# SproutsIO Urban Microfarm

*Interactive Indoor Farming System for Urban Use*

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Submitted to the
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## Abstract

SproutsIO Urban Microfarm is an interactive farming system that enables people to reliably grow and access healthy produce in urban areas. The introduction of a localized system with the capacity to induce scalar impact through citywide collective participation has the potential to redefine our current opaque food system.

SproutsIO incorporates modular components augmented by technology such as monitoring sensors, automated systems, and smart mobile applications with the goal to facilitate aeroponic growing of organic produce in cities. A database and monitoring network has been established to assist users in determining the growing needs and profiles of plant species in order to provide real-time feedback in assisting with plant care. This is the first system to incorporate aeroponic growing technology with sensors, automation, and mobile applications into a fully integrated, networked, and responsive system for ease of use in an indoor urban context.

User studies were conducted to test primary aspects of the system: user interaction with the mobile application, ease of assembly and initial planting of the system, and user experience growing in the system over a weeklong period. The analysis of this testing provides valuable information toward future optimization of the SproutsIO system.

Thesis supervisor: Kent Larson
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# 1 Introduction

*"By that law of our nature which makes food necessary to the life of man, the effects of these two unequal powers must be kept equal."*

Thomas Robert Malthus[1]

In support of sustaining growing cities, industrial agriculture has led to gross inefficiencies that necessitate overproduction and lead to exhaustion of natural resources to offset flawed distribution. Approximately 1/3 of our food is lost due to supply chain inefficiencies and waste[2]. To compensate for deficiencies in getting the food from the farm to the consumers, we overproduce [Figure 1.1]. This leads to over processing and damaging of our land on multiple levels – from pesticides to fertilizers to gross over use of water - over 60% of worldwide freshwater is used for agriculture[3]. Our current high yield, low efficiency agricultural system is not sustainable for a growing population.

The type of food we grow and eat is an important consideration. While fruits and vegetables should serve as the largest portion of our daily food intake, only 14% of adults in the U.S.[4] consume the recommended daily portion of fruits and vegetables. For many consumers this is attributed to access and cost associated with fresh produce. Since fruits and vegetables are the most perishable crops, they comprise the largest portion of the waste with approximately 50% loss [Figure 1.2]. Consumers pay the price of two for only one; one tomato is eaten and the other is wasted in the process. For this reason, people are more inclined to eat packaged foods that are less costly in the short term, but more costly in the long term due to health issues including obesity and diabetes.

Food safety is also a cause for great concern internationally. For example, in Guangzhou, China rice tested in nearly half of the restaurants were found to have excessive amounts of the carcinogen Cadmium in 2013[5]. People are becoming more conscientious about where their food is coming from and its contents. Locally sourced organic foods is one of the fastest growing categories of consumer spending in the United States, as fresh, pesticide free, produce and supply chain transparency are increasingly valued.

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[1] Malthus T.R. 1798. *An essay on the principle of population as it affects the Future Improvement of Society*
[2] Global Food Losses and Food Waste, *Food and Agriculture Organization of the United Nations*, 2011.
[3] Agriculture for Development, *World Development Report*, 2008.
[4] CDC Report, 2009.
[5] "Rice Tainted With Cadmium Is Discovered in Southern China," http://www.nytimes.com/2013/05/22/world/asia/cadmium-tainted-rice-discovered-in-southern-china.html?ref=foodsafety&_r=0

SproutsIO Urban Microfarm introduces a new strategy for producing and consuming accessible and affordable organic produce, implemented locally and scaled globally to reduce consumer dependence on commercial agriculture. Through *urban microfarming* with the SproutsIO system, learning, community building, and growing become a cohesive strategy for rethinking food production, distribution and consumption in increasingly growing urban areas. This thesis presents the concept and vision for *urban microfarming* and the implementation of the SproutsIO system prototype.

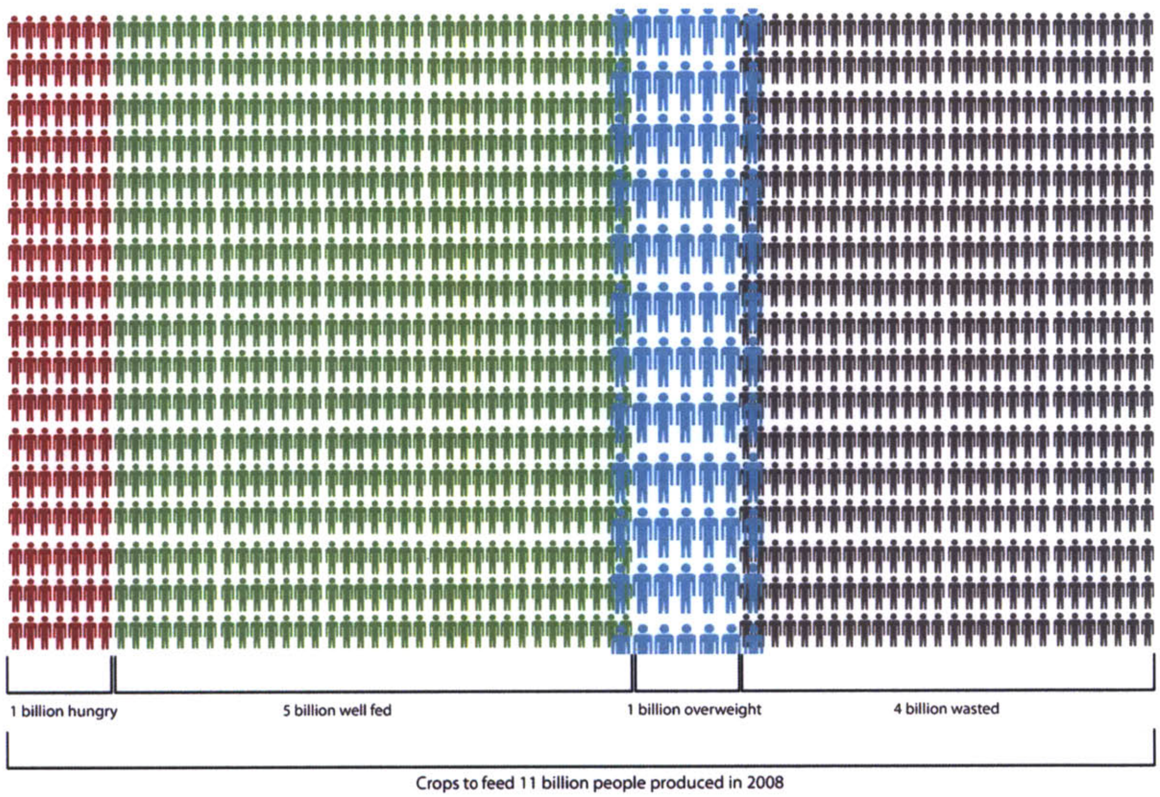


Figure 1.1 In 2008, enough crops were produced to feed 11 billion people, while the world population was at 7 billion. Approximately 1/3 of the food produced was lost due to supply chain inefficiencies and waste.

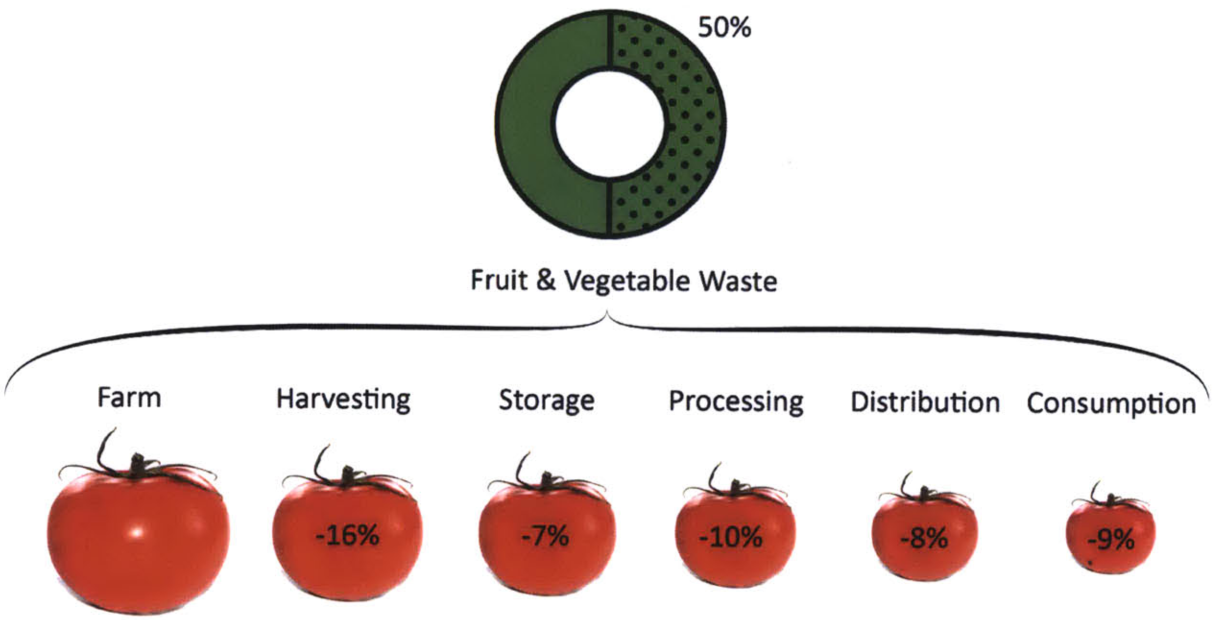


Figure 1.2 Diagram of food loss along distribution chain

# 2 Background

Population density continues to increase in cities. Cities currently house nearly 50% of the worldwide population and are only projected to grow in the coming years [Figure 2.1]. For this reason, many agencies and organizations - from IBM[6] to local government - are considering ways of improving city efficiency and infrastructure. Some of the most immediate areas of consideration are energy, water use, and mobility to address the needs of growing cities. There is great interest to localize these infrastructures to reduce losses that occur in distribution from production to the end user. This localization of infrastructure is often referenced by such terms as "urban mobility" and "distributed energy".

In a similar manner, there is the consideration of food as it pertains to cities. *Urban agriculture*, or "the practice of cultivating, processing, and distributing food in or around a village, town, or city"[7] is a nascent term that is gaining momentum. In order to understand this concept, it is important to consider potentials for how urban agriculture can be implemented in cities.

## 2.1 Food Production Method

There are different methods that can be used for fruit and vegetable cultivation. The primary distinction is whether the plant is grown in a controlled environment (largely indoors), or whether the plants are cultivated outdoors – and therefore subject to fluctuations in the environment. The most commonly understood and practiced method is growing outdoors in soil, however there are myriad techniques that can be employed to optimize growing conditions for plants.

### 2.1.1 Outdoor Growing

Cultivating plants outdoors in soil is an age-old technique known as geoponics. At its most basic, seeds are sown outdoors into nutrient rich soil in the ground with the addition of light and water. Since the 1940's, industrial agriculture has changed the landscape of farming. Prior to this "Green Revolution", a vast majority of the human population labored in food cultivation through subsistence agriculture, or food produced by farmers for themselves and their immediate family as consumers. With subsistence agriculture, food was grown on relatively small plots of land using permaculture, or the growing of different types of food plants within the same area either by crop rotation or in the same growing cycles.

[6] "IBM SmarterCities," http://www.ibm.com/smarterplanet/us/en/smarter_cities/overview.
[7] "Urban Agriculture," https://en.wikipedia.org/wiki/Urban_agriculture.

Industrial agriculture changed this landscape by separating the cultivation of food from the consumer. Large swaths of crops could be grown through monoculture, a single crop grown on the same land continuously, on large plots of land, distanced from the consumers. In order to get this food from the farm to the consumers, distribution networks were created. New technologies were developed for industrial soil farming that attempted to control production of the crop cycles. The mechanization of harvesting processes with the advent of tractors and combine harvesters (rather than using livestock) was a significant technological development. Biotechnology is another area of development targeted toward plant cultivation in the form of genetically modified organisms (GMO), plant hormones, fertilizers, and pesticides.

An alternative to industrial agriculture is organic farming (see 2.3 Organic Farming) on small to mid size plots of land; however this method of food production does not provide enough calories for subsistence of our growing population. Industrial agriculture and the growth of homogeneous crops have had many effects on the food landscape, however there are three key areas to highlight: the substantial increase [Figure 2.2] in the amount of food produced within a given area (in comparison to subsistence agriculture), the separation of the producer and consumer as two separate entities, and considerable change to the natural landscape in order to support industrial agriculture.

Recently, there are some examples that fall within the urban agriculture approach that include geoponics on rooftops such as Brooklyn Grange[8], or on vacant plots of land in cities like Detroit[9], or in community gardens in places such as New York City[10]. These examples generally use a permaculture technique for growing; as they are on small to mid size plots of land. It is important to note that these approaches are gaining popularity not because of efficiency, but because they help urban dwellers connect to the origins of their food and make the process of growing more transparent and participatory.

## 2.1.2 Controlled Environment Agriculture

Controlled Environmental Agriculture (CEA) is any agricultural technology that enables the grower to manipulate a crop's environment to the desired conditions. There are two programs that study CEA extensively in the United States; at Cornell University and the University of Arizona respectively. CEA spans two main categories that can be mixed and matched; the structure in which the plants are grown and the method employed for growing the plants. CEA is a strategy often associated with urban agriculture because it can be integrated into buildings in cities.

The structures that are often associated with CEA include greenhouses, building integrated agriculture (BIA) and vertical farming. Greenhouses are any structure used to enclose plants

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[8] "Brooklyn Grange," http://www.brooklyngrangefarm.com.
[9] Satyanarayana, "Urban Farming Invigorates Detroit Neighborhood."
[10] Gittlemen, "Using Citizen Science to Quantify Community Garden Crop Yields."

that are grown, and are typically based on the ground level. BIA is the growing of food plants on or in a building structure, introduced by Dr. Ted Caplow in 2007. Vertical farming is the growing of food plants on the façade of buildings, which has been brought to widespread attention in the work of microbiologist and ecologist Dr. Dickson Despommier with Columbia University's Mailman School of Public Health in Environmental Health Sciences.

The methods employed for CEA most frequently include hydroponics, aquaponics, and aeroponics; all are considered subsets of aquaculture, or the farming of aquatic organisms (which includes fish, molluscs, crustaceans and aquatic plants). Hydroponics is a method of growing plants with the roots submerged in water with a nutrient mix. Aquaponics includes hydroponics, with the added feature of providing nutrients to plants through a closed loop system in which fish and plants symbiotically coexist. Aeroponics is the method of growing plants by misting the roots with a water and nutrient mix. All three methods have pros and cons, however for the purposes of this thesis, aeroponics is explained in further detail.

## 2.2 Aeroponics

Aeroponics employs mechanical or electronic misters positioned to spray the roots of the plants with a nutrient solution, without the use of aggregate medium, such as soil, around the roots. The roots and the bottom of the stem are enclosed in the misted chamber, and the canopy of the plant is left open. At the point where these two areas meet is a support (often made of a plastic or foam) to keep the plant upright [Figure 2.3].

Aeroponic growing is not a new concept. Many plants naturally grow aeroponically, such as air plants and orchids, because they require so little water that that humid air is the most desirable growing medium. However, many plants need assistive technologies to supply the requisite water and nutrients.

These assistive technologies can be a point of failure for aeroponic systems when not appropriately considered. For example, misters can become clogged or malfunction, causing plants to wilt or loose turgidity. For short durations (few hours), this can be managed, but over long durations this can cause irreparable damage. Additionally, it is important to consider droplet size (recommended 5-50 micrometers[11]) in misting to optimize plant nutrient and water intake depending on the plants type and stage of cycle. If the droplet size is too small, plant growth will be inhibited.

When these technologies are designed adequately, there are many benefits to aeroponic cultivation that greatly increase efficiency such as:

[11] Stoner, "Comparison of Aeroponics to Other Nutrient Delivery Systems."

- Up to 98% less water than soil cultivation[12] (consider currently 70% of worldwide freshwater is used for agriculture[13]).
- Up to 60% less fertilizers than soil[14],
- Lightweight in comparison to soil at 120 pounds per cubic foot.
- Up to 80% increase in plant mass due to direct access of oxygen and carbon dioxide in the root zone.
- Limits the spread of disease among plants because the roots are separated and the nutrient spray can be sterile.

Much of this research has been lead by Richard Stoner in coordination with NASA and detailed in the 2007 report "Progressive Plant Growing Has Business Booming". According to Stoner's report, tomatoes can be grown with 12 crop cycles per year as opposed to the 1-2 supported by outdoor soil growing, with approximately 1000 plants per square meter.

Another important feature is the ability to farm organically using organic disease control (ODC), which is a plant based, closed loop, natural alternative to harmful pesticides that are typically used in soil farming[15].

# 2.3 Organic Farming

Organic farming is the growing of food plants with predetermined safe practices, that vary based on country. In general these practices include:

- no human sludge for use as fertilizer
- avoidance of chemical inputs such as fertilizers and pesticides
- growing on farmland that is free from contamination
- on-site inspections and detailed records of farm practices.

Organic food is a trending market in the United States and abroad. According to the USDA, sales of organic food and beverages have grown from $1 billion in 1990 to $26.7 billion in 2010, and of that $13 billion is organic fruits and vegetables. In 2011, the organic fruits and vegetables industry grew by $1.25billion. While 58% of Americans claim they prefer to eat organic food, organic farmland accounts for only 0.9% of total worldwide farmland (and organic farms produce considerably less than industrial farms). This key segment of the food industry has not kept pace with growing demand; organic farms have struggled to consistently produce sufficient supply, leading to periodic shortage of organic products in urban areas.

[12] NASA, "Progressive Plant Growing Has Business Booming."
[13] "Water Reuse Issues and Agriculture," http://www.fao.org/docrep/003/t0800e/t0800e0a.htm.
[14] NASA, "Progressive Plant Growing Has Business Booming."
[15] Stoner, "Comparison of Aeroponics to Other Nutrient Delivery Systems."

Cost is another obstacle associated with organic produce. Typically, organic produce costs anywhere between 20 – 100% more than its non-organic counterpart at the grocery store. The Organic Farming Research Foundation states that "The organic price tag more closely reflects the true cost of growing the food: substituting labor and intensive management for chemicals, the health and environmental costs of which are borne by society."[16]

The ability to grow organic, aeroponic fruits and vegetables through CEA is advantageous over industrial agriculture and even organic soil growing, because of the considerable yields that can be produced within a small area. Increasing yields allows for expanded supply and the reduction in cost of organic produce.

