evolve in early stage entrepreneurial firms developing revolutionary and disruptive technologies.

The Market
While globally the boba market has a 7.2% compounded annual growth rate, Americans are hopping on board much faster: according to an annual GrubHub survey, searches for “bubble milk tea” was the second-fastest growing term on the platform during the first half of 2021, with an increase of 505%. Furthermore, self-service and food automation technology, which includes kiosks and vending machines, is also on the rise and is projected to grow by $19.2 between 2019 and 2027. Orble is uniquely positioned to increase accessibility to bubble tea to consumers and tackle an unmet part of the market; businesses who want to provide bubble tea in their establishments but currently do not have the space and capital to do so. Orble has particular customer interest across the University and Office space customer segment, which was verified by over ten customer validation interviews through the Penn I-CORPS Program.

Competitive Advantage
As a management team composed of Co-Founders with deep engineering knowledge, the expertise needed to design and build this machine is a significant barrier to entry. The team is positioned to innovate and tackle difficult engineering problems related to automating and streamlining the bubble tea-making process.

Orble is currently part of the Detkin Intellectual Property Technology Clinic (DIPTC), which provides pro-bono transactional patent, copyright, trademark, trade secret and privacy counsel to a variety of clients. This report detailing prior art and freedom to operate discovery will allow us to move forward with IP. Orble is currently in discussion with the legal counsel about provisional patent plans. Components of the machine are particularly innovative and will act as barriers to entry for competitors.

Financial Projections and Requirements
Orble is currently pre-revenue and will be through 2023. Orble will use 1) machine leasing and 2) ingredient supply as primary revenue drivers. Orble estimates that it will generate $50 thousand in revenues in 2024 and $3.7 million in 2025. Orble intends to raise $1.5 million to continue product development, retain certification and permits, and successfully bring the product to market.
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Section I. Introduction

Market Research
Originally a drink from Taiwan, boba has grown in popularity over the years. In 2019, the global bubble tea market size was at 2.4 billion USD, with a projected growth to 4.3 billion USD by the end of 2027 [1, 2]. This exhibits a CAGR of 7.2% [14]. Boba tea has especially had high growth of attractiveness among younger customers, such as teenagers and college students, known as a drink that can be easily customized to fit a variety of flavor profiles. In Southeast Asia, bubble tea demand recorded a 3000% increase in 2018 alone - as data revealed that the average person living in this region is responsible for drinking four cups of bubble tea per person per month [15]. Stateaside, this boom is well on the upswing and fueled by younger consumers. According to GrubHub’s annual survey, State of the Plate, searches for “bubble milk tea” was the second-fastest growing term on the GrubHub platform during the first half of 2021, with an increase of 505% [16]. The self-service market is also increasing rapidly and will reach 47.5 billion dollars by 2027, and food automation is growing globally [17].

Yet, in an era with endless methods to acquire comparable beverages like coffee or soft drinks, the only way of buying a pre-made drink today is by placing an order in a brick-and-mortar establishment. This limitation on boba availability leads to a high price per cup, with much of that resulting from storefront rent and costs, expensive specialty equipment, and barista labor associated with crafting each drink [3]. The costly overhead necessary to set up shop limits opportunities to bring in affordable, high-quality drinks to high-traffic areas. Bubble tea production methods cannot currently keep up with exploding consumer demand and a reduction in the production constraints will increase accessibility and open up new markets [4].

Value Proposition
Orble is a free-standing beverage dispenser for large institutions and independent retailers to increase accessibility to a highly-demanded product currently only offered at limited locations. This machine enables a custom “grab-and-go” boba experience for consumers while our merchants are able to easily monitor real-time drink inventory levels, machine health, and track top sellers from our high-tech diagnostic dashboard.

This machine challenges all of the assumptions bubble tea machine manufacturers make when designing their products. Store-bought bubble tea currently requires an amalgamation of machines for drinks to be made at a consistently high quality, and the stovetops, mixers, and sealers each require unique maintenance, repair, and care [3]. Shops employ a conveyor belt model, where an employee performs a series of sequential tasks while moving from one machine to another, and machines are optimized to be easily operated by employees and perform one step of the bubble tea making process. Orble’s compactness increases efficiency as processes would be able to work concurrently. Components would be fixed and require little movement, resulting in fewer chances of spillage and errors, and restocking of raw ingredient inputs and cleaning would be more streamlined, as they are all input into one unit. However, automation is secondary to the true value add, which is increasing accessibility to a popular food product by increasing affordability and expanding to areas where fresh and good-quality bubble tea cannot be reliably bought. Orble will ensure that bubble tea production will no longer be limited to stores that have invested in ample real estate, high labor costs, and unique, expensive equipment.

With a touch of a button and the footprint of a soda fountain, Orble lets users order and receive a personalized and consistently delicious drink in minutes. Our solution, Orble, is a commercial automated bubble tea machine that can be installed anywhere cold water, waste lines, and electrical services exist. The machine is compact with a footprint of just 1x1m and the height of 1.7m, requires only three hours of service a week, and serves drinks in 3-5 minutes. Orble will conduct the full bubble tea production
process including (1) storing and cooking desiccated boba pearls, (2) mixing customizable drinks from various powdered ingredients, (3) dispensing a cup upon payment, and (4) dispensing the boba pearls, the mixed liquid and ice into the cup.
Section I.X: Social Impacts of Solution

Orble is a timely innovation in the food automation industry. With ventures like Mezli, Stellar Pizza, and Bobacino gaining traction and funding, Orble seeks to contribute to this space with a popular, accessible offering. Orble’s small footprint and low maintenance makes it a convenient option for indoor installation.

The team also envisions novel methods emerging from designs based on Orble’s needs. For example, automating the boiling process for desiccated tapioca pearls has yet to be meaningfully replicated. Rapidly heating large volumes of water to boiling temperatures with short turnaround is a challenge. Relying on gravity, rather than excessive peristaltic pumps to quickly transport food components is another area for food automation improvement.