[16] "Organic FAQ's," http://ofrf.org/organic-faqs.

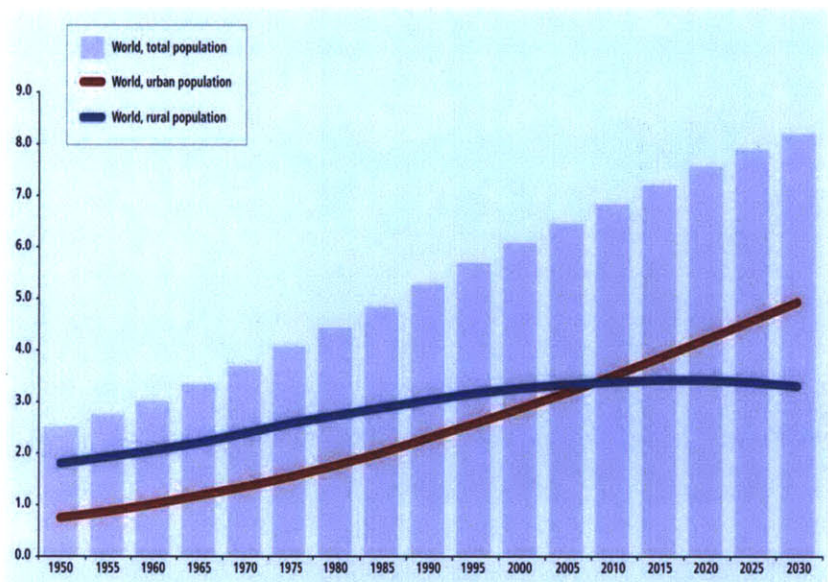



Figure 2.1 2007 report showing the current and projected population increase expected in cities by 2030. *Image courtesy of the United Nations.*

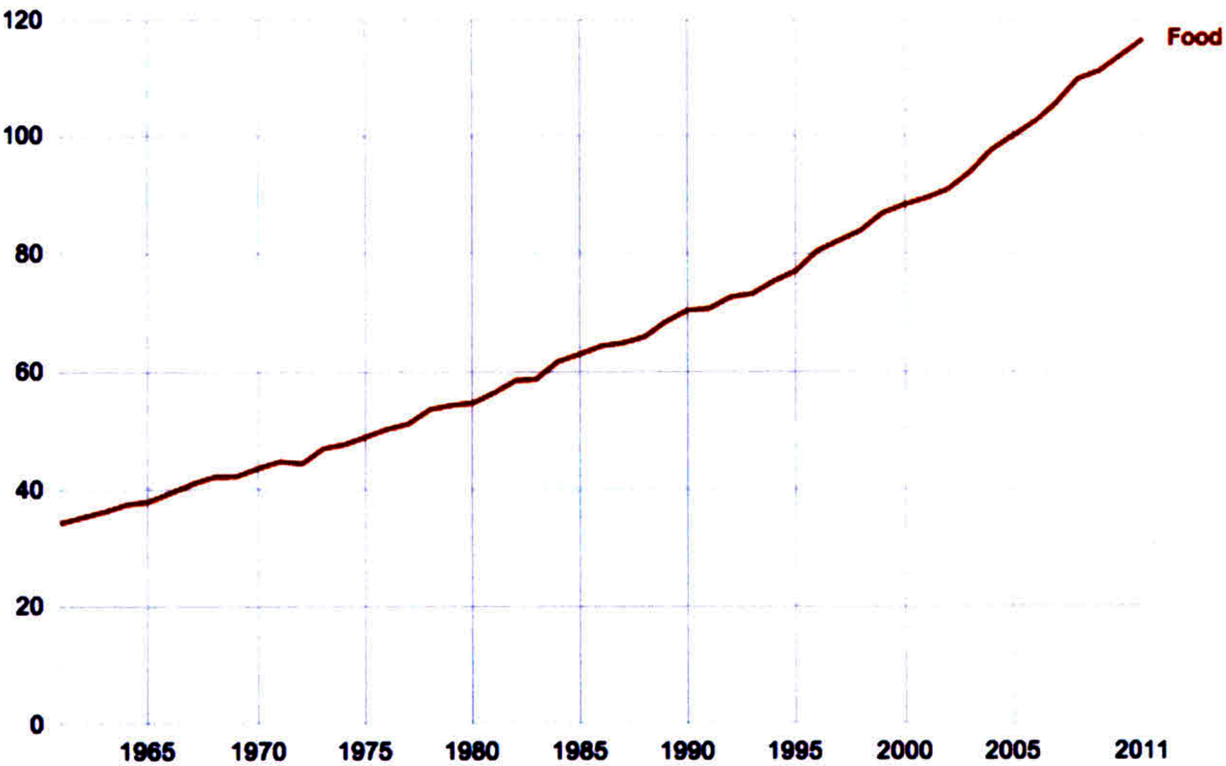



Figure 2.2 Steady incline in food crops grown worldwide relative to base period in 2004-2006 (correlates to 100 on the y-axis). *Image courtesy of World Health Organization.*

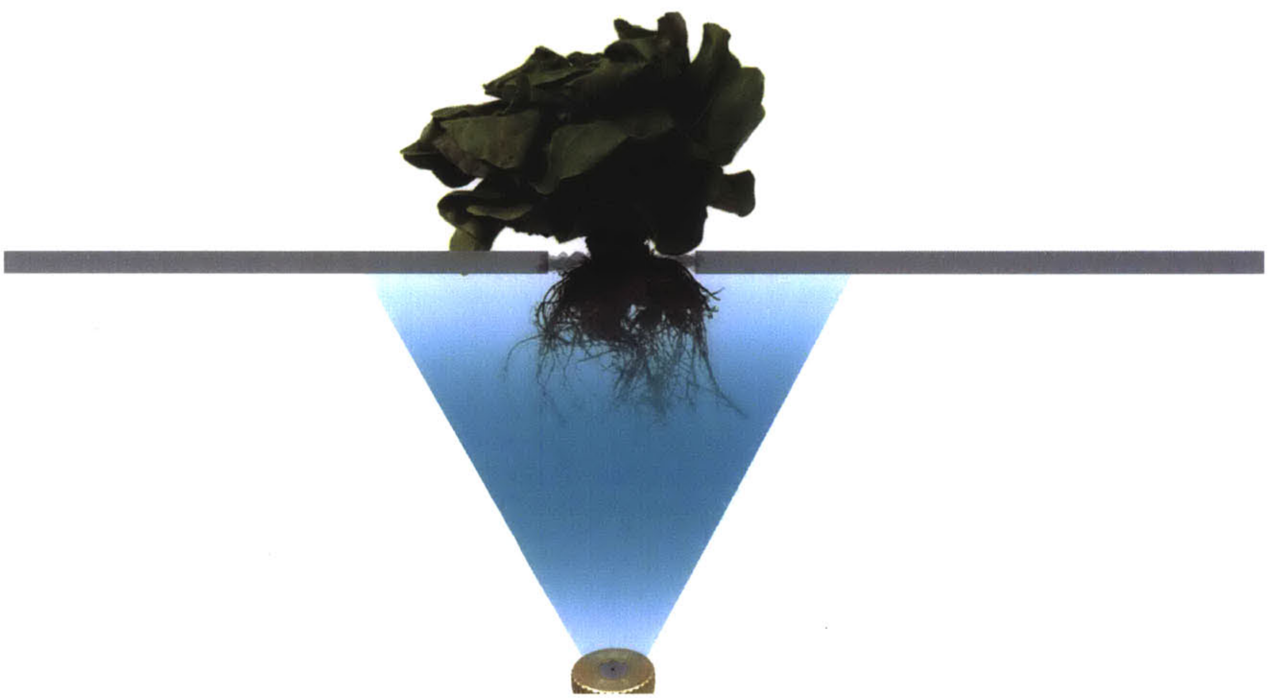


Figure 2.3 Aeroponic configuration for plant growth.

# 3 Urban Microfarm Concept

One hundred years ago, 2 out of 10 people lived in cities. By 2050, it is projected that 7 out of 10 people will live in cities[17]. Targeting urban inhabitants and localizing the production and consumption of food has the potential to make a great impact toward addressing global food concerns including waste, access, health and safety by creating an intimate feedback loop between growing produce and its consumption.

*Urban microfarming*, as defined by this thesis, is a technique in which small growing plots are distributed in urban areas and connected through a community of growers. *Urban microfarming* is a subset of *urban agriculture* as previously defined. The SproutsIO system [Figure 3.1] is a tool developed to facilitate the implementation of *urban microfarming*.

This chapter discusses the vision of *urban microfarming* at a high level, and introduces areas that the SproutsIO system design addresses. Further documentation on prototyping and design of the SproutsIO system are subsequently detailed in Chapter 6: SproutsIO .

## 3.1 Feedback

One of the major negative effects of our current decentralized food system is the opaque process in how food is grown and distributed from the consumer standpoint. Urban consumers are dependent on a process they know little to nothing about, causing disconnect and an anxiety around food cultivation. People have lost confidence in their ability to grow plants and food for subsistence, because they are completely removed from the process of growing. *Urban microfarming* with the SproutsIO system nurtures confidence by assisting people to learn to grow food. Users grow along with their plants, creating a community of consumers as producers.

The more attached people are to the food they produce, the less inclined they will be to discard or waste food unnecessarily. In the same manner that a butcher conserves all of the meat through an intimate connection and resourcefulness of craft, so too does the *urban microfarmer*. In this manner, *urban microfarming* aims to create a symbiotic relationship between people and their food, inspiring positive behavioral change by engendering responsibility.

With the SproutsIO system, users are able to physically cultivate food through a virtual portal with playful features in the mobile app. Similar to the Tamagotchi toy [Figure 3.2] in which a

[17] "Urban Population Growth," http://www.who.int/gho/urban_health/situation_trends/urban_population_growth_text/en.

user maintains the health of their virtual pet, the SproutsIO system enables the user to maintain the health of their physical plants, and by extension the users own heath and wellbeing. In the case of the SproutsIO system, the virtual game has real life implications: the healthier your virtual/physical plants, the healthier the user is through the consumption of nourishing fruits and vegetables.

## 3.2 Networked Cloud Farming

A key feature with *urban microfarming* through the SproutsIO system is a networked capacity that enables the ability to "cloud farm". *Cloud farming* with SproutsIO is the ability to connect multiple systems online, allowing for remote and multi-user management. In this manner, one user can farm a number of systems or a number of users can control one system [Figure 3.3]. The ability to monitor and manage core attributes remotely provides comfort to urban users because it allows for control without being tethered to place. Cloud farming also allows for community or expert support of the system. In this manner, cloud farming aids in electronically extending the green thumb (for more details of prototyping and user testing see 6.1.2 System Software and 8.3 Usability Study: One Week).

## 3.3 Ubiquitous Appliance

The integration of *urban microfarming* with the SproutsIO system into our lives and homes must be a thoughtfully considered solution to yield a lasting and impactful relationship. The design of the SproutsIO system considers aspects in ease of use such as maintenance, durability, size, form, movability, and power consumption (for more details on hardware design see 6.1.1 System Hardware). *Urban microfarms* have the capacity to become as ubiquitous as any domestic appliance, such as the refrigerator [Figure 3.4]. It is possible to envision that *urban microfarming* will become an integral part of our daily lifestyle.

## 3.4 Scalable System

*Urban microfarming* has the capacity to promote scalar impact through citywide collective participation.

The only way to make significant advances toward our urban future is to initiate change at a local, even individual level – and this must happen globally. Calculated and scalable solutions within the city are most impactful, as they can be readily implemented within the framework of current infrastructures and regulations for cities. They have the ability to affect change quickly; stimulating action, and building momentum to further inspire positive change. It is no longer sufficient to provide protracted solutions to problems after they occur, we must anticipate opportunities.

In this manner, *urban microfarming* addresses current food system inefficiencies through a bottom up approach that impacts the user, the community, and the city. *Urban microfarming* can affect the way that food is produced, distributed and consumed in cities. While one *urban microfarm* in a home is novel, one million *urban microfarms* in a city are impactful [Figure 3.5].

Figure 3.1 Rendering of SproutsIO system

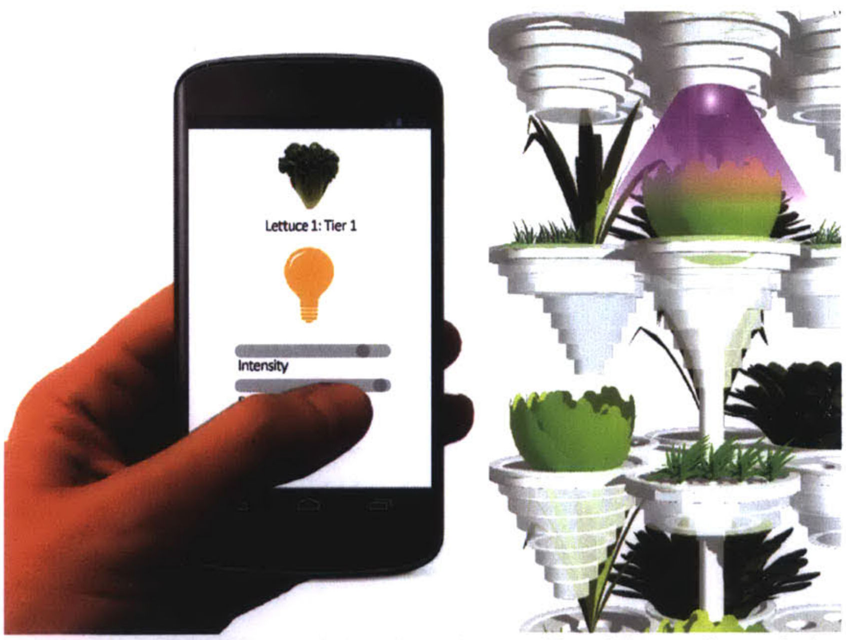




Figure 3.2 Tamagotchi virtual digital pet designed by Akihiro Yokoi and Aki Maita, above. SproutsIO system GUI interface, below, showing interaction between the virtual and physical plants.

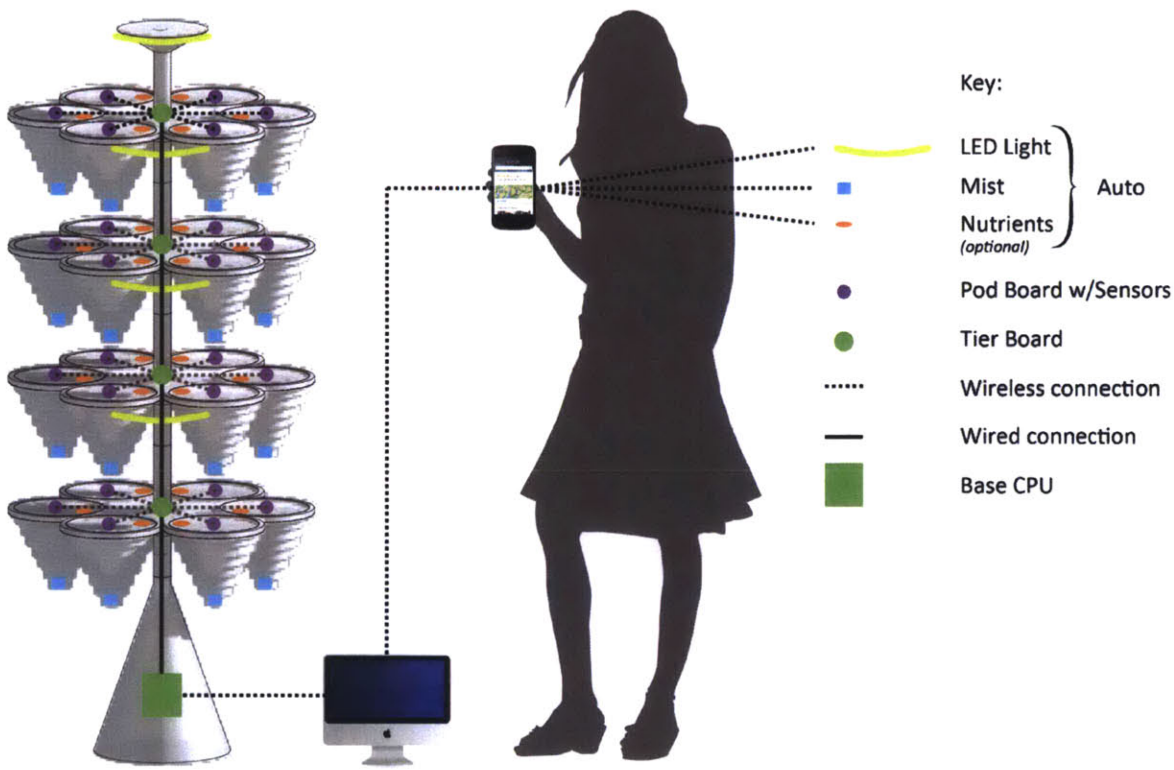



Figure 3.3 Network diagram showing how users can control SproutsIO system remotely. Multiple users can control the same system, or one user can control multiple systems.

Figure 3.4 SproutsIO system installed as an appliance for the home. Multiple systems can be installed in one home depending on the amount of food desired.


Figure 3.5 *Urban microfarming* scales through collective participation in urban food production. The greater the number of users, the more effective *urban microfarming* is at addressing larger food system issues.

# 4 Related Work

Globally, we have reached a tipping point where consumers are beginning to learn and care about where their food is coming from and how it is produced. The popular food writer Michael Pollan, in such books as the Omnivores Dillemna and In Defense of Food, has done a superb job of uncovering and illuminating issues concerning the food system and policies in the United States and abroad. Many thought leaders have entered the space, including environmental journalist Simran Sethi and author Tristram Stuart who analyzes global food waste.

Food is an important issue that concerns everyone. While thought leaders have begun mining and mapping these issues, there is much to be done in the solution space. The concept of urban agriculture and new technologies for food production is a nascent and important area of research with tremendous growth forthcoming. Highlighted is related work with objectives in alignment with the SproutsIO concept.

See for a table that shows attributes of the following technologies and indoor growing systems in comparison to the SproutsIO system and ideal proposed *urban microfarm* system.

## 4.1 Technologies

The use of sensors in commercial agriculture is becoming more pervasive, however these systems are generally costly and complex to use. Recently, there are a few new technologies for the novice market; these largely incorporate sensors such as temperature, humidity, pH, and light which are either adapted to geoponic or hydroponic growing methods. The sensor units are then coupled with an analytics component. Additionally, there are also a few new sensors that have been developed specifically for monitoring plants themselves, rather than the environment in which they are grown. See Figure 4.1 for a view of these technologies.

Koubachi is a plant care mobile application coupled with a sensor bulb that can be added to a potted plant indoors or outdoors. The free mobile application is intuitive and playful, and can also be used without the purchase of the sensor bulb. The mobile application includes a plant library for learning about plants, and a timer setup that can approximate when your plants need to be watered. However, without the use of the sensor, this information is relatively inaccurate. The sensor is calibrated for soil and the system is largely for use at the hobby scale. A number of sensor units ($99) would need to be used for each plant, which becomes cost prohibitive for larger scale use.

Bitponics is a sensor base station ($499) with a mobile application that provides online analytics for plant growth and care (service for $49 a month). Bitponics was recently a Kickstarter project and is under development. The Bitponic system is focused on hydroponic growing, and has the ability to be used on small to large systems by multiplying the number of sensor bases used. Bitponics provides sensor feedback and recommendations to the user.

PlantSmart by Black & Decker ($45) is a commercially available plant sensor and online tracker that provides customized feedback for plants in soil. For each type of plant (or large change in soil area), a new sensor would need to be used. On the Do It Yourself (DIY) side is the Botanicalls sensor kit ($100) that allows plants growing in soil to Tweet status updates online.

Agrihouse Leaf Sensor is a small (1" x 1/4") sensor that can be clipped onto the leaf of a plant in order to measure turgor pressure. This is perhaps one of the most advanced methods of understanding how a plant is responding to its environment, however the system is quite costly, as each sensor is $290, and the analytics and software component is $1300. In contrast, Public Lab has recently developed Infragram, an IR filter that depicts the health of plants through reflected light ($10 for simple filter). This filter can be added onto any camera or video camera to convert it into an IR lens.

While there is an expanding novice market for sensors and technology to augment the growing process, this technology is in all cases decoupled from the plants, the growing method, and the growing system. This is problematic because it creates a barrier to entry for the novice market, making it more difficult to begin the growing process. Technology must be integrated into the system for ease of use as holistic solution.

# 4.2 Indoor Growing Systems

Potted plants in soil are the most basic type of indoor growth. However, this method cannot support the growing of food for sustenance in urban areas as it is heavy and takes up a substantial amount of space. Space in urban areas is already in high demand and will only continue to increase in parallel with density. Hydroponic and aeroponic systems for home use are largely comprised of DIY components that are purchased piecemeal from hardware and gardening supply stores. There are few systems that provide for instant ease of use in growing, and much less that provide the ability to produce a substantial amount of food within a small area for urban dwellers. See Figure 4.5 for a view of these indoor growing systems.

Aerogarden ($180 midsize system) is a small unit that allows for the growth of plants aeroponically indoors. This was one of the first systems on the market for indoor growing outside of soil. Different seed kits and accessories are also available for purchase online. This is a tabletop system that allows for different plants to grow within it. The system is for hobby scale growing.

Click and Grow ($79) is a recent product that is smartly designed and considers ease of use. It employs a proprietary seed cartridge that can be inserted into the system that assists in plant growth by providing nutrients. You can select from 6 different types of plantings currently:

mini tomato, coxcomb, basil, chili pepper, mixed flowers, and mixed herbs. An optional LED light extension ($49) can be added to the system. While this system is very thoughtful, it is for use at the hobby scale, and is a tabletop product.

Windowfarms ($199 for starter) is a system to grow plants hydroponically near a window. The project originally started as a DIY kit using readymade materials, and then was developed into a commercial product with Kickstarter support. The system uses a basic pump with manual timer setting for water circulation through the system. Seeds and nutrients can also be purchased through the Windowfarms website, which also includes a community forum for exchange. Windowfarms, while considerate of design and supportive of a growing community, supports growing at the hobby scale.

The Aeroflow and Aerojet series of aero and hydroponic systems (from $430 to $1,175) are modular in design to accommodate plant growth desired. While the system is robust and reliable, it leaves much to be desired in terms of usability and smart design for the home.

Towergarden ($499) is a aero/hydro system that can produce a more substantial amount of food within a small area, however the system is best used in an outdoor environment on balconies, patios, terraces or rooftop gardens – since it incorporates a large water reservoir and is cumbersome for indoor use.

These systems provide a basic armature for growing indoors using the method of hydroponics or aeroponics. However, there is no optimization for high yield within a small footprint, or consideration of a holistic solution coupling hardware with technology and software. The design of these products is for the hobbyist rather than an urban food producer.

| | | Urban Microfarm Proposals | | | Technologies | | | | | Indoor Growing Systems | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Ideal Urban Microfarm | SproutsIO | SeedPod | Koubachi | Bitponics | PlantSmart | Agrihouse Leaf Sensor | Infragram | Aerogarden | Click & Grow | Windofarms | AeroFlo | Towergarden | Genesis |
| Method | Soil (or engineered soil) | | | | X | | X | X | X | | X | | | | |
| | Aeroponic | X | X | X | | | | X | X | X | | | | X | X |
| | Hydroponic | | | | | X | | X | X | | | X | X | | |
| System | Modular | X | X | X | | | | | | | | X | X | X | X |
| | Distributed System | X | X | | | | | | | | | | | | |
| | Distributed Reservoirs | X | X | | | | | | | | | | | | |
| | Central Reservoir | | | X | | | | | | X | X | X | X | X | X |
| | Pump System | | | X | | | | | | X | X | X | X | X | X |
| | Lighting | X | X | | | | | | | X | | | | | X |
| | Networked | X | X | | | | | | | | | | | | |
| | Compact Design | X | X | X | | | | | | X | X | | X | | X |
| | Seed Cartridge | X | | | | | | | | | X | | | | |
| | Supports Plant Growth Stages | X | X | | | | | | | | X | | | | X |
| | Simple or No Assembly | X | X | X | | | | | | X | X | X | | X | |
| Component | Product | | | | X | X | X | X | X | | | | | | |
| Data Processing | External Database | | | X | | | | | | | | | | | |
| | Custom Database | X | X | | X | X | X | X | | | | | | | |
| Sensors | Light | X | X | X | X | X | X | | | | | | | | |
| | Temperature | X | X | X | X | X | X | | | | | | | | |
| | Humidity/Moisture | X | X | | X | X | X | | | | | | | | |
| | pH | X | | | | X | | | | | | | | | |
| | Turgor pressure | X | | | | | | X | | | | | | | |
| | InfraRed | X | X | | | | | | X | | | | | | |
| | Fertilizer | X | | | | | X | | | | | | | | |
| | Sensors readings by Plant | X | X | | X | | X | X | X | | | | | | |
| | Sensors readings Multiplant | X | | X | X | X | X | X | X | | | | | | |
| Automatic | LED lighting | X | X | | | | | | | | | | | | |
| | Moisture w/out Pump | X | X | | | | | | | | X | | | X | X |
| | Moisture w/ Pump | | | X | | | | | | X | | X | X | | |
| | Water Supply | X | | | | | | | | | | | | | |
| | Nutrient Supply | X | | | | | | | | | X | | | | |
| User Interface | Computer Program | | | | | | | X | | | | | | | |
| | Automatic Scheduling | X | X | | | X | | | | | | | | | |
| | Website | X | | | X | X | X | | X | | | X | | | |
| | Mobile Application | X | X | | X | X | | | | | | | | | |
| | Notifications | X | X | X | X | X | X | | | | X | | | | |
| | Recommendations | X | | | X | X | X | | | | | | | | |
| | Online Community Interaction | X | | | | | | | X | | | X | | | |
| Expense | $ (up to $100)<br>$$ ($100 - $300)<br>$$$ ($300 - $500)<br>$$$$ ($500 +) | $$ | $$$$ | $$ | $ | $$$$ | $ | $$$$ | $ | $$ | $ | $$ | $$$ | $$$ | $$$$ |
| Scale | Hobbyist<br>Production | Production | Production | Production | Hobby | Production | Hobby | Production | Hobby | Hobby | Hobby | Hobby | Hobby | Production | Production |
| Experience Level | Novice<br>Mid-Level<br>Professional | Novice | Novice | Novice | Novice | Novice | Novice | Professional | Novice | Novice | Novice | Novice | Mid-Level | Mid-Level | Professional |

Figure 4.2 Attribute table that shows technology and systems comparison to SeedPod, SproutsIO and ideal urban microfarm.

Figure 4.4 Clockwise from top left: Koubachi plant sensor and mobile application, Bitponics sensor base station and online analytics service, Botanicalls DIY Kit for sensing and tweeting plant information, Agrihouse Leaf Sensor that monitors turgor pressure of plant, Public Labs Infragram camera meaures plant photosynthesis, Black and Decker PlantSmart sensor.

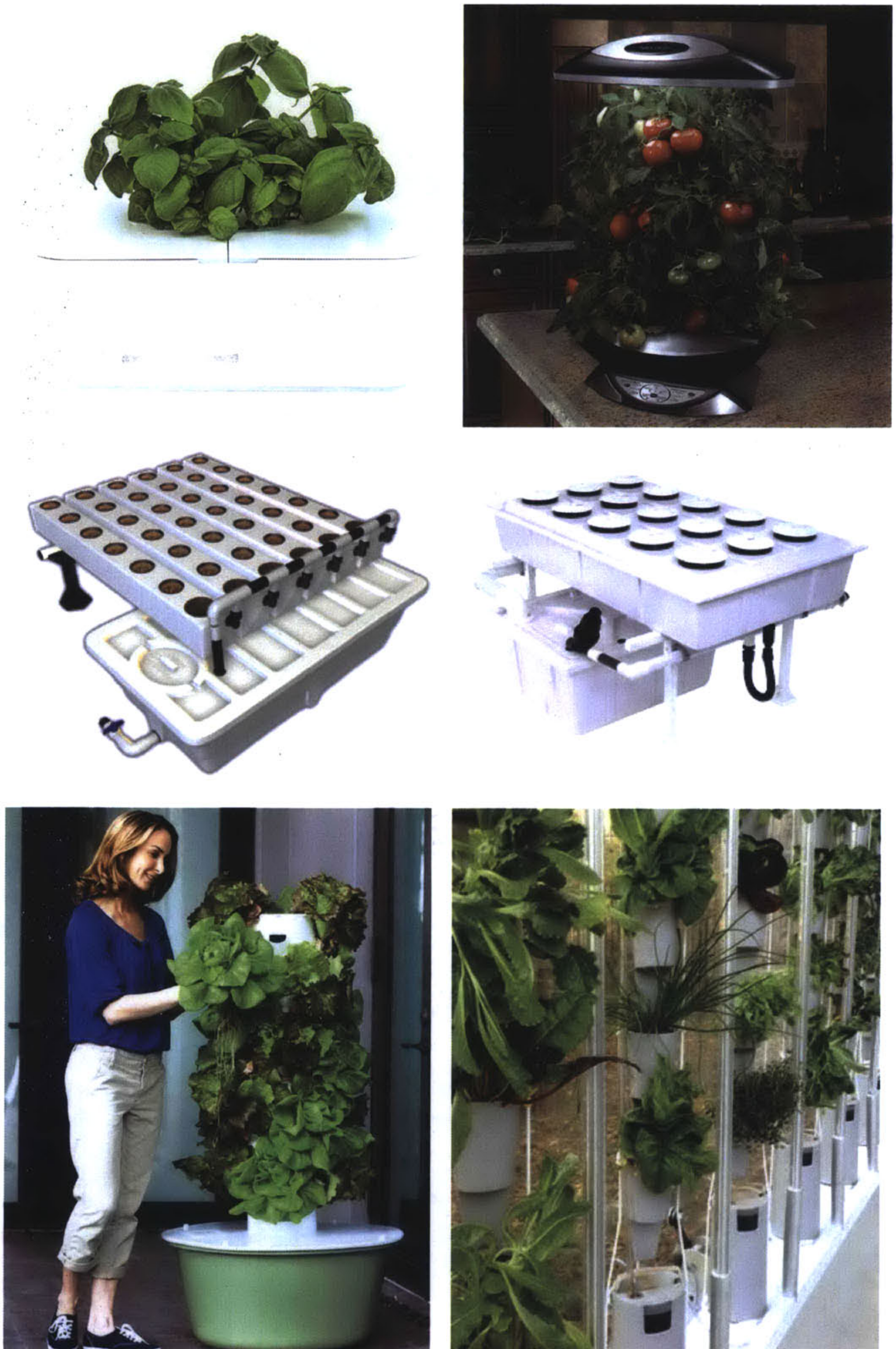


Figure 4.5 Clockwise from top left: Click and Grow, Aerofarms, Aerojet, Windowfarms, Tower Garden, and AeroFlo system.

# 5 SeedPod (Alpha Prototype)

The SeedPod system is an early prototype that began investigations into aeroponic indoor growing with the addition of sensors and a Twitter notification setup. The target objective for this design was to make it lightweight, inexpensive and easily transportable for potential use in disaster relief or developing countries. The exploration was a productive one, and a determination was made to pivot direction of the initial user base for the development of SproutsIO (as mid to high-income users can more easily be targeted for early adopters of new technology).

The Dearborn Middle School in Roxbury tested the system with a group of students as part of their activity period for STEM research blocks within the new curriculum for the school. Working with FoodCorps[18] and teacher Neal McDonald, a curriculum was developed for students to learn about food cultivation indoors with the SeedPod system and outdoors in soil. For a period of 2 weeks, students assisted in growing tomatoes, basil and peppers in the SeedPod system [Figure 6.2]. Students posted findings to a Posterous (now defunct) web blog. The web postings were not as successful because the student and teacher interaction was largely hands-on with the system.

Process documentation of the SeedPod prototype and student testing can be found in the Appendix.

## 5.1 Demonstration Design

The demonstration SeedPod unit is 4'-0" x 2'-0" x 6'-0" in size with a steel frame (only necessary for moving purposes) on casters that can support three levels or "tiers", with six growing chambers or "pods" each – for a total of eighteen growing pods [Figure 6.3]. Each pod (1'-0" x 1'-0" x 6") can support up to six plants depending on plant size and growth stage. The system utilizes a central reservoir that distributes water and nutrients to the whole system through a high-pressure pump. On the interior of each pod are two misting heads that spray the roots of the plants. Each pod can be attached and removed with a Velcro and snap closure to horizontally strung aircraft cables.

Each tier has a light and temperature sensor that connects to a central Arduino Duemilanove at the base of the frame. The Arduino connects via Ethernet to Pachube/Cosm to upload real-time sensor data. Pachube/Cosm then parses the sensor data and once a specified threshold is reached for either temperature or light, a notification will be sent to Twitter to be posted as a tweet [Figure 6.4] to a feed (@Seed_Pod). Through Twitter, a user can subscribe to the feed

[18] "FoodCorps," https://foodcorps.org.

and have email notifications sent directly to a users inbox. As another measure of monitoring the system, during the study, a UStream channel was set up to record student interaction with SeedPod demonstration unit [Figure 6.4].

# 5.2 System Atrributes & Improvements

The SeedPod system has many positive attributes, however the demonstration showed many areas that could be improved upon in future versions of the system to ensure robustness, enhance user experience, and accommodate different types of plants more effectively. There were two consistent problems with the system design. The first was a mechanical issue with a slow water leak from the reservoir. The second was related to pump failure and the lack of a user interface to control the pump. Below are the key attributes and improvements that were noted from the user study with Dearborn Middle School to be considered for the next (SproutsIO) prototype.

SeedPod Attributes

- Aeroponic
- Lightweight
- Modular planting pods
- Basic Sensors (light/temp) data online to Pachube/Cosm with Twitter notification
- Automation for pump hardcoded into Arduino script
- Interconnected Misters with central reservoir

Future System Improvements

- Reconsider central water reservoir
- Reconsider central pump for independent misters
- Entirely modular components
- Sensors and connectivity not robust
- Maintenance and durability of pod components/materials to be reconsidered
- Automation of watering, misters and lights with scheduling for plant needs
- No UI for user interaction with sensor feeds or automation of the system
- No design consideration for networked connectivity between systems


Figure 5.1 Top: Students at Dearborn Middle School with the SeedPod system. Bottom: students planting the tomato plants into the SeedPod system.


Figure 5.2 SeedPod demonstration unit.