Orble is excited to tackle the many unique engineering problems that arise from automating a brick-and-mortar, labor-intensive process. Moreover, Orble is dedicated to rapidly designing and prototyping a minimum viable product that is crafted with critical safety standards and compliance in mind.
Section II. Characteristics and Constraints

Characteristics and constraints of the machine are demanded by certain stakeholder needs (Section II.X). The objective of Orble is to fit into already existing workflows and operations, to allow for ease of use and understanding of the machine.

Machine Characteristics
I. **Compact**: Boba accessibility has not grown to sufficiently satisfy increasing demand. This is partly due to high overhead costs like rent and counter space that traditional boba shops encounter. These restrictions have limited the number and location of boba shops. Orble's compact vending machine footprint increases the accessibility of boba to areas that can support existing vending infrastructure.

II. **Fast and Accessible**: Boba shops often include a visual experience of witnessing baristas quickly prepare beverages, though often this comes with a wait time. Customers have to walk to their nearest boba tea store, which can be far away, depending on the area. Orble's machine can be installed anywhere, therefore increasing accessibility to the drink. The machine incorporates a vertical process, allowing multiple inputs to be made concurrently, making the overall drink-making process fast and easy for the customer.

III. **Ease of Installation and Maintenance**: Orble requires only a water source, a standard outlet, and a waste line to function. Installation is easy and fits easily into pre-existing installation workflows in establishments. Parts are easy to remove for replacement of singular parts and manual washing if necessary. This makes Orble easy to maintain.

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<th>Table 1: Machine Characteristics</th>
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Primary system characteristics are related to the size of the machine. In order to fit into existing maintenance workflows, subsystems requiring re-stocking need to be easily accessible, and should have the capability to be refilled once every 24 hours. Subsystems direct to food should be easily detachable for manual cleaning when necessary. Waste lines need to be easily accessible and at least 3 ft long to interface with pre-existing waste line infrastructure in buildings [13]. Water entering the machine has to be potable.
Section II.X Stakeholders, Business Model, Intellectual Property

Stakeholders
Throughout the project timeline, Orble has also conducted stakeholder outreach across several segments and markets. In the Fall of 2022, conversations were primarily focused on understanding the market and the needs and specifications of currently existing complementary products. Interviews with 1) facilities owners and managers, 2) food automation companies, 3) food and health industry experts and 4) boba market experts were conducted to understand the general food and beverage industry and bubble tea market. Conversations with facilities owners and managers, allowed us to analyze current industry standards regarding distribution. Buildings and large establishments primarily use vending machines and other food distributors to provide food and beverage services in their buildings. Design considerations such as dimensions, access to resources (water, waste line, power) and maintenance logistics were learned and considered in our design. We have spoken extensively with other food automation companies and bubble tea shop owners in order to determine standards related to machinery and cleaning, along with exploring the current customer base and standard business models for similar technologies. Conversations have given us insight into when to initiate conversations with health and safety regulators, understand the extent of current existing technologies, and observations on how to approach difficult engineering problems such as cleaning and frequency re-supply. Food and health industry expert discussions have been held in order to gauge applicability of regulations to our machine and the nuances that come with food automation.

Market Characteristics and Customers
Orble's primary customer segments can be split into two groups: large establishments and independent retailers. Large institutions include establishments such as offices, University buildings, and community centers that can either offer the machine as a complimentary amenity where the self-serve machine will not have an integrated payment system, or as an additional earnings for organizations who are interested in charging a fee per cup. Orble's second group of customers are smaller retail locations such as movie theaters, mall kiosks, apartment complexes with lobby beverage amenities, and convenience stores. These clients already employ hourly employees to service existing machinery and would not be interested in a leasing plan that involves third-party servicing. Both of these groups have similar particular characteristics and constraints that have to be fulfilled by the design of the machine.

Competition
Orble will complement other vending machine beverage products such as coffee vending machines and Cola Freestyles, allowing merchants to diversify their drink offerings. Our biggest competitors are the existing channels of purchasing a boba drink for the average consumer: going to a boba shop, or taking the time to make it at home. Specifically for boba shops, variability and quality with the drink, along with quick service, are primary reasons why the current channel is popular. Though lack of convenience (having to go to the store) and price are large pain points for customers that would be solved via an automated bubble machine solution. Currently, there are also emerging technologies that are looking to innovate the boba tea industry. Several early stage startups in the space have created robotic tea bars consisting of a robotic arm that navigates around a small booth to grasp and position a cup beneath various off-the-shelf machines like sealers and ice dispensers. These companies are selling the novelty of witnessing a robot create a drink, leading to an expensive upfront cost and complicated maintenance procedures. These robot arms serve as connectors between existing machinery, failing to challenge the status quo, which is the belief that the best method of making a tea drink is exactly the way a human would. We contend that these companies have misidentified consumer needs: boba drinkers want good
quality boba tea in a timely manner, and currently these robot machines serve as purpose of entertainment, with incomplete reliability.

**Cost**
The current major sources of cost of technical development and prototyping (R&D), as current design iterations of the machine require food safe components, materials and parts. Though, these R&D costs will be concentrated in the early development phases of our machine. Other costs we foresee are minimal labor costs associated with machine ingredient delivery and re-supply, along with periodic maintenance over the machine lifetime.

**Revenue Model**
Orble will follow the industry norm with respect to retaining revenue. For larger established institutions such as Universities, co-working spaces and chain movie theaters, multiple units of the machine will be leased across several locations. Ingredients and re-supply will be automatically re-ordered by lessees through Orble. Installation and maintenance would be taken care of by Orble during the leasing period. For smaller establishments and individuals, such as convenience stores, recreational spaces and family-owned shops, merchants can one-time purchase the machine. Installation will be owned by the merchants with additional maintenance fees should they prefer to have repairs done by Orble. We will partner with ingredients suppliers to provide our machines with consumable inputs, enabling a streamlined supply chain. We also are currently looking to partner with a vending machine supplier company, such as Canteen, where our machine could be incorporated into their catalog and accounts.