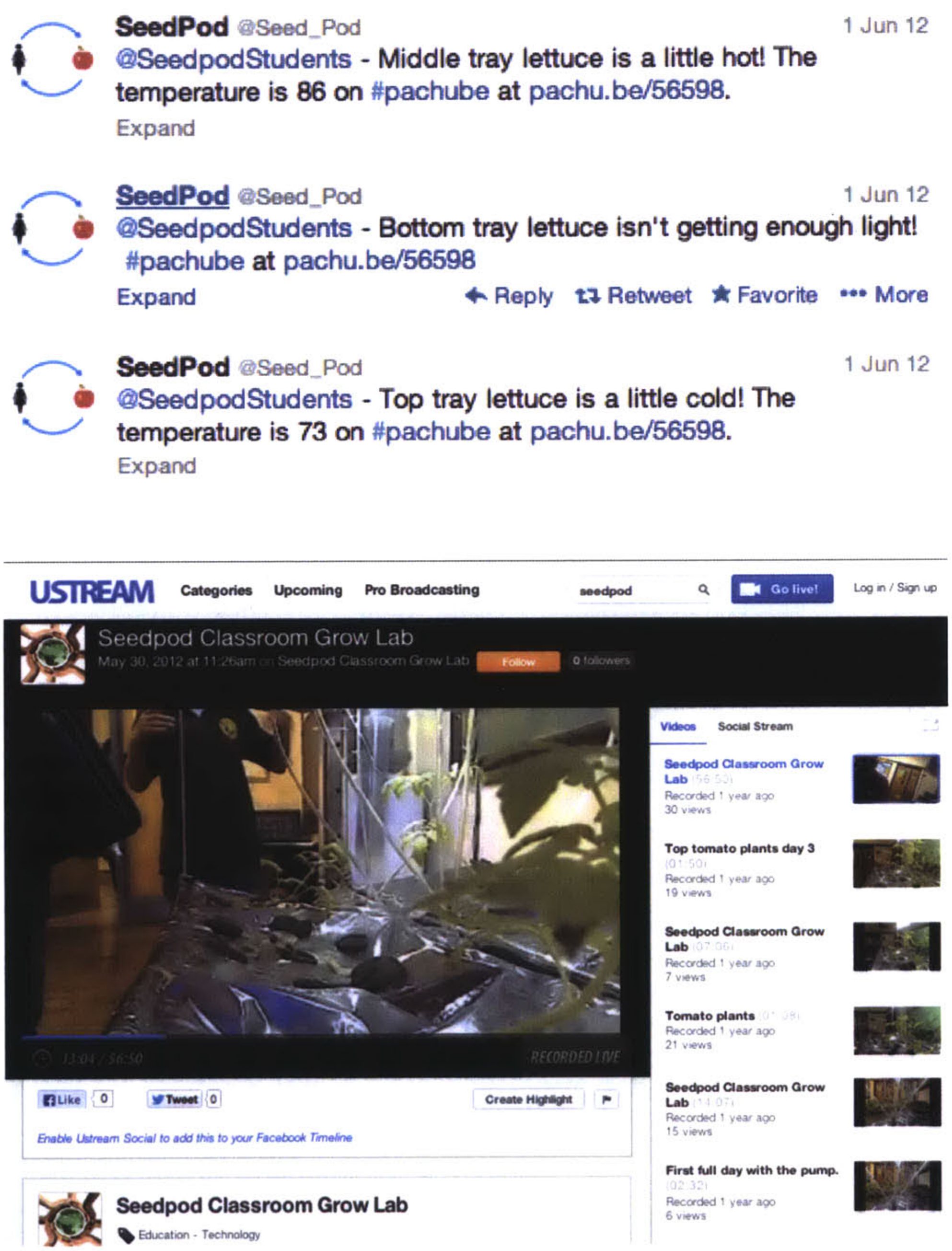



Figure 5.3 Top: Twitter feed from the SeedPod system during installation at Dearborn Middle School. Bottom: UStream channel with live footage of system at Dearborn Middle School.

# 6 SproutsIO (Beta Prototype)

The SproutsIO Urban Microfarm introduces a new strategy for producing and consuming accessible and affordable organic produce, implemented locally and scaled globally to reduce consumer dependence on commercial agriculture.

SproutsIO incorporates modular components augmented by technology such as monitoring sensors, automated systems (misting and lighting), and a smart mobile application to facilitate ease in growing aeroponic produce in cities. A database and monitoring network is set up to assist in determining the growing needs and profiles of plant species in order to provide real-time feedback in assisting with plant care. The mobile application allows for one or multiple users to access one or multiple systems remotely. In this manner, SproutsIO enables a networked community of food producers and consumers. It is the combination of hardware and software with networked capability that has the potential to change the way food is produced and consumed in cities.

## 6.1 SproutsIO System Design

The integration of the SproutsIO system [Figure 6.] into our lives and homes must be a thoughtfully considered solution to yield a lasting and impactful relationship. SproutsIO needs to serve the essential purpose of providing viable sustenance, while becoming a welcome and pleasing addition to the home. There are three main considerations in the design and implementation of the SproutsIO system as they pertain to the hardware, software and user interface: minimizing system failure and maintenance, maximizing the variety of plant types supported and the production of food in the home, and creating a meaningful user experience.

The following sections describe the design of hardware, software and user interface in detail.

Process documentation of the SproutsIO prototype can be found in the Appendix.

### 6.1.1 System Hardware

The SproutsIO system hardware (tower) considers aspects in ease of use such as maintenance, durability, size, form, ergonomics, movability, and power consumption. A balance between manual and automatic features of the system (misting and lighting) encourages personal involvement and investment while minimizing time necessary to operate and maintain tedious system tasks. Sensor technology is integrated into the hardware components to provide a seamless experience between plants, system and user.

The SproutsIO tower is designed to support the growth of a number of plant varieties (see the Appendix for a full listing). It is comprised of modular, unitized assembly of components for a scalable system that can be tiered for multilevel growing. The tower can readily adapt and reconfigure based on plant type and size, growth stage, and production capacity. The demonstration unit (described from bottom to top) is comprised of one base, three connector busses, two tier supports, two tiers, twelve growing pods, twelve sleeves, and one LED top.

See Figure 6. for a diagram of components and tower installation and Figure 6. for a series of component images.

#### 6.1.1.1 Base

The base incorporates the power and CPU for the system while providing the support that keeps the system in balance. There is a 120 V AC to 24 V DC power supply that supplies the main power to the system, as well as a Raspberry Pi, that serves as the central control – that takes in all tier board commands and outputs to the database via Ethernet (see 6.1.2 System Software for further information). The system power is designed to support up to six tiers on one system.

#### 6.1.1.2 Connector Bus

The trunk, or connector bus, supplies the main power and Ethernet to the system. The trunk has an explicit directionality with a front face for Ethernet and power connectors to mate with the tier support, and top and bottom connectors that only attach in one direction for ease in assembly. The connectors are robust for power needs and reinsertion, with design consideration to isolate water and electrical contacts. The power lines use 10 gauge stranded wire with fuses to protect the user and system should it come in contact with water or a high voltage surge.

#### 6.1.1.3 Tier Support

The tier support is a three-piece 3D printed ABS plastic substrate that is hollowed for insertion of power and Ethernet lines with their respective connectors. The tier support not only acts as a support for the weight of the tier, it also transfers the lines from vertical to horizontal within the system. The support can be clamped onto the trunk segments with magnetic closures at 6" intervals to allow for flexibility in plant height throughout the system.

#### 6.1.1.4 Tier & Tier Board

The tier is the most complex component of the SproutsIO system. On the exterior, it provides the support for each of the pods, or growing chambers, through a series of laminated acrylic laser-cut sections. On the underside of each tier are the LED fixtures that provide illumination to the plants on the tier below. Sufficient heat-sinking for high output LED's is also a material consideration. On the interior it holds the tier board, which serves as the intermediary controller between the CPU and the pod boards. The tier board is the main control of all of the automated components of the system: misters, lights (and setup for future water valves and cameras). It also takes in sensor data via I2C from each of the six pod board sensors. The tier board runs 5 power supply lines for the system: 24V (misters), 15V (LED's), 9V (cameras), 5V (AVR Microcontroller), 3.3V (Multiplexer to/from pod boards).

#### 6.1.1.5 Pod

The pods are the main growing chamber for the plants. The pod structure is made of collapsible food grade silicon that allows for the form to adjust depending on plant size and root growth, accommodating a variety of plant types and growth stages. The pod can also be removed from the system for easy harvesting and can be placed in the dishwasher for ease in maintenance.

At the base of each pod is an ultrasonic mister with an in-use LED and a water level sensor that provides a fine mist of water and nutrients when water is added to the pod. The use of the ultrasonic mister is an improvement to the system design from the earlier SeedPod prototype, as it allows for misting uncoupled from a centralized pump; a frequent cause of failure in many aeroponic systems.

#### 6.1.1.6 Sleeve & Pod Board

The sleeve sits into the pod to hold it in place within the tier opening, and serves as the primary support structure for the plants. The sleeves have a variety of hole openings and diameters to accommodate different plant sizes with growing substrates (laser-cut neoprene or small growing baskets) that sit into the sleeve.

The sleeve also has an opening that allows for the pod circuit board to rest in it. The pod board incorporates sensors that have the ability to make plant health transparent and assist in early detection of problems. Light, temperature, pH and humidity are the major sensor feeds of the system that are transferred via I2C to the tier board with the use of a waterproof connector.

#### 6.1.1.7 Top

The top is a two-piece 3D printed ABS plastic substrate. There is one top per system, and it should be the last component added to the system. The top houses a small regulating circuit and LED lighting for the tier below (it can also can serve as a future reservoir for water/nutrients to be distributed to the system).

### 6.1.2 System Software

While hardware is the primary tool to aid in plant cultivation, software communications brings the system to life. The SproutsIO system incorporates a database platform for automation and real-time sensor analysis that can be accessed via mobile application.

While the early SeedPod prototype utilized largely external API's (Pachube, Cosm) and communication interface (Twitter) to display simplistic information about the system, the SproutsIO software integrates the inputs and outputs to the system hardware through a primarily custom designed architecture. This is implemented in order to facilitate scalability, customization and control of system attributes. See Figure 6. for a system wide protocol diagram.

However, there are some limitations to the software architecture that would need to be addressed for future scalability such as server size and access with MIT protocol, and the implementation of interrupt-driven I/O rather than polling based sampling in communication between the database and the mobile application/system hardware.

The major system software occurs at two levels: tower communication (between pods, tiers and towers) and tower to database communication, as detailed below.

### 6.1.2.1 Tower Communication

The center of the tower communications is the CPU or Raspberry Pi that interfaces with the server through HTTP requests. The Raspberry Pi coordinates with all the tiers on a single SPI line. On each tier, a script running on the AVR microcontroller communicates with up to six pods with eight sensors on each over its single I2C lines. The conflict of the I2C addresses for each pod is resolved by using a multiplexer to select the appropriate lines.

### 6.1.2.2 Database

The SproutsIO mobile application must speak through a server-based program (PHP scripts) to the SproutsIO tower and vice versa via JSON strings. This server-based program is designed to push and request settings that are then stored and accessed through the database.

The database that the PHP script uses is run in MySQL. The tables within the database have been organized to represent certain groups of information that are associated with pods and plants. A "tower" contains multiple "tiers" which contain multiple "ports" (or the holes in which a pod is placed). This is meant to correspond closely with a physical SproutsIO tower. Each tower is given a unique id. The tiers within a tower are numbered in increasing order with a starting index of 1. The ports are numbered in increasing order in a counterclockwise direction from the front of the tower. A "pod" in the database is a specific tower/tier/port combination and is denoted as such:

{"tower": 36, "tier": 2, "port": 1}

This is an example of a JSON string used to communicate between the tower and the mobile application.

## 6.1.3 System User Interface

The SproutsIO mobile application is developed for the Android platform on both mobile phone and tablet devices. The application is designed to emulate the physical interaction with the SproutsIO tower through pictographic icons associated with the tower/tier/pod structure. Users are able to control the system through these three categories. For example, a user can control the LED lighting settings for an entire tower, and can then enter the settings for each pod to customize the LED lighting for that pod.

Each of these categories has a customized menu depending on what features are accessible. All three screens have a "Home" button to return to the home screen, a "Notification" button, that gives the status of the system through notifications, a "Reload" button, which fetches the latest status and sensor readings from the server for that category, a "Control" button, to change scheduled misting and lighting cycles, and a "Settings" button to customize background colors and change the name shown at the top of the screen based on category. In addition, the tower and tier display screens have a "Search" button, which allows searching for plant and pod information. The menu on the pod status screen has a "Library" button that allows you to search through different plant types that can be planted in the system.

The tower [Figure 6.] and tier [Figure 6.] screens function in a similar manner; when an area is highlighted green, the plant status is in good condition. If the area is highlighted in magenta, then a setting should be changed to improve conditions for the plant(s). The pod screen [Figure 6.] has a different configuration that allows for modification and viewing of sensor data.

### 6.1.3.1 Automation & Scheduling

Scheduling of automated components is a very important consideration of the system in order to allow for ease in maintenance and control of planting environment. The scheduling automation features can be accessed via the mobile application [Figure 6., Figure 6., Figure 6.].

Scheduled misting (frequency/duration) on a daily or weekly basis is supported through the application. The misting can be controlled on a tower, tier or pod level. LED lighting (on/off) can be controlled on a time allotted daily or weekly basis.

Settings implemented on the tower level cascade through the whole system. Changes to the tier level effect only that tier and its representative pods. A change made to the pod level removes any settings made at the tower or tier level above as it relates to the pod. The remaining pods in the tier are no longer attached to a tier or tower command. This aids in avoiding multiple schedules running at one time.

### 6.1.3.2 Sensor Data

SproutsIO incorporates sensors that have the ability to make plant health transparent and assist in early detection of problems. The sensors are located on the pod board housed in the pod sleeve, in close proximity to the plants that are being monitored. All sensor data collected is pulled to the server database and fetched by the mobile application. Sensor information can be found in the pod level category of the application.

Light, temperature, pH, humidity and water level are the major sensor feeds of the system. These sensors were selected because they are the most applicable, readily available, and cost effective in monitoring plants.

The photocell array measures not only the intensity of light, but also the color of light for Red, Green, Blue and Infrared values. This array can assist in accommodating the best light spectrum for the specific plant profile. The incorporation of infrared allows for the measurement of plant health through reflectivity of light. The temperature sensor, and humidity sensor are simplistic analog gauges. The pH sensor is a circuit devised in order to accommodate pH readings for an aeroponic system through resistance readings. The water level sensor is a valve that triggers an automatic shutoff if the water level in the pod rises above a certain level to protect water spill.

These sensor feeds are pulled to the database, monitored over time and aggregated to assist with optimizing plant growth. The mobile application will pull this data, providing visualization and recommendations for optimizing plant growth [Figure 6.].

Figure 6.1 SproutsIO demonstration prototype.

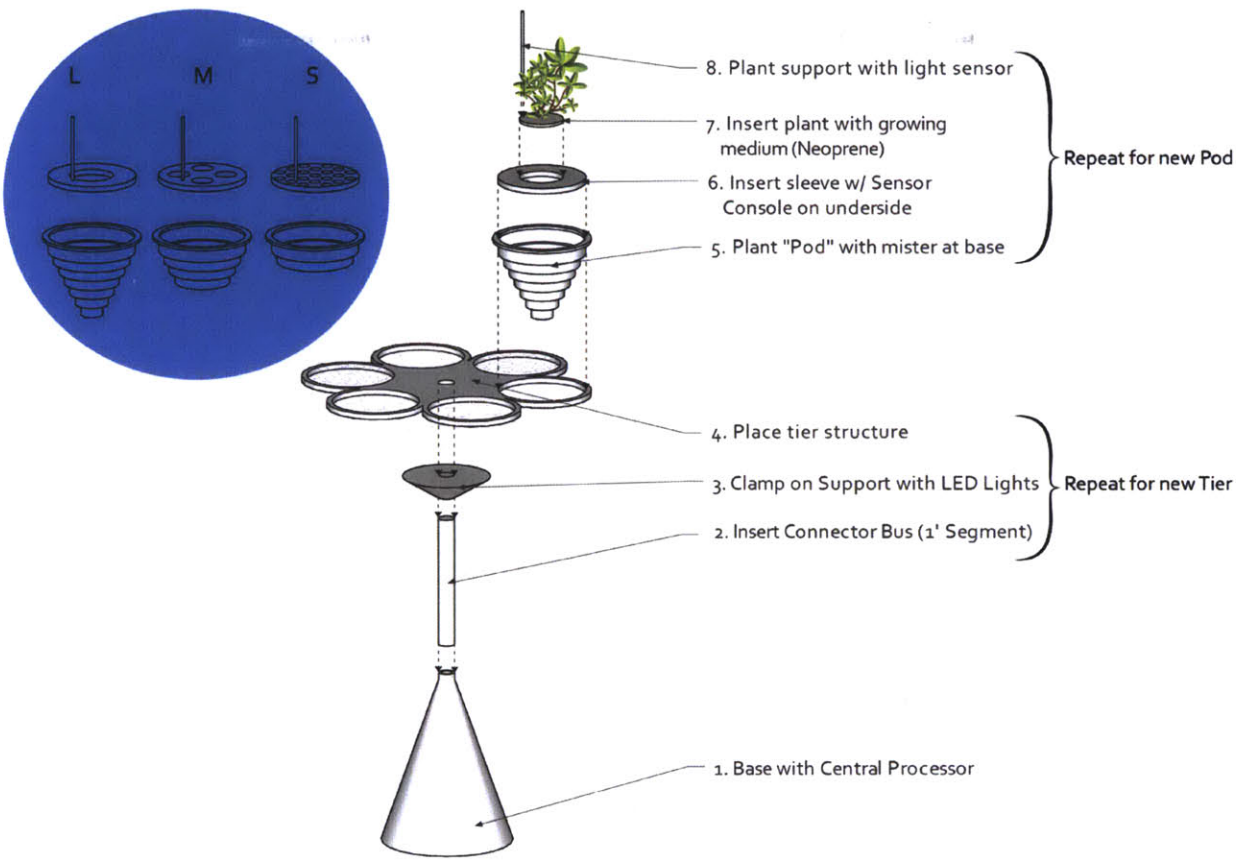
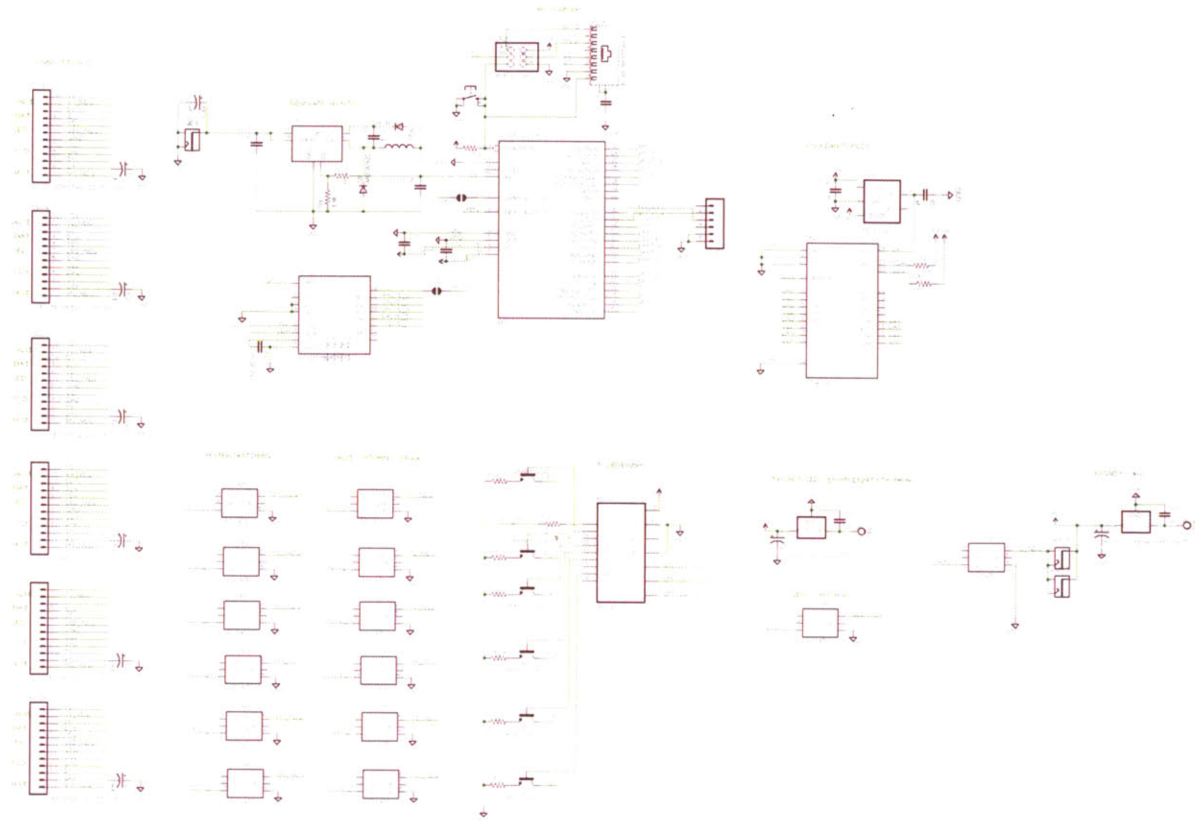



Figure 6.2 SproutsIO modular component description and installation diagram.

Figure 6.3 Six steps to install the modular system, repeat as needed for number of tiers added to system.



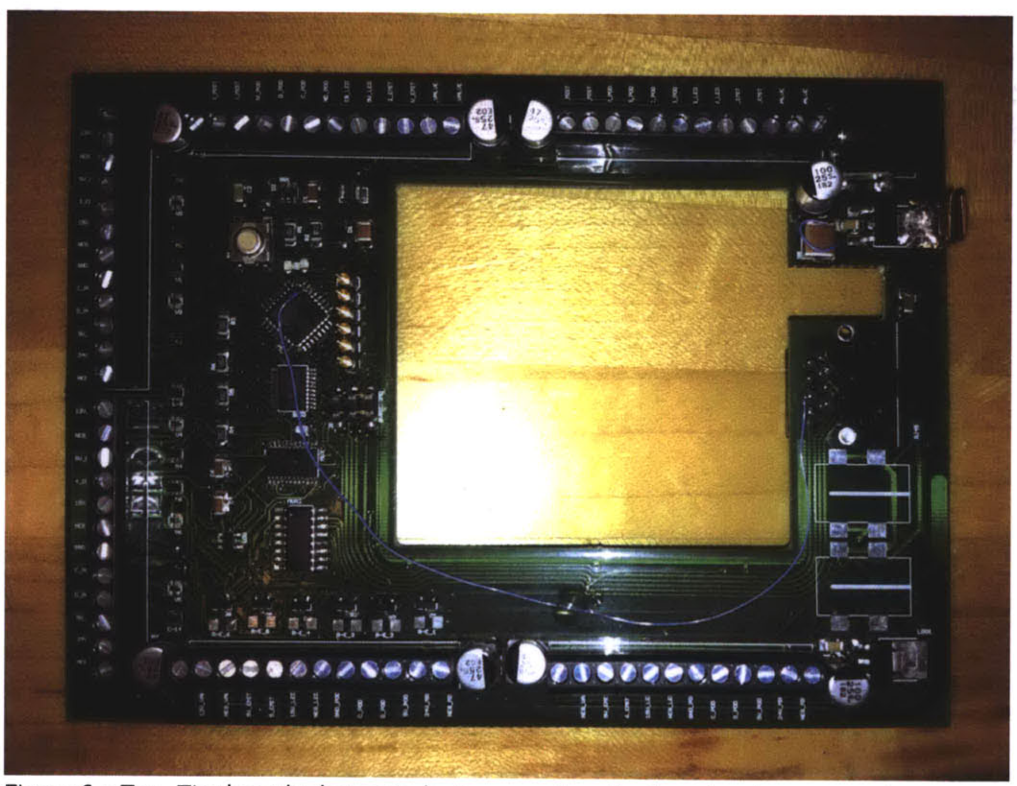


Figure 6.4 Top: Tier board schematic, bottom: custom tier board and components.

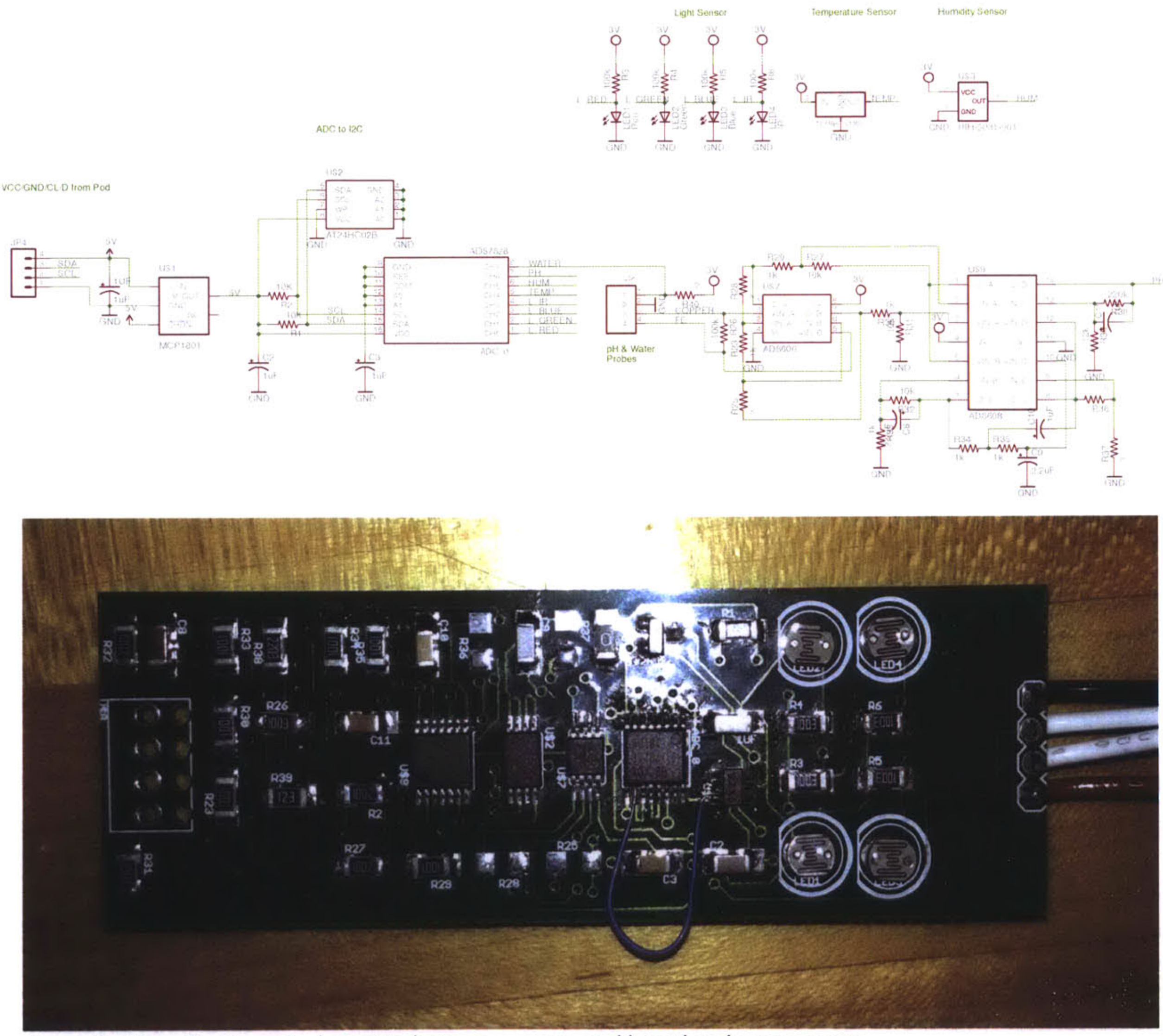



Figure 6.5 Top: Pod board schematic, bottom: custom pod board and components.

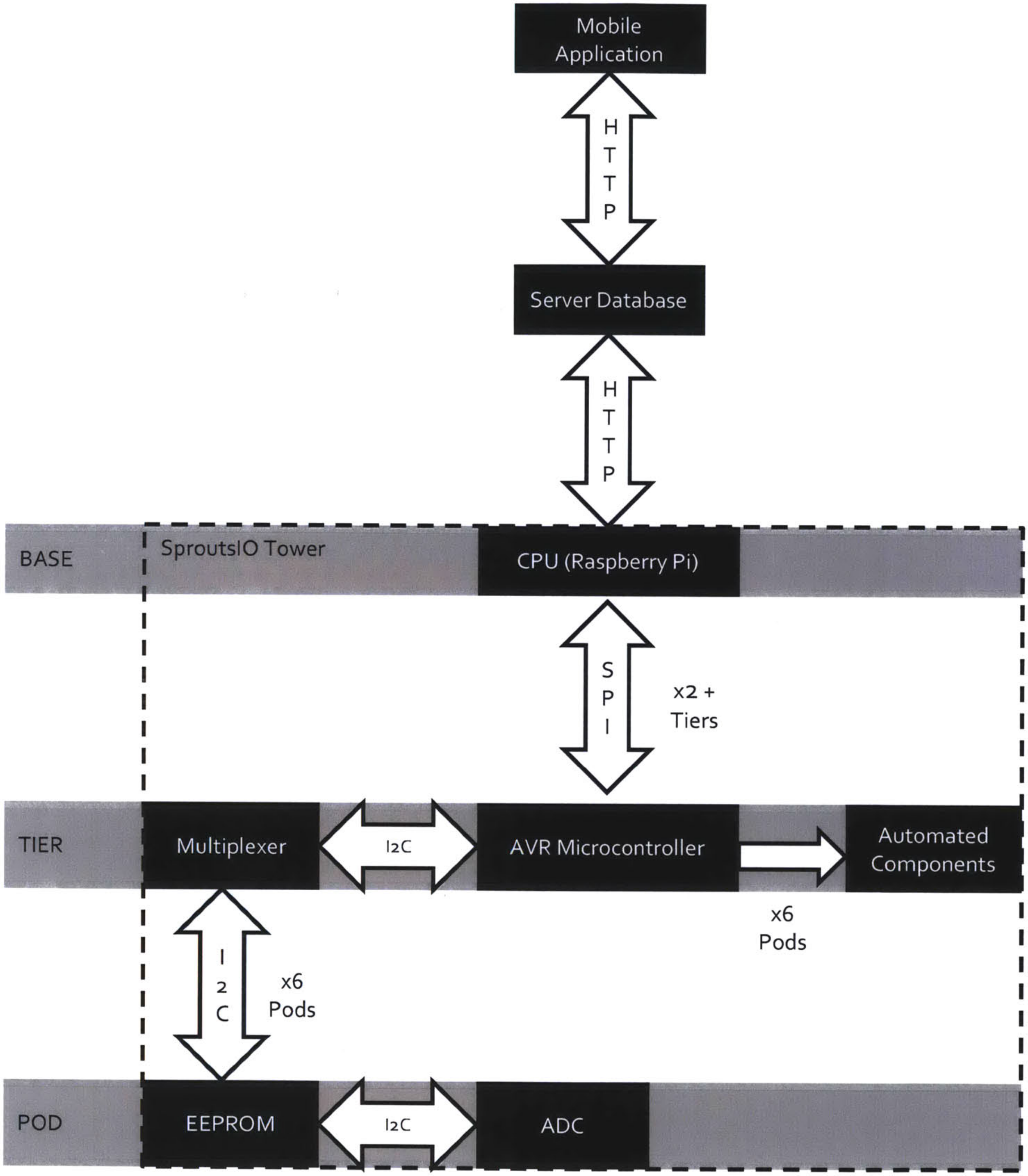


Figure 6.6 System protocol diagram

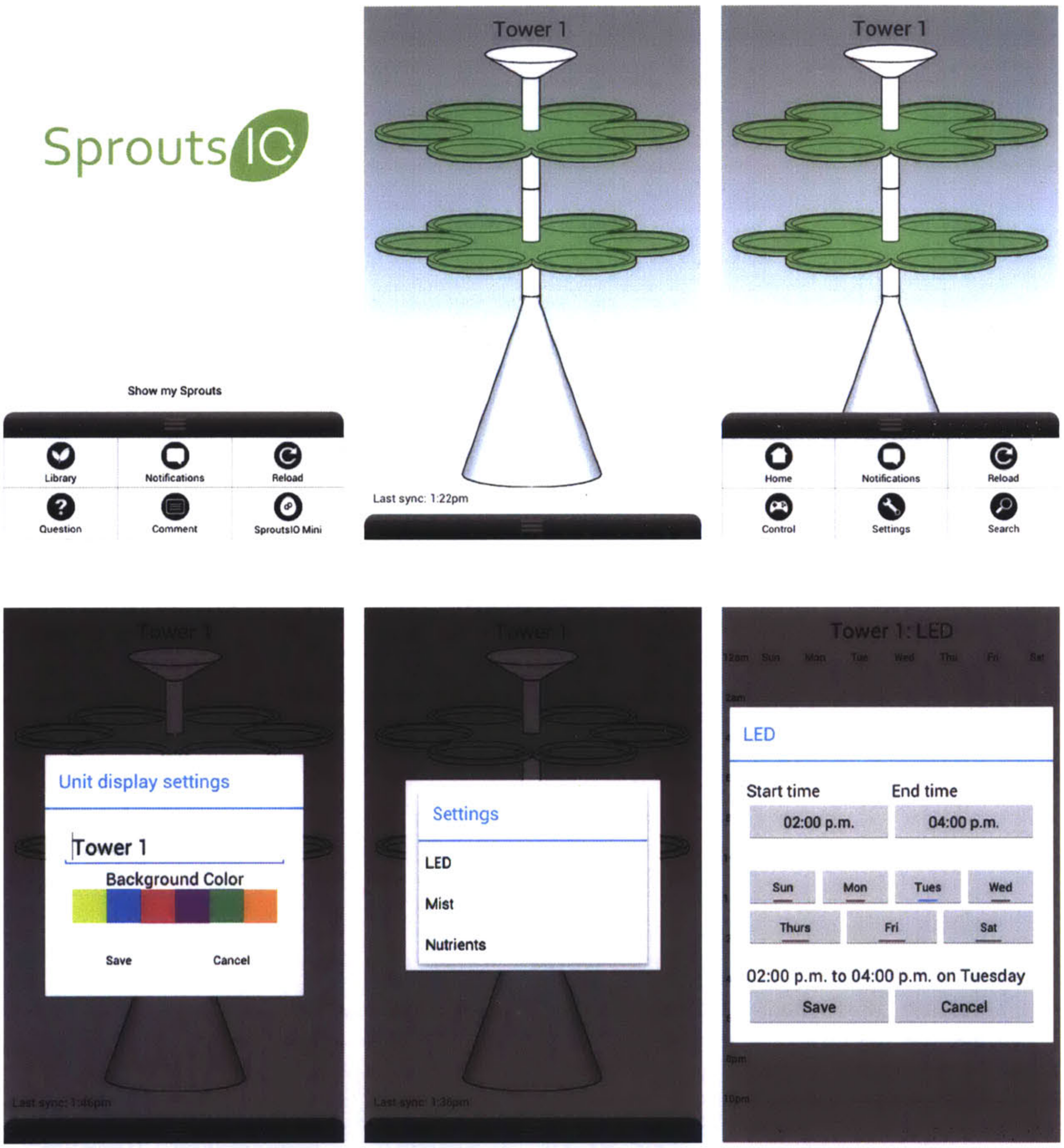



Figure 6.7 Tower level navigation of mobile application. Top: Enter application with menu, tower level control, menu for tower level. Bottom: changing settings for the tower, change control settings on a tower wide basis for LED, mist and nutrients, changing calendar scheduling for LED lighting for the tower.

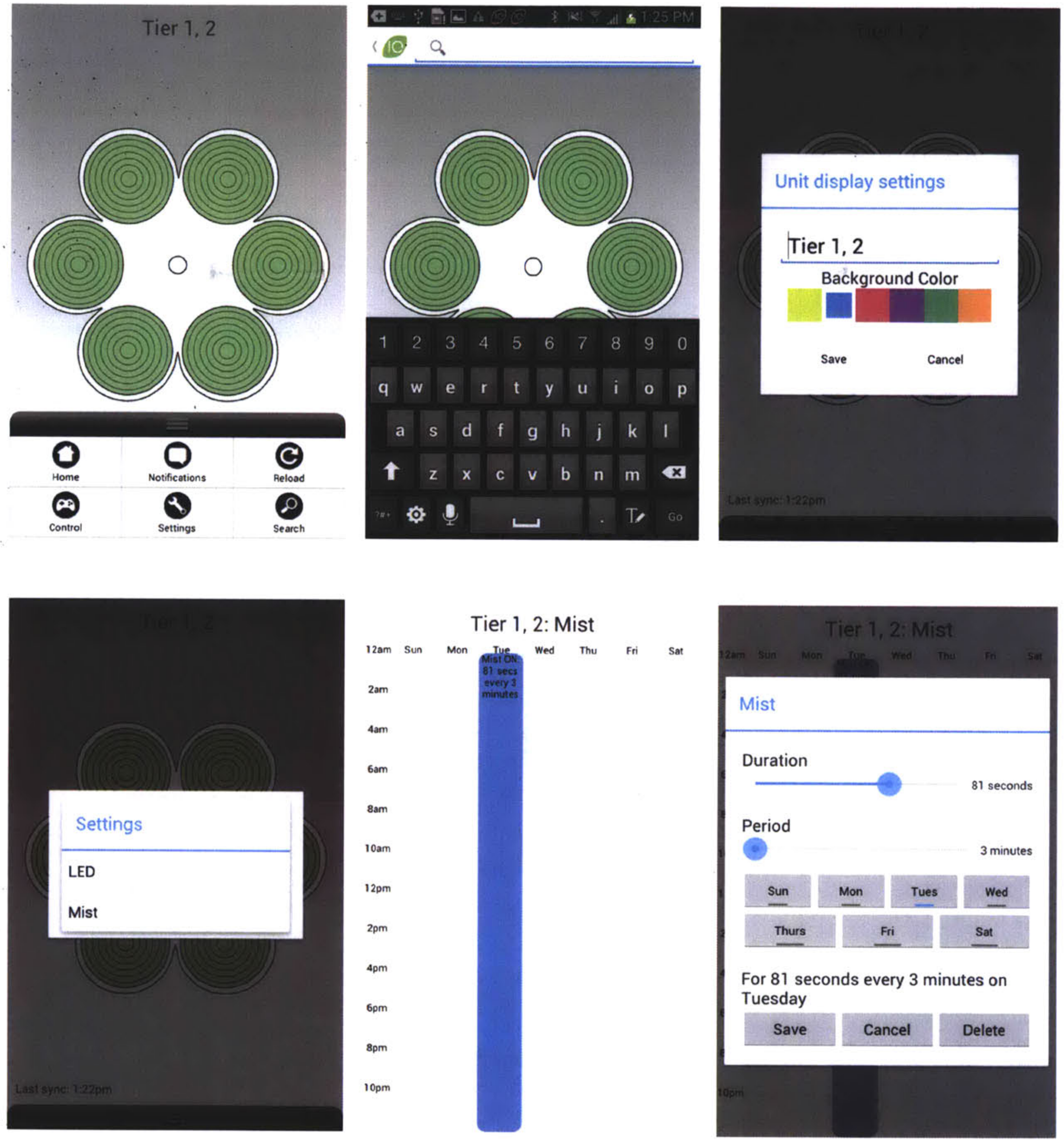



Figure 6.8 Tier level navigation of mobile application. Top: menu bar, search, settings button to change name and color associated with tier. Bottom: Control settings for LED and Mist, scheduling calendar misting on a tier wide basis, changing calendar settings.