**Intellectual Property**
Orble is currently provisional patent filing in July 2023. Intellectual property support has been provided by the legal counsel team at the Detkin Intellectual Property Technology Clinic (DIPTC), housed in Penn Carey Law. DIPTC provides pro-bono transactional patent, copyright, trademark, trade secret and privacy counsel to a variety of clients. This report has detailed prior art and freedom to operate discovery which will allow us to move forward with IP. Components of the machine are particularly innovative and will act as barriers to entry for competitors.
Section II.XX Design Impact of Standard

Orble prioritizes seven standards for safety in the realms of food and water handling and electrical management. While the full model is still in development, the team has made design decisions informed by several standards and numerous stakeholder conversations.

**NSF/ANSI 51/61** [5]

NSF Standards 51 and 61 relate to food equipment materials and drinking water system components, respectively. These standards impact materials and finishes in components that come into contact with food or water. These include tubing, pipes, fittings, valves, and sealing among others. These standards are often grouped together when certifying individual materials. Orble is exclusively using NSF 51/61 certified high-temperature silicone tubing. This tubing transports all of the powdered and liquid components throughout the subsystems. These standards also guided expensive prototyping decisions like valve selection. Although not all of the twelve valves currently used in the assembly are not NSF 51/61 certified, the team used stainless steel valves to be mindful of the ideal, albeit more expensive, final form.

**NSF/ANSI 18/25** [6] [7]

NSF Standards 18 and 25 are pertinent to food and beverage dispensing equipment. This impacts material selection, component design, and construction requirements for equipment or devices that dispense food or beverages in portions or bulk. The sole difference between NSF 18 and NSF 25 is that NSF 25 pertains specifically to vending machines, or equipment that accepts payment. For example, a breakroom Bunn coffee machine that is open to use for all employees falls under NSF 18. However, a chips and candy vending machine that accepts cash, coins, credit cards, or virtual payments is classified under NSF 25. Even if they dispense the same products, the standards differ on the lines of accepting payment. The equipment must still be manufactured and inspected to NSF standards. Presently, Orble could fit into either category depending on the installation location and business needs for that customer. To obtain this certification, Orble would need to have an NSF consultation session and fully manufacture a machine [8]. From there, the NSF would tour the manufacturing facility and then rigorously test the machine before granting certification [8].

**Philadelphia Department of Public Health Office of Food Safety** [9]

To operate in the City of Philadelphia, food vendors need approval from the Office of Food Safety, within the Department of Public Health. The Office requires vendors to submit a plan for review and approval before operation may begin. Before the Office will consider reviewing a plan, the equipment must already be NSF certified. Whomever is operating the machine must submit the plan and bear responsibility for its products. For Orble, this could mean having direct liability for the machine, or having that responsibility passed to a business or individual who operates and maintains the machine independently from the original manufacturer.

**NEC 422.51** necessitates the usage of a GFCI in our electrical design as a safeguard in the event of electrocution [10]. This is very important due to the system’s high power requirement as well as the presence of water in the machine.
IEC 60335-2-75:2012 requires that the machine be rated below 250V as a single phase dispensing appliance [11].

Additionally, two Orble members are ServSafe certified, allowing them to work with food in commercial settings. The ServSafe certification examination tested team members on food safety, allergens, contaminants, kitchen practices, and general health information.
Section III. Design, Engineering, and Realization

Machine Overview
Orble is looking to build an automated boba vending machine dispenser, akin to the Coca-Cola Freestyle and other similar beverage dispensers such automatic coffee machines, that will plug into a standard outlet, create a variety of customizable boba beverages to-order, at a market-equivalent price point, and within the average crafting time of three to five minutes.

The automated bubble tea machine dispenser will look similar to a vending machine, except it will function to create a drink from start to finish, freshly made to a consumer's specifications. The machine will have the capability to (1) store and cook boba pearls, (2) mix drinks from various powders (including sugar, tea, and powdered creamer), (3) dispense boba pearls, the mixed liquid and ice into a cup, and (4) dispense the cup, ready for pickup by the customer. Essentially, this machine will automate the boba making process that is currently produced in boba tea stores.

The design features two parallel processes that share some elements while completing independent tasks. They are split between the Powder Chain and the Boba Chain. The boba chain streamline focuses on the boba pearl component of bubble tea drinks. It consists of the following sub-systems: the Dried Boba Storage (Fig 2.3), the Boba Cooker (Fig 2.4), and the Cooked Boba Storage (Fig 2.5). The dried boba storage stores desiccated (boba) tapioca pearls before they have to be cooked. When a batch needs to be cooked, it dispenses a predetermined amount of pearls into the boba cooker, where they are boiled until ready. After boiling is complete, the water is drained from the cooker and the boba pearls are moved into the cooked boba storage. Since the boba cooker cooks in large quantities, cooked pearls are stored in the cooked boba storage until a customer orders a drink. Once ordered, it will dispense the correct amount of pearls into the cup.

The powder chain streamline focuses on the liquid component of bubble tea drinks. It consists of the following sub-systems: the Powder Dispenser (Fig 2.1) and the Powder Mixer (Fig 2.2). Drawing from and heating up a common water source, powders drop from the dispenser container and mix with hot water to form flavorful tea. After the mixer has incorporated all the powders (sugar, tea and powdered creamer) into a homogenous mixture, the liquid is dispensed into a cup. Enough liquid is made for a single drink, and is mixed on an order-by-order basis.

The machine also includes other subsystems that will be purchased off-the-shelf and will integrate with the machine in the long-run. These are the manual cup dispenser, a cup sealer (similar to solutions used in stores), and an ice maker. Ongoing conversations are still occurring regarding our hot water source, which will either be custom designed or purchased off the shelf. The machine would be self-cleaning: the mixer would run cleaning after every order to ensure readiness for a new order using hot water. A full cleaning cycle with necessary sanitization would occur every few hours to ensure safety and health.

Fig 2. System layout, isometric view

Fig 3. Vertical dispenser: funnel and helix
**Powder Chain**

**Powder Dispenser**

The purpose of the powder dispenser is to (1) store powder ingredients such as sugar, tea and creamer, and to (2) dispense these powders into the powder mixer once the order is placed. Tea, creamer, sugar and flavor powders are to be stored in the machine and dispensed in necessary amounts when the drink is being made.

We have a custom design which features a large helical screw (Fig. 3, right) placed vertically in the center of a container. This screw is connected to a DC motor which, when powered, rotates the screw, enabling it to dispense a consistent amount of powder on each turn. At minimum, the lower levels of the container housing the powder will be shaped as a funnel feeding the powder into the screw, and the lowest part of the container will be a cylinder tightly hugging the screw (Fig. 3, left), so that no powder slips in between the helix and the walls, and the only way to dispense it further down is to turn the screw. The DC motor will spin the helix until enough powder has been dispensed, and turned off when not in use. The powder will be transported into the mixer via tubing, and valves that will be actuated to open when powder is required.

We also have a pre-made solution which is a hopper used in Bunn hot chocolate machines (Fig. 5). The hopper is a container with a wheel inside of it meant to keep the contained powder from clumping together. At the very bottom, the hopper has a spring which is powered by a motor. When the motor turns, the spring is compressed, resulting in powder being pushed out. The auger in the off-the-shelf design was replaced with a custom made helix (Fig. 4). This helix design has led to consistent output of powder per rotation, with $0.5 \pm 0.05g$. This hopper will be primarily used as the powdered creamer and storage solution, as its strengths are in dispensing large quantities of powder in a short amount of time. The vertical powder dispenser solution serves to better adhere to smaller quantities of powder, such as tea.

**Powder Mixer**

The powder mixer receives and mixes ingredients from multiple streams. This process forms the liquid component of the final drink. Pre-heated water at $60^\circ C$ enters the mixing chamber followed by tea crystals, powdered non-dairy creamer, and granulated sugar from the powder dispensers. Dispensing the water prior to powders minimizes clumping. The team consulted the Food Innovation Lab’s Kitchen Manager Lauren Hooks for the dispensing order, and conducted experiments with the same immersion blender. The current mixer design is custom, and is composed of modified off-the-shelf components, including an immersion blender (Fig. 6).

Presently, the mixer is made of a stainless steel bain marie container with a rounded bottom to enable free draining by gravity. The connections and valves will be reinforced with food-grade sealants to ensure no leakage. The lid is machined from stainless steel shim stock and attached to the container lip using...
food-grade silicone sealant. All connecting input lines will be sealed to prevent leaks. The mixing component itself is a modified immersion/stick blender. The blender has one speed controlled by a single button, and plugs into a standard outlet. To simplify control, the team disassembled the blender and soldered a permanent contact for the button to be “on”. This means that now, whenever the blender receives power, it will start spinning without an additional button press. The protective “umbrella” was machined off to expose the blades and prevent the ingredients from falling and clumping on top. This allows all of the powders to reach the water and receive stirring. Trials in the test kitchen have shown that mixing should take ten seconds or less with hot water and appropriate ingredient ratios.

After mixing, the liquid dispenses through a valve and directly into the cup, its final destination. The cup will already have received cooked boba pearls and ice before the liquid is dispensed on top. This mimics the assembly order of an in-store experience, and will help regulate the temperature of the final beverage. While cleaning procedures are still in development, the team believes the mixer will aid its own cleaning by being a simple, food safe container that takes advantage of gravity, can withstand high temperature, and has its own spinning abilities.

**Boba Chain**

**Dried Boba Dispenser**

Boba tea shops typically purchase dried uncooked boba pearls in bulk and cook large batches in boiling water ahead of opening. These tapioca pearls are sold in large dehydrated vacuum sealed containers that can be stored at room temperature for up to six months. Once opened, uncooked boba can only be stored for up to 48-hours before losing freshness. This increases both the maintenance burden and the waste associated with the machine. Two current custom solutions are being explored for this functionality.

The first custom design includes a boba pearl chamber container that can hold up to four bags (2.2 lbs each) worth of boba that sends the product to the boba cooker through a propeller-like dispenser. The boba chamber will have a cylindrical shape subdivided into four equally-sized sub-chambers that have a vacuum pump attached to them to ensure boba pearls stay dry. The containers will be built to funnel boba pearls into the propeller. Each chamber will have a propeller dispenser attached to the bottom of it that connects directly to the boba cooker. When more boba pearls are required to cook, the dispenser propeller will be actuated and rotate, dispensing the necessary amount into the boba cooker to begin boiling.

The second solution functions similarly to the powder dispenser helix designs. Boba pearls are stored in a box-shaped container with a flat bottom. The helix is angled to transport the boba pearls into the cooker through the helix that is spun by a DC motor. The helix would be placed either horizontally or slightly up at ~30° to ensure that pearls do not jam in the exit.

**Boba Cooker**

We leverage gravity in our design to move boba from the top to the bottom of the machine as it is in turn released into the cooking chamber, cooked, and moved into cooked storage. We drain the water used for cooking separately from the pathway designated for boba through custom design features of the cooker including uniquely shaped mesh inserts.

The current design of the cooker consists of a sealed upside down stainless steel pot (with a lid) with holes drilled into the top, bottom and side of the pot to enable connections with the rest of the machine. In the future, the off-the-shelf pot will be replaced with a similarly shaped custom stainless steel container without
unnecessary components (such as handles) and with all required connection holes (Fig. 7). The three holes in the top of the container are used for water intake, dry boba intake and steam exhaust. All holes are connected to pipes and equipped with on/off valves for shutting off water supply, preventing steam from entering the dry boba storage (as that may result in clumping of the boba or preemptive spoiling of the food product due to the creation of a high humidity environment), and regulating the amount of steam exiting the pot respectively. The hole in the side is used to dispense boba into the cooked boba storage container, similar to the others it connects to a pipe with an on/off valve to prevent leakage and ensure easy dispensing. We are using a full-port stainless steel motorized ball valve. The structure of a ball valve ensures none of the boba pearls get caught on any part of the valve or jammed during the opening/closing process.