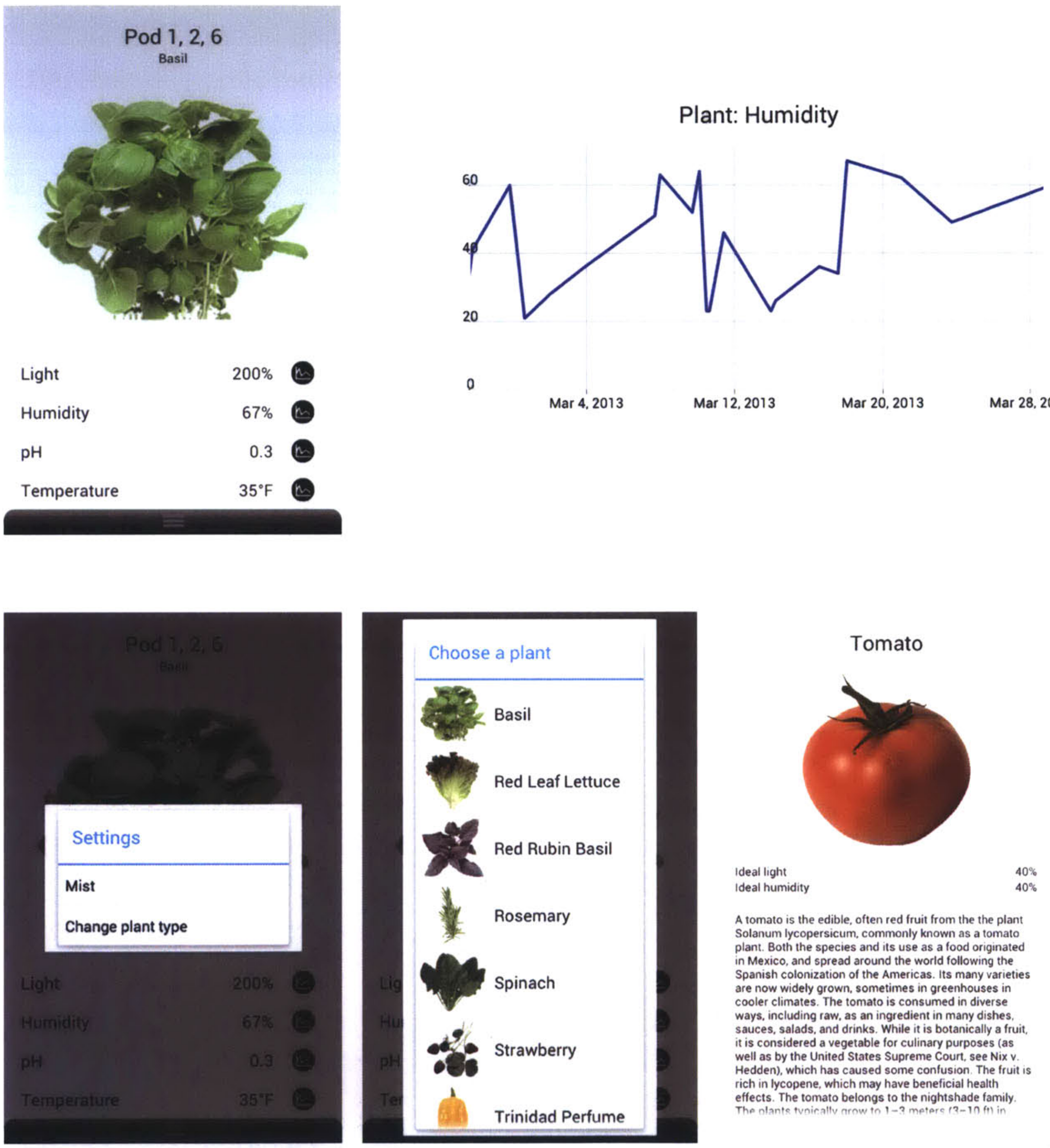



Figure 6.9 Pod level navigation of mobile application. Top: accessing sensor data feeds with history for each plant. Bottom: changing the plant type via the plant library for the pod.

# 7 Cost & Production Analysis

An important metric to consider when determining the viability of an *urban microfarm* system is the purchase price, which for the purposes of this thesis, will be drawn in comparison to a conservative estimate for produce grown by the consumer over a yearlong period. The idea is to create a 100% return on investment to the user within a one-year interval as a baseline value proposition.

An analysis is conducted comparing standard vs. organic produce that can be grown in a *urban microfarm* over a typical one-month period [Figure 7.1] through the online urban grocer, Fresh Direct in New York City. This analysis shows that cumulatively over a one-year period, approximately $560 worth of organic produce purchased would need to be grown in the *urban microfarm* per person.

In an analysis conducted with varied food plants for an *urban microfarm*, estimates show that it is possible to provide 112% of a persons' yearly fruit and vegetable intake within one square meter of growing area [Figure 7.4] (considering that all produce is able to be grown in the SproutsIO system as detailed in the Appendix). With a three tiered, or 12 square foot, SproutsIO system configuration, ample margin of error is accommodated to grow the projected $560 worth of organic produce over a yearlong period.

In order to determine a target projected system cost, the average manufacturer markup value used by the DOE for household appliances averages at 1.26[19]. Addressing the target audience of consumers who purchase organic produce in urban areas, the target cost of goods is estimated at $444 for the projected three-tier SproutsIO system.

In consideration of expanding the market to consumers in urban areas that do not typically purchase organic produce, the cost of goods is estimated at $297 for the projected three-tier SproutsIO system in comparison to commercial produce pricing.

The SproutsIO prototype is well beyond the cost of these projections. The estimated cost from the Bill of Materials (BoM) is approximately $2230 for a 3 tier system as described. In order to reduce the cost of the system, value engineering and design considerations would need to be made for mass production.

[19] "Appliance Standards: Manufacturer Markups," http://www1.eere.energy.gov/buildings/appliance_standards/residential/pdfs/aham2_dfr_ch06_markups_2011-04-13.pdf.

freshdirect®

SproutsIO Cost Analysis August 2013

| Produce | Organic | Commercial |
|---|---|---|
| Arugula | $2.99 | $1.99 |
| Boston Lettuce | $2.99 | $2.99 |
| Broccoli | $3.99 | $2.99 |
| Beets | $7.98 | $5.36 |
| Cilantro | $2.49 | $1.99 |
| Garlic | $2.00 | $1.60 |
| Green Zucchini | $4.49 | $4.12 |
| Cucumber | $7.98 | $3.00 |
| Leeks | $3.99 | $2.99 |
| Vine Tomatoes | $8.38 | $5.57 |
| Grape Tomatoes | $7.98 | $5.98 |
| Green Beans | $11.98 | $3.98 |
| Red Bell Pepper | $7.19 | $3.59 |
| Orange Bell Pepper | $3.50 | $2.00 |
| Yellow Bell Pepper | $3.59 | $1.60 |
| Yellow Onion | $4.18 | $2.97 |
| Romaine Lettuce | $2.99 | $2.49 |
| Gold Potatoes | $4.77 | $7.15 |
| **Comparable SproutsIO Produce Total (for 2 people)** | $93.46 | $62.36 |
| **Cost Per Person/Month** | $46.73 | $31.18 |
| **Cost Per Person/Year** | **$560.76** | **$374.16** |

Figure 7.1 Cost analysis of standard vs. organic produce that can be grown in the SproutsIO system over a typical one-month period (groceries purchased originally for two people).

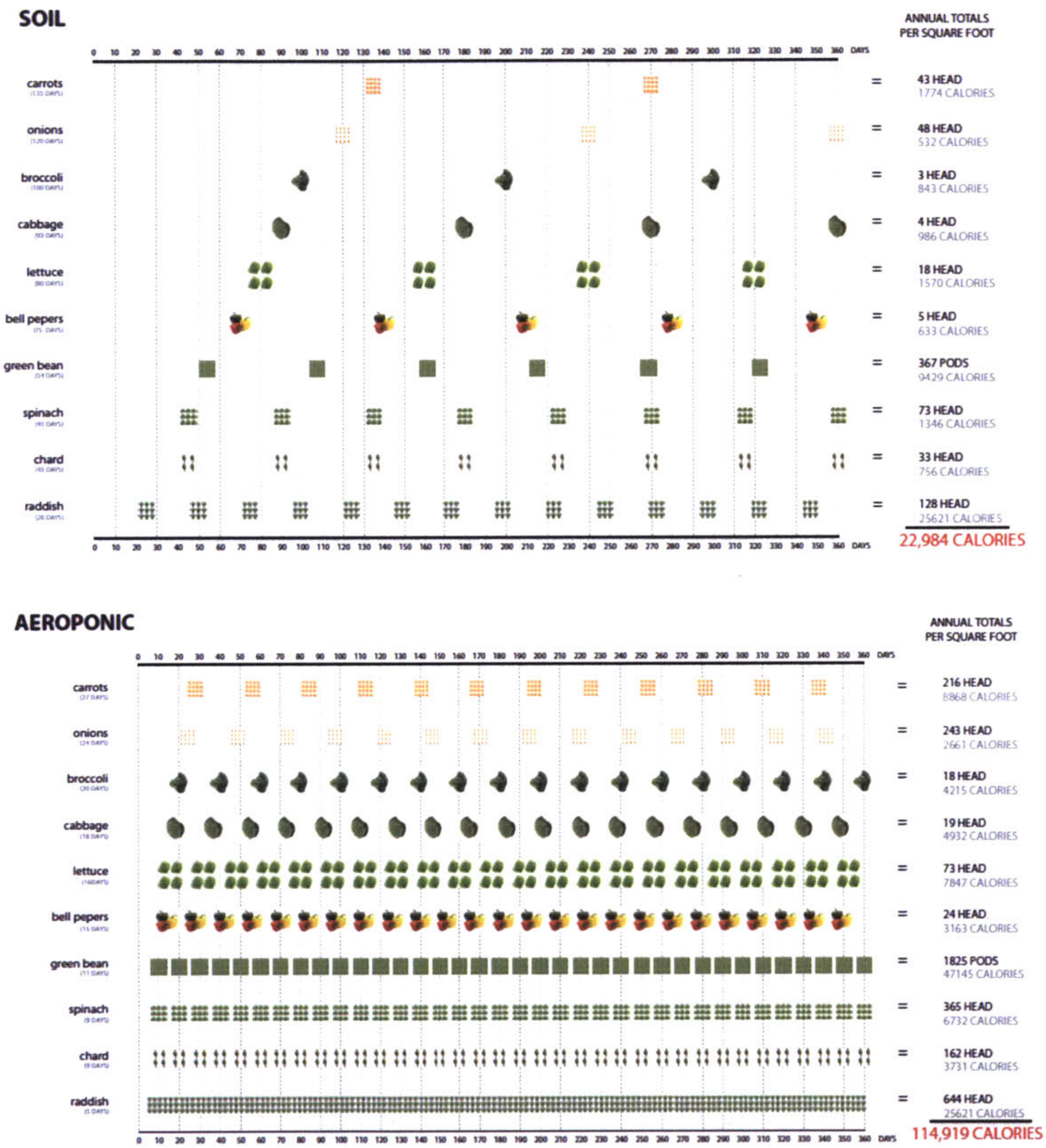



Figure 7.2 Comparison between soil and aeroponic growing in 10 square feet (1 square meter) for 10 varieties of fruits and vegetables (with Living Labs class, MIT Media Lab).

SproutsIO BoM

| Area | Use | Quantity/System | Cost/Part | Cost/System |
|---|---|---|---|---|
| **Materials** | | | | |
| Tier | 7A Receptacle | 3 | $0.21 | $0.63 |
| Tier | 7A Pin | 6 | $0.11 | $0.66 |
| Tier | Tier Structure | 6 | $55.76 | $334.56 |
| Tier | Tier Top | 3 | $37.60 | $112.80 |
| Pod | Sensor, Waterproof Recept | 18 | $3.34 | $60.12 |
| Pod | Sensor, Waterproof Plug | 18 | $2.30 | $41.40 |
| Pod | Mister, Waterproof Recept | 18 | $2.02 | $36.36 |
| Pod | Mister, Waterproof Plug | 18 | $1.80 | $32.40 |
| Pod | Waterproof Pin | 108 | $0.10 | $10.80 |
| Pod | Waterproof Socket | 108 | $0.10 | $10.80 |
| Trunk | 7A Receptacle | 2 | $0.21 | $0.42 |
| Trunk | 7A Pin | 2 | $0.11 | $0.22 |
| Trunk | 2" PETG Tubing | 3 | $6.89 | $20.67 |
| Trunk | Ethernet Splitter | 6 | $0.98 | $5.88 |
| Trunk | 6" Ethernet Cord | 9 | $0.50 | $4.50 |
| Trunk | 50A Power Receptacle | 3 | $1.37 | $4.11 |
| Trunk | 50A Power Plug | 3 | $1.26 | $3.78 |
| Trunk | 50A Pin | 6 | $0.56 | $3.36 |
| Trunk | 50A Socket | 6 | $0.56 | $3.36 |
| Sleeve | 7A Plug | 3 | $0.23 | $0.69 |
| Sleeve | 7A Socket | 3 | $0.15 | $0.45 |
| Sleeve | 6" Ethernet Cord | 3 | $0.49 | $1.47 |
| Base | 24V DC @ 25A (4 Tier) | 1 | $159.95 | $159.95 |
| **Electronics** | | | | |
| Pod | Analog-to-Digital Converter | 18 | $8.94 | $160.92 |
| Pod | EEPROM | 18 | $0.13 | $2.34 |
| Pod | OpAmp | 24 | $2.41 | $57.84 |
| Pod | OpAmp | 18 | $3.66 | $65.88 |
| Pod | Humidity Sensor | 18 | $11.89 | $214.02 |
| Pod | Photocell | 72 | $1.58 | $113.76 |
| Pod | Temp Sensor | 18 | $0.83 | $14.94 |
| Pod | Circuit Board | 18 | $20.00 | $360 |
| Tier | Capacitor | 36 | $0.14 | $5.04 |
| Tier | Capacitor | 54 | $0.08 | $4.32 |
| Tier | Capacitor | 36 | $0.66 | $23.76 |
| Tier | Capacitor | 6 | $0.22 | $1.32 |
| Tier | DC Jack | 9 | $1.89 | $17.01 |
| Tier | LDO | 3 | $0.52 | $1.56 |
| Tier | MUX | 3 | $3.31 | $9.93 |
| Tier | Microcontroller | 3 | $3.05 | $9.15 |
| Tier | IR Emitter | 18 | $0.50 | $9 |
| Tier | Switching Regulator | 3 | $4.73 | $14.19 |
| Tier | Mosfet, for DC | 21 | $0.75 | $15.75 |
| Tier | LDO | | $1.88 | $0 |
| Tier | LDO | 3 | $1.88 | $5.64 |
| Tier | Capacitor | 6 | $0.47 | $2.82 |
| Tier | Shottkey Diode | 3 | $0.26 | $0.78 |
| Tier | Multiplexer | 3 | $2.25 | $6.75 |
| Tier | Circuit Board | 3 | $68.00 | $204 |
| Tier | Terminal Block | 18 | $2.41 | $43.38 |
| Tier | Shottkey Diode | 3 | $0.26 | $0.78 |
| Tier | Capacitor | 3 | $0.42 | $1.26 |
| Tier | Inductor | 3 | $0.29 | $0.87 |
| Tier | Diode | 3 | $0.17 | $0.51 |
| Tier | Header | 3 | $0.62 | $1.86 |
| Tier | Capacitor | 18 | $0.54 | $9.72 |

Figure 7.3 SproutsIO general Bill of Materials (BoM)

# 8 User Testing

A series of user testing experiments were conducted to analyze three important areas of system design and function. In each study an analysis of purpose, conditions, procedure, and analysis in the form of data or a case study is documented. The surveys given for each study can be found in the Appendix.

## 8.1 User Interface Study

One of the main features of the SproutsIO system is the ability to care for your physical plants remotely and virtually through the SproutsIO mobile application. The purpose of this study was to understand how intuitive and useful the application is and how users respond to growing remotely and areas for improvement. See Figure 6., Figure 6. and Figure 6. for a view of the mobile application.