On the inside of the pot a custom mesh “strainer” is secured (Fig. 8). The “strainer” is shaped in a way that allows the boba to slide down from anywhere in the pot to the dispensing hole on the side once the water is drained, since for a few minutes after the water has just been drained both the mesh and the boba are slippery enough to allow easy motion of boba down the slope of the mesh. Thus, when dry boba enters through the top of the pot it falls and lies on the mesh, then the pot is filled with water and cooking occurs, then the water is drained through the bottom of the pot and once the valve attached to the boba dispensing hole on the side is open the boba slides down the mesh and into the pipe. Steel mesh is sturdy enough to hold a shape that aligns with the hole in the pot on one side, and pot perimeter on the other (Fig. 9). The edges of the mesh were secured to the pot by drilling holes around the perimeter of the pot and putting bolts through that screwed into u-clips on the inside. This mechanism clamped the strainer edges to the pot through the force of the bolted connection.

Since the mesh is shaped in a way that the majority of the boba will end up on one side of the pot with the other side of the mesh raised to create the slope required for the dispensing that uses only gravity, the other side of the pot has extra space at the bottom which will be utilized for an immersion heater. The water needs to be boiling the entire time the boba is cooking, therefore a heater is necessary inside the cooker to maintain the temperature at boiling because the water comes in already pre-heated to 60°C. The heater will be placed in the empty space under the raised portion of the mesh which would ensure it will always be immersed in water while never touching the boba pearls. If the pearls came into contact with the 1500 Watt heater, this could result in burning the pearls, which compromises the heater and cleanliness of the entire cooker. The pot exterior will be covered in sheets of heat insulation to help maintain temperature and minimize heat loss. The pot interior will be equipped with a temperature sensor to monitor temperature.

**Cooked Boba Storage**

After being cooked the boba is dispensed into the cooked boba storage container which will hold several drinks worth of boba that was cooked in the previous step and dispense it into the cup. In order to keep
boba from sticking together and make it easily dispensable, it needs to be stored in room temperature water.

The boba storage itself will be implemented similarly to the boba cooker described above with a (smaller) stainless steel pot containing a mesh strainer, a water drainage at the bottom, boba dispensing hole on the side, as well as the boba receiving hole and water inlet at the top (Fig. 10). Steam exhaust is unnecessary for this stage since the water coming in is room temperature, and therefore is not present, similarly there would be no immersion heater in the boba storage container either. However, an air pump was included in the design to help prevent sticking of boba pearls together.

In order to preserve water, we plan to implement a feedback water loop. Every time a certain amount of boba needs to be dispensed into the cup, all the water from the storage container will be drained into a separate compartment, thus allowing the boba to be dispensed through the side hole with no water. This design avoids using a slotted pipe and a shorter regular pipe can be used instead. After the necessary amount of boba is dispensed, the drained water will be pumped from the compartment back into the boba storage container.

Each batch of cooked boba can be safely stored for 4 hours, after which it has to be disposed of due to health related concerns. Once 4 hours pass, all water will be drained from the storage and the remaining boba dispensed through the regular outlet but into a waster chamber instead of a cup. A new batch of boba would then be dispensed into the storage along with fresh water.

Connections and Valves
The overall system design largely relies on gravity to transport liquid and powdered components throughout subsystems. Jason Hejna, one of the Coca-Cola Freestyle team members, recommended using translucent or opaque tubes or pipes to minimize bacterial growth [12]. The machine currently uses a flexible, translucent tubing from McMaster-Carr. It is rated for high-temperature food-safe applications. The tubes are either connected to valves with brass fittings, or sealed directly onto stainless steel components like container lids.

All components that require sealing have used a silicone sealant rated for high-temperature and food-safe applications. Brass fittings are male to NPT barbs. The valves in the machine are NPT female threaded on both sides. Threaded connections between the brass fittings and valves are sealed with wrapped Teflon tape. The steel full-port ball valves all use solenoids or motors to actuate independently of human interference. The voltage selections were limited to simplify the number and complexity of control circuits. Five of the twelve valves are specifically used to transport water to and from different subsystems. Orble is grateful to Ian Howard of SMC Corporation for discussing valve implementation options with the team, and sponsoring these five valves for use in the machine.

Timing and Automation
The functionality of the machine as a whole is contingent on an embedded system which enables processes such as dispensing dried boba pearls into the boba cooker.

The embedded system consists of actuators to automate the different processes, sensors to determine the current state of the machine and a microcontroller to interpret data from sensors as well as control the actuators.
The different subsystems of the machine are primarily actuated by motors, electrical valves and AC components. Motors are primarily used for dispensing the input materials. In future iterations, they would also be used for powering the exhaust fans found in both the boba cooker and powder mixer, and running the peristaltic pump used in the cooked boba storage. Electrical valves are used for enabling the passage of liquids and boba pearls through different components of the machine. AC components such as the stick blender in the mixer, the heating element in the cooker, the water pump and the water heater are used for other tasks such as mixing powders in water, boiling water, supplying water and preheating water respectively.

While our first prototype doesn’t currently use any sensors, the final machine will be required to use them in order to track state. A weight sensor would be used under the surface onto which the cup will be placed. This would relay pertinent information such as whether there’s a cup present to receive a finished bubble tea drink or whether there’s boba pearls in the cup, meaning that the mixed tea can be dispensed. Weight sensors would also be used to track the levels of powders, dried boba and stored cooked boba. Temperature sensors would be used for tracking water temperature, which is necessary for getting water hot enough for sanitation as well as to a boil for cooking boba. Water sensors would be used to measure flow rate into the subsystems that require water. A tablet would be used as the user interface for signaling the machine to begin crafting a drink and would also specify the customization of the drink, such as flavor and sweetness level. These parameters would modify how the embedded system proceeds to power actuators in order to create the desired product.

The microcontroller used for the machine is a Raspberry Pi 4. It has a series of input and output pins that connect to sensors and actuators respectively. The microcontroller is programmed to activate actuators to perform the processes accordingly. This includes the order in which actuators are powered as well as the duration for which they are powered. In future iterations, it would be programmed to also read in data about the state of the machine from sensors.
Section IV. Final System Form

Background
The final system form is a commercial automated bubble tea dispenser with a footprint of a vending machine for use by institutions and independent retailers. It will use standard connections and take in dry ingredients to create a variety of customizable drinks of quality comparable to a bubble tea shop and with an average crafting time of five minutes.

Prototyping
The majority of prototyping efforts were centered around subsystems and components previously discussed in Section III. Design, Engineering, and Realization above.

Validation
While the team works to complete assembly and preliminary integration, we created plans to test and validate the system in parts and as a whole. This includes conducting trials with the water heater to obtain a realistic estimate of the time needed to boil various quantities of water. Sealed connections were leak-tested and further leak-proofed if faulty. Total valve actuation and centralized control was verified in a number of settings, including: empty, with dry components only, with liquid components, with all components.

In terms of business development, the team was actively involved in the Penn I-Corps program. Membership entailed conducting upwards of 70 customer validation interviews across seven potential customer segments. These interviews were insightful to understanding the types of businesses, spaces, and institutions that would invest in Orble’s completed machine.

System Functions
With the goal of creating a bubble tea drink, the system’s main functions are described as follows: storing, dispensing, draining, heating and blending.

Storing applies to input materials (tea, sugar, creamer and desiccated tapioca pearls) as well as cooked boba. Dispensing applies to all of the aforementioned items as well as the mixed drink that comes out of the powder mixer, ice from the ice maker and water from the water lines. Draining occurs at the boba cooker and cooked boba storage in order to get rid of waste. Heating occurs at the water heater in order to get water ready to be used in the boba cooker and powder mixer. Heating also occurs in the boba cooker to get the water to a boil in order to properly cook the tapioca pearls. Finally, blending occurs at the powder mixer.

System Diagram
All subsystems are assembled on a multi-level chassis. Positioning components at different levels vertically and horizontally is essential to maintaining free draining of many drink components via gravity (Fig. 11) The primary structure is an adjustable metal shelf with removable particle board shelves. Additional 80/20 aluminum extrusions have been cut to size to interface with the shelf width. These extrusion lengths replace the particle board shelves to provide a more skeletal support structure. While subsystem arrangement is still variable, this allows more flexible positioning of containers and fixturing for valves and DC motors. To support the smaller DC motors, the team drilled 4-40 fastener clearance holes into corner machine brackets to interface with existing 4-40 internal threads on the back of DC motors. These bracket motor fixtures were clamped to the chassis legs or 80/20 extrusions.

The distribution of heated water cannot rely on gravity, because of the size and weight of the water heater. The heater alone weighs 22 lb, and can hold four gallons of water for an additional 33 lb [18]. To
maintain a sturdy, balanced machine, this component will be housed on the bottom of the chassis. Therefore, to reach the mixer and boba cooker, a pump will route heated water up the chassis to these subsystems.

![Machine System Diagram](image1.png)

**Fig 11. Machine System Diagram**

![Machine Overall Electronics Diagram](image2.png)

**Fig 12. Machine Overall Electronics Diagram**
Orble is centrally powered, controlled, and monitored. The final machine is composed of both AC and DC components. The AC components include a stick blender, an AC DC converter, a heating element, a Raspberry Pi, a water pump and a water heater. The DC components are twelve motorized valves and three DC motors for dispensing. Wall power is routed to each AC element through the use of two distribution blocks—one for routing hot and neutral and the second for routing ground (Fig. 13). DC power is routed similarly from the AC DC converter to the valves and motors through the use of a single distribution block (Fig. 12). The converter is rated for 120V AC to 24 VDC conversion for up to 360W.

The entire system consists of 22 circuits. 15 of the circuits control the DC motors and motorized valves. Of the remaining 7, six of them control each of the AC elements and the last is a wired up GFCI outlet for overcurrent protection. The AC element circuits are simple switching circuits that rely on solid state relays. The 15 DC control circuits come in two types: MOSFETs for single direction control and h-bridges for bidirectional control. Eight of the 15 circuits are MOSFET circuits and the remaining seven are h-bridge circuits. The MOSFET circuits are used for the dispensing DC motors and the water valves. The h-bridge circuits are used for the non-water valves. All control circuits are signaled by the Raspberry Pi which enforces the correct order of operations as well as the correct duration of each operation.
Section V. System Performance

The machine was tested on several levels: component, subsystem and system. Looking at the powder chain first, both vertical and horizontal powder dispensers were tested individually with a kitchen scale to assess the consistency of output by weight. It was discovered that the vertical dispenser outputs small quantities with high accuracy of +/- 0.02g per 0.5g dispensed and thus satisfies tea dispensing requirements where high precision and small quantities are required. Horizontal dispensers are able to output several hundred grams of powder relatively quickly but with lower accuracy, which is acceptable for large quantities of creamer and sugar used in the recipes. The other part of the powder chain - the mixer - was also tested separately before being sealed shut. Overall quality of powder dissolution and free draining through the outlet at the bottom were confirmed in those tests.