### 8.1.1 Conditions

This study was conducted with ten users over the course of a two day period at the Changing Places conference table at the MIT Media Lab. All users were between the ages of 20 – 35, male and female (target user age). The users were asked to rate their growing experience on a scale of one to five with associated experience listed. All users fell in the categories of no experience (one) to mid level experience (three: I grow in my home with potted plants, and I have gardened outdoors occasionally). Each user interacted with the application independently, without assistance other than the completion of tasks outlined on the survey. The user was required to complete each task before moving to the next, and a suggested time limit per task was listed. At the end, the user could come back to any of the questions and fill in areas that may have been missed the first time through.

### 8.1.2 Procedure

A user is given an Android phone with the SproutsIO application preinstalled. They also have access to a laptop where they can read the instructions and submit responses to the survey. A series of introduction questions are asked to understand the the background of the user annonymously. The user is then asked to view a short video on the SproutsIO to understand the concept and ideas behind the project.

The user is given 15 minutes to answer a series of questions. Question 1 asks the user to orient themselves with the application to familiarize themselves and then provide an initial response. Questions 2-10 ask the user to complete a series of specific tasks to access main features of the application. These questions are answered as either complete/incomplete or with a short answer. No instructions were given to complete tasks in order to understand how intuitive the application is. Questions 11-15 are short answer questions that ask the user to provide feedback and respond to their experience with the mobile application.

### 8.1.3 Results & Observations

For the initial play interaction, users generally appreciated the pictographic format of the application and were able to navigate easily through the menus and features, however there were specific comments noted to increase useability. These comments were largely focused around how to make the location of specific plants in the system easier for the user to find.

- Signal to scroll through the different towers/tiers to access additional plants.
- Suggested numbering of pods on the tier level – to quickly access which plants
- Showing an actual picture of the plant in the pod when it is planted on the Tier level
- Values for sensors need to be equated to plant health in a more graphic manner.
- A few people mentioned that they were not experienced using android applications, so some of the conventions for android were not clear.

The second section addressed specific tasks that are the core attributes for the mobile application.

Completion rate for Mobile Application tasks:

90% - Q2: Misting Scheduling on Tower level
80% - Q3: LED Scheduling on Tier level
80% - Q4: Change Plant Type on Pod level
90% - Q5: Search for Plant Type
100% - Q6: List Attributes for Sensors on Pod level
80% - Q7: Select Sensor Attribute on Pod level
40% - Q8: Sync system on Tower level
90% - Q9: Use settings to change color and name on Tier level
70% - Q10: Check notifications and add plant to Pod

It is important to note that complete/incomplete rates were not random, as two users had consistant difficulty with the application. One user did not determine how to access the menu, which overall became a problem in completing tasks. The other user had trouble understanding the numbering and placement of the plants in the tiers/towers. From this interaction, it would be useful to create a more intuitive numbering/picture system to access each plant growing, and to make the menu more apparent to access or duplicate the functionality on screen rather than in a pull up dashboard. General areas to be improved are the syncing feature to update the system, and notifications access.

In regards to the feedback and experience, 100% of the users agreed that they would be interested in using the application for growing plants. Users liked the pictographic display of the system, the plant library feature, and the notification ability. Users asked for the addition of cameras that could monitor the system and would be accessible on the mobile application. Improvements could be made to access of the menu, specific plant location within the tier/tower, logical comparison of sensors to plant health.

# 8.2 System Design and Construction Study

In order for the SproutsIO system to become a welcome and pleasing addition to the home, it is important to understand ease of use in assembly and planting of the system. The first interaction with the physical system is extremely important in ensuring longevity of use. If users become frustrated with the installation or initial planting, then the likelihood of adoption is slim. Positive reinforcement and affirmation in growing during a users first encounter with the system is key towards promoting adoption of the system.

## 8.2.1 Conditions

This study was conducted with eight users over the course of a two day period on the fifth floor of the MIT Media Lab. All users were between the ages of 25 – 60, male and female. The users were asked to rate their growing experience on a scale of one to five with associated experience listed. All users fell in the categories of no experience (one) to upper level experience (four: I grow plants frequently, indoors and outdoors.). Each user assembled and planted the system independently, without assistance other than the completion of tasks outlined on the survey. The user was required to complete each task before moving to the next, and a suggested time limit per task was listed. There was supervision during the course of the assembly and planting with involvement only if a serious problem occurred (such as damage to the system) – there was only one instance where a user needed guidance.

## 8.2.2 Procedure

The user enters a space where they can assemble the system. All contents are inside of a box. There is also a table set up that has water, nutrients, seeds and growing medium for planting the seeds into the system. The user is given a tablet device with the survey in which they can input their response. A series of introduction questions are asked to understand the the background of the user annonymously. The user is then asked to view a short video on the SproutsIO to understand the concept and ideas behind the project. Once this video is completed, the user inputs the time.

Part I is the "Let's Build" portion. The user is shown an image of the whole system assembled as a finished product, and then an overall axonometric assembly diagram of how the components are added to the system. The user is then guided through a nine-step process with complementary images to assemble the SproutsIO tower.

Part II is the "Let's Grow" portion. The user is guided through an eight-step process to plant the SproutsIO tower.

In both Part I and II, the users can view all of the steps at one time for reference, however they are asked to complete each step in the order given. At the end of each session, the user inputs the time, and the assembly/planting is reviewed for proper installation.

Once the user is finished assembling and planting SproutsIO [Figure 8.1], the user is asked to provide feedback on their experience through a series of short answer questions.

## 8.2.3 Results & Observations

The table shows the general profile of each user for reference.

| | Gender | Age | Experience Level | Build Time (mins.) | Grow Time (mins.) |
|---|---|---|---|---|---|
| User 1 | Male | 43 | 2 | 36 | 12 |
| User 2 | Female | 56 | 3 | 17 | 7 |
| User 3 | Female | 34 | 4 | 22 | 6 |
| User 4 | Female | 28 | 2 | 27 | 13 |
| User 5 | Female | 27 | 2 | 22 | 5 |
| User 6 | Female | 58 | 3 | 49 | 8 |
| User 7 | Female | 56 | 3 | 40 | 18 |
| User 8 | Male | 27 | 2 | 13 | 7 |
| Average | | | | 28.25 | 9.5 |

The experience level is based on the metric of:

1: Never tried it.
2: In my home/office with potted plants.
3: I grow in my home with potted plants, and I have gardened outdoors occasionally.
4: I grow plants frequently, indoors and outdoors.
5: I am an experienced grower, my family/myself has grown on a farm.

The average build time for the system based on this analysis is approximately 28 minutes, while the average grow time in approximately 10 minutes. Users generally enjoyed the process of assembling and planting the system. None of the users felt that the time was too long to assemble/grow – even those who spent more time during assembly. In answer to the questions: "Did you enjoy the process? How about the length of assembly - to long/too short?", the response was "Yes! It was fun and the timing is good", "Yes once I got it it was fun and easy." "I did and the assembly time seemed adequate for the unit". All users completed assembly and planning of the system within a one hour time period.

In terms of design improvements for assembly and planting, the most frequent comment was difficulty with the tier support – both in understanding how and where to add it to the system. Additionally, users sometimes confused the top with LED lights for the tier support because they have a similar appearance. Another cause of concern for system design is the possibility of adding two tiers onto one trunk – this has the potential to cause weight distribution problems when planted. Users did not initially understand that the foam support on the sleeve could be expanded to insert the seeds. People were inconsistent in making sure that the pod tops were completely pressed in – this is problematic because can lead to water loss/leakage in the system. The tops must be more easily designed to snap in. Last, use of the proper opening for passage of the mister wire through the sleeve was not always consistent. More explicit directions could alleviate some of these issues; others would need an amendment in system design. See Figure 8.2 and Figure 8.5 for a view of some of these inconsistencies.

Another point of interest is the lack of clarity that the the tiers could be added at varying 6" increments. When one of the users installed it differently than the image in the accompanying survey, they thought that it was assembled improperly. They did not realize that the system could be configured at different heights for different plant types. This along with a feedback from one user of a desire to put the system together in a more flexible way (not step by step), were comments that could aid in the improvement of the general instructions for assembly and growing.

All users responded positively to wanting to have a SproutsIO system in their home/office, and finding it pleasing as an object in their live/work space. All of the users surveyed purchase organic fruits/vegetables to varying degrees. When asked to estimate how much they spend monthly on organic produce, answers ranged from $75 upwards to $400. However, when asked how much they would be willing to spend on the SproutsIO system (in the context of producing a persons yearly organic fruit/vegetable intake), answers ranged from $75 to $1000, with a majority in the $200 to $350 range. It is clear that even when a cost is placed directly in comparison between organic produce and the SproutsIO system, users do not understand or equate the true value of the system. This is an element that needs to be clearly highlighted and examined for the future.

# 8.3 Usability Study: One Week

An one-week usability trial was conducted to test the following system attributes:

- Installation/Assembly
- Component Durability
- Mobile Application
- Database Storage
- Tower Communication
- Electronics
- Automated Scheduling

- Sensor Feeds
- Plant Growth
- User Experience

The trial period was completed, however the study did not progress as intended due to system failures with tower communications and electronics components.

## 8.3.1 Conditions

This study was intended to be conducted with 2 users over the course of a 1 week period. Because of system malfunction, the study was held to 1 user over the course of 1 week. The SproutsIO prototype was installed and planted in the users office at the MIT Media Lab the evening before the start of the trial. A web camera was installed with a UStream channel setup to watch the system remotely. The top tier of the system was planted with tomato plantlets that were germinated prior to installation into the system. The bottom tier of the system was left unplanted for the user to plant as desired.

## 8.3.2 Procedure

On the morning start of the trial period, the user was emailed a set of instructions on how to care for the system, in addition to the .apk installation package for installation of the mobile application on the user's mobile phone. The user was given a username and password unique for their trial period. The user was also asked to complete a daily questionnaire and an exit interview in this introductory email, however this protocol was not followed through because of system failure.

## 8.3.3 Results & Observations

Following is a timeline and conclusions that show a log of the trial session. This format is used to detail areas of issue concisely.

### 8.3.3.1 Timeline

System Install:

- Evening - The prototype was assembled, installed and tested to check for any system issues or inconsistencies. UStream channel was set up to view system remotely. All systems were in check at the time of departure. The system was left plugged in and connected that evening.

Day 1:

- Morning – I reviewed the UStream channel and noticed that the webcam was not recording. User emailed that misters were consistently on, user turned system power off because misters seemed hot.
- Afternoon – User opened office for me. I reset the system, and started UStream camera again. I checked on system status via the backend and the mobile application for troubleshooting. The mobile application can control the system on a tower, tier and pod basis. Settings were not being cleared from the backend when cleared from the mobile application. Troubleshooting system software and mobile application.
- Evening – LED lighting not turning on and off via mobile application direction. Misters seem to be working. System is left on overnight with the LED hardcoded on.

Day 2:

- Morning – I check system early, appears to be running steadily. User emails warning later in the morning - misters are consistently running and not turning off. Misters are hot. User powers off system.
- Afternoon – Ustream channel is down – Internet connection in office area is not consistent – it is determined that this is causing problems with the stream. Troubleshooting mobile application and software backend. Testing circuit hardware also to see if mister mosfets are not switching on and off. Timestamp issues, scheduling not imputing properly from software backend to hardware. Mobile application troubleshooting is resolved with scheduling. Database is functioning properly.
- Evening – System is turned off overnight to avoid mister overheating. Plant sleeves are removed from pod tops, and placed in bucket of water with nutrients to combat root damage.

Day 3: Weekend – No System Access

Day 4: Weekend – No System Access

Day 5:

- Morning – No access to system, user not in.
- Afternoon – User gives access to office. Troubleshooting microcontroller programming to test mosfets. Troubleshooting software system backend and timestamp issues.
- Evening – Troubleshooting continues for hardware and software. System is left off in the evening, misters and LED scheduling continues to be sporadic.

Day 6:

- Morning/Afternoon/Evening – Troubleshooting tower communications and electronics. System on and off intermittently throughout the day.

Day 7: End of Trial

### 8.3.3.2 Conclusions

While the system was not able to run consistently, it was still possible to test certain attributes of the system for functionality. Below is a list of the system attributes that were tested and associated results:

- Installation/Assembly – Completed according to schedule.
- Component Durability – OK. While the system was not running consistently to check normally functioning operation, it was still possible to learn from how the system behaved in the event of failure and through adverse conditions. While the misters and LED's became warm when switching was irregular they did not fail. None of the misters or LED's stopped functioning even though they were running well beyond their expected durations.
- Mobile Application – Complete. Initially, there were issues associated with the clearing of Automated Scheduling settings. This problem was resolved, and the mobile application was functioning as intended.
- Database Storage – Complete. The database is pulling and receiving information as intended.
- Tower Communications – Incomplete. This is the largest point of system failure because there are multiple channels of communication. This is the most complex portion of the SproutsIO system. Timestamp issues, pulling and receiving of information and microcontroller programming issues need to be resolved.
- Electronics – Incomplete. Circuit boards and components are largely functioning as intended; however there may be issue with the mosfets selected. This can only be determined once the tower communications is resolved.
- Automated Scheduling – Incomplete. Issues with tower communications and electronics of system made true testing of automated scheduling not feasible.
- Sensor Feeds – Incomplete. Issues with tower communications and electronics of system made true testing of automated scheduling not feasible.
- Plant Growth – Incomplete. Plant growth study could not be properly measured because system was not consistently running throughout trial period. However, it should be noted that plants were extremely resilient given the adverse growing conditions.
- User Experience – Incomplete. It was not possible to clearly test user experience when the system was not consistently functioning. User was minimally involved the first three days of user testing, and then not involved the last four days due to system failures.

Figure 8.1 Images of users after assembly and planting.

Figure 8.2 Review of problematic assembly configurations. Top: users created a variation with two tiers on one trunk, which could lead to problematic weight distribution. Middle: users installed the LED top early, there was confusion in form between the LED top and the tier supports. Bottom: users installed the tier support upside down.

Figure 8.3 Problematic wiring of misters through center of sleeves, this may be addressed through the insertion of the sensor circuit board. Also note that not all sleeves are secured within the pod.


Figure 8.4 One-week user study evaluation. Above: Day 1 evening streamed on UStream, below: Day 2 daytime while user checks on water in pods.

# 9 Future Work

Urban agriculture and new food production technologies are part of a pioneering field of inquiry that holds much promise. SproutsIO relies on many key fields, from urbanism and engineering to biology and human psychology. A substantial amount of research, design, prototyping and vision is necessary in order to elevate this project from early stage to advanced development.

The scope of this thesis considers the construction of prototypes and user study evaluation, with initial investigations into production metrics and the societal sphere. While this is a substantial amount of work, it does not cover the entire complexity or capacity that the SproutsIO concept can yield, both in terms of research scope and in physical manifestation from prototype to production.

## 9.1 Next Steps

The most immediate next steps for SproutsIO fall into two categories: improvements to prototype and quantitative testing.

The SproutsIO system would benefit from the addition of automated water and nutrient supply lines feeds. The system is currently designed to incorporate these feeds, but a substantial amount of work and calibration is needed to make function properly. The pod boards for the sensor feeds need to be better calibrated and made more robust in order to acquire substantial data for quantitative testing. The LED lighting currently installed is not up to the standard needed for ideal plant performance. Sylvania has agreed to provide high efficiency LED lights for testing, which will need to be incorporated into the system and redesigned for heat sinking.

A series of quantitative analysis studies are needed to determine functional parameters of the system such as power use, durability and sensor feed aggregation. The quantitative analysis will shed further light on how to optimize the system for the next production run. The quantitative analysis will need to be conducted once the physical amendments to the system above are incorporated.

## 9.2 Future System Design

The SproutsIO tower prototype is the first step in implementing a much larger strategy for reconsidering our food system. The vision is to provide a platform that empowers people to be contentious producers and consumers. In order to do this, the system, as well as the means in which this system is utilized must be considered in order to provide a holistic solution.

## 9.2.1 Cloud Farming Marketplace and Forum

The SproutsIO system is designed to allow for a number of users through the mobile application and server database structure. This potential can be tapped into through the networked connectivity of the systems. In this manner the physical and virtual systems can be accessed or viewed by one or multiple users, unlocking a new world of community growing and marketplace possibilities. The online forum is no longer a static entity but can be connected in realtime to the SproutsIO system and user community. Sensor feeds, and data aggregation can be constantly tuned and improved. Automation and scheduling can be viewed and manipulated to improve plant-growing techniques. The marketplace could provide tools and peripheral supplies to SproutsIO users, as well as becoming an online marketplace for people to share or exchange food in the SproutsIO community, and beyond.

A whole extension of services can be connected to the system, such as a virtual farming assistant, or physical harvesting companions. Imagine that every apartment in a building has a SproutsIO system that could be assisted by building farming crew. Or an entire floor is delegated for SproutsIO growing, with food that can be distributed to the building, like an in house, community supported agriculture (CSA) program. The possibilities are vast.

## 9.2.2 Plugin Seed & Nutrient Cartridge

In order to optimize plant growing, the development of a proprietary plugin seed and nutrient cartridge can offer additional ease to users. Different plant varieties and nutrient requirements can be supported. The seed cartridge also offers a razor and blades market model, where users continue to purchase seed cartridges through the SproutsIO marketplace.

## 9.2.3 Plant Database

There will need to be a comprehensive plant database that supplies information about the growth chraracteristics of plants grown in the SproutsIO system. These metrics will be paired with data collected from SproutsIO pod sensors. The more that people collectively participate and crowdsource the sensor feeds of their plants, the more fine tuned the plant growing profiles will become.

## 9.2.4 Manufacturing Considerations

The next prototype phase will consider design for scalability. There are a number of considerations such as the standardization of production techniques such as injection molding of components, UL waterproof connectors, robust misters and electronic components, and high efficiency LED lighting. One important factor in the design and production of this batch run is to consider cost cutting measures through fabrication techniques and standardization of components, as well as value engineering for system design. The target for this phase is to produce a batch run of 50 – 100 units with an installation and testing site. Some potential sites for installation could include a partnership with a local and organic focused restaurant, a school, or an office.

After testing and installation of the batch run, further design and engineering modifications, market strategy, and cost projections can be estimated with an aim toward a production run. The initial strategy is to target mid to high income uraban dwellers as a beta test for early adopters. As the technology continues to develop, streamline, and prices lower for the technology developed, considerations can be made for different markets.

# 9.3 Future Research

In order for the SproutsIO concept to achieve the vision of widespread adoption, research, education and outreach around the concepts inherent to the system is paramount. Without this backbone, the system cannot be effective in providing a new platform for food production and consumption.