Once the chain was assembled on the chassis and connected through valves and tubing more tests were conducted. First, the direction and timing of all electrical components was tested to make sure the helices inside dispensers are spinning in the correct direction to output powder and the valves have enough time to open before powder is dispensed, as well as that all valves are open and closed at the designated times (e.g. all valves are closed when the mixer is on, the mixer output valve does not open until the blender is off, etc.). The test results were for the most part satisfactory, the chain functioned with correct timing and output components such as powder consistently. However, one significant issue was discovered in that testing. Most connections in the machine use screw terminals to allow for individual disassembly and testing of the components. The board with screw terminals connected to the mixer output valve is located on the same chassis panel as the valve and mixer themselves. When the blender is on, it creates vibrations that propagate to the board causing the screw terminals to loosen and resulting in inconsistent functioning of the valve. A short term solution for that is to move the board further away from the mixer itself. In the long term, more permanent connection methods are necessary. Despite that issue, the entire powder chain was successfully tested. Water was pumped up from our water reservoir through an off-the-shelf water heater (which raised the temperature to 60°C) and into the mixer. Both the pump and the water inlet valve were controlled by our Raspberry Pi and powered through the distribution block inside the machine. After the mixer was filled, powder valves were opened and powder was dispensed into the mixer, then the valves were closed and the blender was turned on for a few seconds, after which the mixed drink was dispensed from the outlet valve. There were a few small issues discovered and resolved through that testing. First, if the water then powder process is reversed the powder falls through the bottom of the mixer into the output valve and does not get dissolved, thus water must come first. Second, when first turned on a longer pumping cycle is required to get the water through the pipes leading up to the mixer. Lastly, for testing purposes the system was left unfastened to easy trouble-shooting which led to some minor misalignments and powder spills. In the future, a locating scheme needs to be designed to align the components more precisely.

The boba chain was tested in a similar manner starting from individual components. While being developed the mesh inserts inside the cooker and storage were continuously tested with both dry and cooked boba to ensure it slides down towards the output opening on the side. Once the cooker and storage were sealed they were continuously tested with water until all leaks were sealed. Finally, the heating element that goes inside the boba cooker and the circuit required to power it were tested separately in a plastic bucket first to ensure safety and accessibility during the testing. Once assembled with the cooker, the heating element was tested as well. The cooker was fully filled with water and the water was boiled using the heating element inside, while the temperature was being monitored through a temperature sensor also installed inside the cooker. It took the water about 30 minutes to reach boiling from 60° C, which is what the temperature of the water coming in from the off-the-shelf water heater would be.
Once the boba chain was assembled on the chassis more testing was conducted. First several water tests were conducted and new leaks that appeared due to the straining on the connections during assembly were sealed. Then cooked boba was passed through the machine to test the dispensing functionality. About 90% of boba pearls that were dispensed into the system went through to the bottom. The rest got stuck inside until the next water cycle brought them closer to the output valves. This was a result of imperfections in the mesh shape, which can be fixed in the next iteration by either modifying an off the shelf strainer instead of creating our own or perfecting the shape using a mockup made of a material that is easier to work with first. Additionally, this issue will be less significant if the cleaning cycle is implemented since flushing water through the chain did help the pearls exit the system. Unfortunately, due to the delays in assembly caused by various factors such as purchasing and shipping speed, leaks taking 24 hours to seal each time and soldering issues, we did not have enough time to debug the electronics and test the full functionality of the boba chain before design day. Things that are yet to be tested include timing of the electrical components in the boba chain, incorporation of temperature sensor feedback and fully cooking boba inside the machine.

The final test for our machine was the transportation to the design competition, which pointed out the same issue as the mixer testing. Electrical connections we used did not survive the vibrations of the trip there, and therefore in order to be mobile our machine needs a different wiring scheme. We anticipate using custom printed circuit boards and soldered or bolted connections instead of screw terminals in the future.
Section VI. Conclusions and Future Work

Conclusions
The boba machine prototype we have created in this project successfully demonstrates the primary functionality we set out to achieve. The powder chain consistently dispenses various powders with precision and accuracy necessary for the tea recipe we have created in the kitchen. The mixer is able to fully mix and dissolve the powders creating a homogenous drink that is then dispensed into the cup. The boba chain is capable of dispensing both dry and cooked boba all the way through the chain using just gravity from the dry boba dispenser at the top to the cooked boba storage output at the bottom. Cooker and storage can hold enough water for preparation and storage of the pearls without sticking. Water can be boiled inside the cooker using our heating element and the temperature monitored through the temperature sensor installed inside. More work needs to be done to make the machine more robust and efficient, but the core design has proved to be viable and effective.

Future Work
Orble has received several accolades and funding for work on this project: this includes but is not limited to the Berkman Fund, M&T Summit First Prize and Viewer's Choice, Francis G. Tatnall Prize in the Mechanical Engineering Department (MEAM), and the Wharton Implementation Fund. Orble has also secured $10,000 in funding from the Venture Lab Startup Challenge “Summer Venture Award” to continue work on the project over the summer and into next year. The team was semifinalists at the Wharton 2023 Startup Challenge and finalists at the SEAS Senior Design Competition. The team will be seeking provisional patent filing in July 2023.

Orble is also finalizing discussions regarding machine installation and use in pilot programs this upcoming fall. Orble will be bringing the machine to the ARCH Building on University of Pennsylvania's campus in the Fall of 2023, with verbal agreements confirmed, and contracts signed in early June. ARCH is a home for many undergraduate students at the University and the space of the campus' cultural houses. In the greater University City area, we will validate our product in the office retail space through installation at the Pennovation Center. As an area serving the daily comings and goings of 400 people, the machine will primarily serve young professionals and graduate students who use the center. Along with the Pennovation Center, we are having ongoing conversations about further expansion into other Penn’s non-academic real estate holdings, including real estate partnerships, off-campus housing, retail and third-party leasing. Bankcard Analytics, a mid-sized tech company, will have Orble as an office amenity for their employees in the Winter. Orble will use this opportunity to analyze customer data and volume.
Section VII. Statement of Roles

Orble is an Interdisciplinary Senior Design team housed in the Mechanical Engineering and Applied Mechanics Department. Orble has two students in Computer Engineering: Esther Amao and Nastassja Kuznetsova. Orble has three students in Mechanical Engineering and Applied Mechanics: Sophia Anzai Takahashi, Lada Korotaeva, and Sarah Tadlock. Additionally, Sophia Anzai Takahashi is a dual-degree student in the Jerome Fisher Management and Technology Program concentrating in Management.

Over the academic year, Orble has grown and had external support from undergraduate students David Cooper, Ann Kang, Noor Majeed, and Shrey Pasricha. Their roles and contributions are enumerated in Section VIII. Acknowledgements.

The core team of five brings unique skills from their various course work and extracurricular experiences:

Esther Amao used her background in hardware-software integration to actuate the powder dispensers and valves throughout the system. She also used her knowledge in embedded and real-time operating systems to time and execute the multiple tasks of the machine. She spent time mapping out the power management of the entire system to ensure that the machine’s power draw at any given time does not exceed the limitation of a wall outlet.

Sophia Anzai Takahashi used management experience and business acumen and a mechanical engineering background to contribute to efforts related to funding, market research and validation, and project management. Sophia participated in subsystem ideation and prototyping efforts, and CADded and 3D printed components related to the powder dispenser. Sophia also spent a large portion of time in the test kitchen refining ingredient output and recipes, and has ServSafe certification in food safety.

Lada Korotaeva used her mechanical engineering background to design, prototype and test boba chain components and assist with design of other subsystems, such as dispensing. She used her manufacturing and prototyping experience to design, machine and 3D print connections and alter off-the-shelf parts, as well as contribute to assembly efforts and creating overall system flow.

Nastassja Kuznetsova used her computer engineering background to actuate the dried tapioca dispenser. She also applied her knowledge of AC systems to design and test the water heating portion of the machine. Nastassja also used her experience in software development to architect the UI approach that Ann Kang is implementing under the supervision of Esther Amao. Nastassja also used her previous experience to contribute to efforts related to funding, market research, and customer validation as well as handle all of the ordering logistics for the team.

Sarah Tadlock used her pipe system knowledge to select food-conscious tubes, fittings, and valves. She applied her precision machining skills to manufacture customized prototype components from off-the-shelf elements and stock. She also CADded and 3D printed several components to interface with both off-the-shelf and custom parts. She was active in assembly and sealing efforts. She also spent significant time in the test kitchen refining recipes, and becoming familiar with NSF standards and ServSafe compliance to continuously prioritize food safety.
Section VIII. Acknowledgements

Academic
Dr. Jeffrey Babin - Engineering Entrepreneurship
   Dr. Babin has assisted Orble in obtaining financial awards through the Berkman Fund. He has also discussed Orble’s approach to customer validation and the near-term market strategy.

Dr. Tomás Isakowitz and Elizabeth Mazhari - Penn I-Corps
   Tomás and Elizabeth have offered their expertise through Orble's participation in the Penn I-Corps Program, focused on validating engineering projects through conducting customer validation interviews.

Dr. Jacqueline Kirtley - The Wharton School
   Dr. Kirtley has offered her management expertise throughout the academic year to scrutinize Orble’s initial customer survey questions, numerous presentation decks, and business plan iterations.

Waseem Moorad, Esq. and DIPTC Associates - Detkin IP Clinic
   Waseem has led the Penn Carey Law associates, who have offered their expertise to analyze patentability of engineering innovations related to the project. Orble is currently part of the Detkin Intellectual Property Technology Clinic (DIPTC), which provides pro bono transactional patent, copyright, trademark, trade secret and privacy counsel to a variety of clients. This report detailing prior art and freedom to operate discovery will allow us to move forward with provisioning patent efforts. Orble is currently in discussion with the legal counsel about provisional patent plans.

Dr. Sangeeta Vohra - M&T Director of Integration
   Dr. Vohra has guided Orble through the M&T requirements of the Senior Design project, and assessed team progress throughout the year. She has provided valuable feedback to the business plan and assessed our efforts to participate at the M&T Summit Finals.

Lauren Hooks - Food Innovation Lab
   Lauren is the Kitchen Manager at Tangen Hall’s Food Innovation Lab. She has been a food safety expert and assisted with two team members’ ServSafe certification process. She has connected Orble to numerous contacts in local food spaces, and food venture resources. She has also helped Orble prepare for the Future of Food Conference and assisted with marketing efforts through Tangen Hall.

Orble Team
David Cooper - Carnegie Mellon University
   David is an undergraduate student at Carnegie Mellon University. He offered his skills in UI/UX to create the machine’s customer-facing tablet ordering interface and backend metrics tracking.

Ann Kang - Carnegie Mellon University
   Ann is a fourth-year undergraduate student at Carnegie Mellon University. She has offered her skills in UI/UX to create the machine’s customer-facing tablet ordering interface and backend metrics tracking.

Noor Majeed - The Wharton School
Noor is a first year undergraduate student at The Wharton School. She is a Business Fellow who has assisted Orble with customer validation efforts. She has interviewed many stakeholders and potential customers.

Shrey Pasricha - New York University
Shrey is an undergraduate student at New York University. He has offered his skills in marketing and website development to create Orble’s webpage and improve upon the final system render.

Corporate
Ian Howard - SMC Corporation
Ian is a Sales Engineer for SMC who offered his valve and pneumatics expertise to assess the machine’s material transport plans. He provided insights to the types and sizes of valves that may be best suited for the machine. He generously donated five valves from SMC for use in our machine.

Regulatory
Allena Najor - National Sanitation Foundation (NSF)
Allena is a Business Development Manager who offered her experience in the NSF Product Certification process. She helped Orble determine which NSF category the machine belongs to, and the process of obtaining formal certification through the NSF.

Brian Shon - Philadelphia Department of Public Health
Brian is a Plan Review and Technical Supervisor at the Philadelphia Department of Public Health’s Office of Food Protection. He explained the connection between NSF certification and operation requirements in Philadelphia. He explained that the first step in getting approval to operate in Philadelphia is for the manufacturer to ensure the machine is NSF certified, and then whomever will operate and maintain the machine must submit a plan through the Office of Food Protection.
References and Citations