## 9.3.1 Education & Outreach

The early SeedPod prototype was a good example of how learning about alternative growing methods could be incorporated into school curriculum. Familiarity with these concepts at an early age allows for acceptance and understanding further in life. Working with the Dearborn Middle School in Roxburry was a wonderful opportunity to see how this can effect and positively ignite the imagination of students.

However, students are only a portion of the population, as adults often forget they too can still learn! Creating programs and workshops for adults to understand the process of cultivating food with CEA methods through the SproutsIO system is also important.

Teaching and learning in context of developing countries and disaster relief scenarios is also important. The ability to adopt the techniques into a particular culture takes time and effort to effectively make a difference. It is key that populations are able to adapt the concepts into their livestyles in a manner that is useful to them.

Another segment of the population that would greatly benefit from learning about CEA growing and SproutsIO concepts are farmers; and often they are the most difficult to approach with new technologies. When people have already incorporated a certain methodology into their lifestyles that seemingly works, it is very difficult to change this habbit – even if the benefits are substantial in the long run. However, a program that introduces these concepts to farmers would be of great benefit not only to farmers, but also to the consumers who are by extension effected by the growing methods employed by farmers.

### 9.3.2 Aeroponic Testing

There are a number of studies that have been done to understand the production metrics and benefits of aeroponic cultivation, however the more institutions doing research in this area, the better. The SproutsIO system and concept can add to this growing body of research through user testing and prototype deployment.

### 9.3.3 Long Term System Testing

In order for the SproutsIO system to go to market at a production scale, additional testing needs to be done. System reliability, maintenance, durability, productivity, and performance all must be analyzed in a comprehensive manner. The ability of the SproutsIO system to output of fresh, organic, fruits and vegetables for people in urban areas sounds simplistic – however the technology needed to do this task effectively is not simplistic. Plants are biological systems that need myriad inputs in order to grow well. Light, water, nutrients, proper temperature and plant support, all need to be maintained through the system in order to provide the best growing environment possible for myriad plants throughout their lifecycle. The SproutsIO system must negotiate between the best environment for the plant and the user – both groups need to benefit and kept in equilibrium in order for the system to serve its purpose.

## 9.4 Future Applications

The SproutsIO concept can be extended into new user groups and markets, however the system design needs to be adapted to facilitate these new contexts. Once the technology has been deployed and tested with the early adopter target market for mid-income urban dwellers, it will become easier to streamline the technology and cut costs for these new markets.

### 9.4.1 New Building Construction

The SproutsIO concept is one that could be integrated into new building construction large scale production and standardization. Like a refrigerator, the SproutsIO system could be incorporated into the building system and plumbed with water and nutrient feeds, as well as electricity. The system could be incorporated like an appliance throughout units in a new apartment building, or could be installed as a prefabricated curtain wall unit on the façade of the building for a large farming surface.

An earlier project investigation (in collaboration with Fluxxlab, Boswyk Farms and the New York City Parks Department) called FaçadeFarm [Figure 9.1], considered the fabrication of a prefabricated façade unit that could be installed for new building construction on the façade of a building. The system used a hydroponic raft system, and was intended to be primarily outdoors, utilizing square footage typically assigned to balconies – the idea being to utilize typically underutilized balcony space as leasable square footage for a new building tenant as a farming service for building occupants.

## 9.4.2 Developing Countries and Disaster Relief

The SproutsIO concept could also be applied to developing countries and disaster relief scenarios. There are a number of benefits of aeroponic cultivation that would be particularly suited these contexts. First is the minimal use of water to cultivate food, this is especially important in countries where fresh, clean water is a precious resource. Second is the ability to cltivate out of soil. In Fukushima, Japan the soil has been compromised by both salt and nuclear contamination from the recent tsunami and nuclear explosion. Farmers and consumers in this region would greatly benefit from a system that allows controlled growing of crops that without contamination. Third is the consistency of CEA systems, where yields are more stabilized due to controlled growing conditions. Food price and access drastically fluctuate globally due to drought, blight or myriad other inclement growing conditions. Fourth is the ability to grow substantially more produce within a smaller footprint – which is beneficial with food shortage that generally is characteristic of developing countries and disaster relief contexts.

The SproutsIO design and implementation would need to be modified to accommodate growing in these settings. It would need to be lightweight, easily transportable and adaptable – it would also need to function in an outdoor setting, utilizing as much as possible natural sunlight. Additionally, the technology used would need to be robust and simplified to cut cost and function in harsh environments. The early SeedPod prototype design, with collabsible, lightweight, and inflateable modules [Figure 9.2], could be adapted for use in this context. However, the cost of the technology would need to lower and the system would need to be more standardized in order for this business model to be feasible – a future incarnation of the SproutsIO system.

Figure 9.1 FaçadeFarm in collaboration with Fluxxlab, Boswyk Farms and the New York City Parks Department, is a prototype for a prefabricated farming module to be attached to the façade of new building construction. *Image courtesy of Lee Mandel*

Figure 9.2 Lightweight, modular growing units in the early SeedPod prototype could be considered for disaster relief and developing countries contexts.

# 10 Conclusions

*"Tools don't build houses. Carpenters build houses.[20]"*

Marshall Ganz

*Urban Microfarming* introduces a new strategy for producing and consuming accessible, affordable organic produce, implemented locally and scaled globally to reduce consumer dependence on commercial agriculture.

The efforts described in this thesis show the first steps toward this much larger vision, not only in terms of hardware and software, but also by engaging users in learning through growing.

The early SeedPod prototype begins investigations into indoor food production using a lightweight and simple system with the characteristics of modular assembly and technology enhanced growing through notifications. SeedPod also initiates a dialogue to introduce alternative growing methods to middle school students through STEM curriculum integration.

The SproutsIO prototype expands upon these investigations through the use of easy to assemble modular components augmented by technology such as monitoring sensors, automated systems (misting and lighting), and a smart mobile application to facilitate ease in growing local, organic aeroponic produce in cities. A database and monitoring network is set up to assist in determining the growing needs and profiles of plant species in order to provide real-time feedback in assisting with plant care. User testing was conducted in order to evaluate the system and process toward implementing future improvements.

*Urban microfarming* proposes a platform that empowers people and communities to become conscientious food producers and consumers through active participation. This platform invites collective participation through feedback of a networked, scalable, and prospective ubiquitous system. Myriad benefits can arise from turning consumers into producers, from more efficient local distribution and reduction of waste to ease of access to healthy and safe organic produce.

*Urban microfarming* has the potential to become a new paradigm for our food system and must be situated as such for the following reason:

It is dangerous that people do not understand that industrial agriculture – an outdated technology, but a technology all the same – is inherently volatile, simply because we depend on it. It is a slow ticking bomb, and is much more unstable than new technologies in the food

[20] "Humanities Greatest Challenge and Its Solution," http://www.huffingtonpost.com/kim-cranston/humanitys-greatest-challe_b_196128.html.

production space, such as SproutsIO. While *urban microfarming* does not presume to replace industrial agriculture, it provides an alternative – and the option for people to make a choice. Turning doubters into believers is necessary for SproutsIO to have a global impact that will make a difference in our food system. This is a large task, but an important pursuit in consideration of future cities.

The reintroduction of localized plant cultivation through the SproutsIO system into our daily lifestyle must be a thoughtfully considered solution in order to yield a lasting and symbiotic relationship between the user and produce. Through *urban microfarming*, learning, community building and growing become a cohesive strategy for rethinking food production, distribution and consumption in increasingly growing urban areas.

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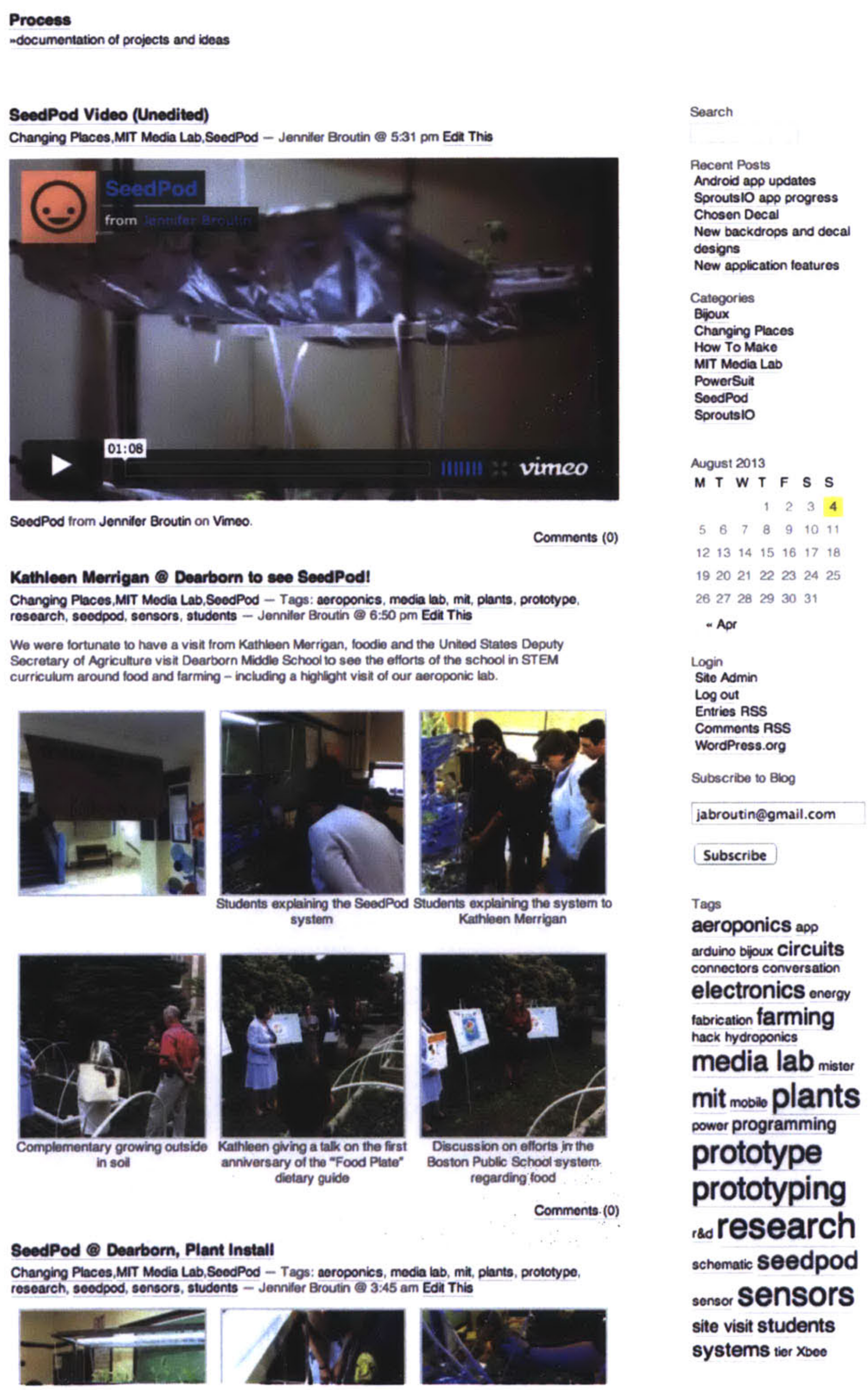
# Appendix

Appendix 1: Process documentation of the SeedPod prototype. See website documentation at: http://www.jenniferbroutin.com/process/category/seedpod/



**Process**
»documentation of projects and ideas

**SeedPod Video (Unedited)**
Changing Places, MIT Media Lab, SeedPod — Jennifer Broutin @ 5:31 pm Edit This

SeedPod from Jennifer Broutin on Vimeo.

Comments (0)

**Kathleen Merrigan @ Dearborn to see SeedPod!**
Changing Places, MIT Media Lab, SeedPod — Tags: aeroponics, media lab, mit, plants, prototype, research, seedpod, sensors, students — Jennifer Broutin @ 6:50 pm Edit This

We were fortunate to have a visit from Kathleen Merrigan, foodie and the United States Deputy Secretary of Agriculture visit Dearborn Middle School to see the efforts of the school in STEM curriculum around food and farming – including a highlight visit of our aeroponic lab.

Students explaining the SeedPod system

Students explaining the system to Kathleen Merrigan

Complementary growing outside in soil

Kathleen giving a talk on the first anniversary of the "Food Plate" dietary guide

Discussion on efforts in the Boston Public School system regarding food

Comments (0)

**SeedPod @ Dearborn, Plant Install**
Changing Places, MIT Media Lab, SeedPod — Tags: aeroponics, media lab, mit, plants, prototype, research, seedpod, sensors, students — Jennifer Broutin @ 3:45 am Edit This

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### Planting Module Prototyping

Changing Places,MIT Media Lab,SeedPod — Jennifer Broutin @ 3:58 pm Edit This

Continuation of mockups for module with different materials, thickness and sizes.


Seams at the sides


New mockup with one large interior plant pouch


Testing seams


Metalic material to reflect and block sunlight


Testing pouch sizes and materials

Comments (0)

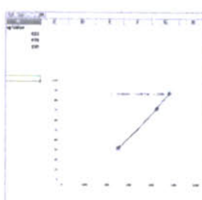
### Sensor Calibration and Humidity Sensor

Changing Places,MIT Media Lab,SeedPod — collaborator @ 2:35 am Edit This

In order to get out sensors calibrated, I took some data utilizing an IR Temperature sensor and different temperatures of water mixtures. However, I found that the IR sensor wasn't particularly consistent in calculating the temperature. Nevertheless, I got a curve utilizing three different points.

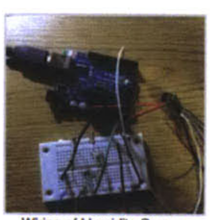
Additionally today I got the humidity sensor up and running. I utilized instructions from **this** website to help write the code for this sensor. One important thing to note is the problems and solutions that were noted in the comments of the webpage. I also noticed that I unfortunately soldered on the wrong wires for the power for the chip. But I checked this before I plugged anything in, so this is just something to keep in mind for the future.

Running the code copied from the same site, I was able to get relative humidity sensor values which increased when I blew out air towards it.


EXCEL sheet used to determine temperature formula


Temperature sensor calibration


The humidity sensor


Wiring of Humidity Sensor


Connection to Arduino


Humidity sensor values, varied as

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Appendix 2: Process documentation of the SproutsIO prototype. See website documentation at: http://www.jenniferbroutin.com/process/category/sproutsio/

**Process**
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## Android app updates

Changing Places,MIT Media Lab,SproutsIO — collaborator @ 5:26 pm Edit This

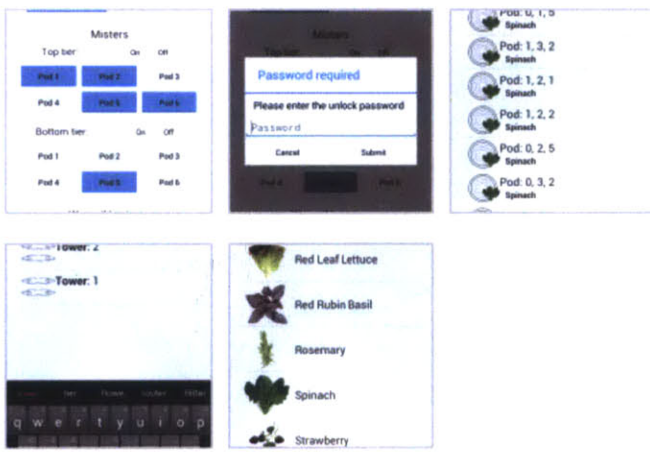
Hooray! The demo works! Jenny, Blake, Louis, and I have been working quite a bit this past week on getting the tower into a demo-able state, and it looks like everything has paid off. On my part of the demo, the "Try me" screen on the app has improved quite a bit in terms of usability and design. There are now misting controls for individual pods, as well as buttons to control misting on a tier level. The water/nutrient dispenser buttons are now password-protected, to keep people from accidentally overflowing anything.

Search has also improved quite a bit; in particular:

- Matched text is displayed in bold
- Searching plant names shows the plant's library listing, then pods with that plant
- Clicking on a search result shows either the plant's library listing or the clicked tower/tier/pod

Also, new plants have been added. Something to note: it would also seem that scientific names are going to be inadequate for uniquely identifying a type of plant, since "red leaf lettuce" and "lettuce" are both called "Lactuca sativa".

Still to do is add some demo notifications, and figure out what towers/tiers/pods/plants should be shown for the demo.



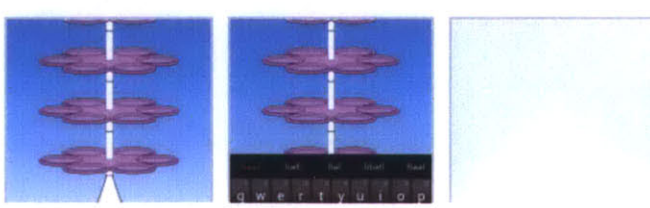

Comments (0)

## SproutsIO app progress

Changing Places,MIT Media Lab,SproutsIO — collaborator @ 9:26 pm Edit This

Hello, Alex again. Still working on implementing existing features, mostly by making menu buttons work. This week, I added actual functionality to the "Search" button (see pictures below). The current implementation searches the name of all systems, tiers, and pods, as well as the name and information for each plant type. Nothing fancy, just string matching, then prioritizing the results. I've also been working with Blake to get data from the server; currently there's code written to pull sensor readings, but no buttons to actually activate syncing. Hooking up the two is on my to-do list for this week, along with general UI prettying-up for Member Week. Also on the list is setting up communication with a SeedPod Mini; I built a UI demo last week, but the actual functionality is nowhere near ready.

Jenny and I decided to put off actual scheduling of misting and lighting until after the big demo, favoring instead a "Try Me" approach. To that end I've added a (really) basic screen with some switches to turn lights and misters on the SproutsIO on and off. Also, the feedback screen works; it sends any comments to a PHP script hosted on my MIT web_scripts folder, which emails the results to somebody.



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**Process**
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## SproutsIO: Cardboard Tier Mockup

Changing Places, MIT Media Lab, SproutsIO — collaborator @ 9:41 pm Edit This

After making a Solidworks model of the tier, we made a cardboard mockup to determine that all the dimensions were correct.





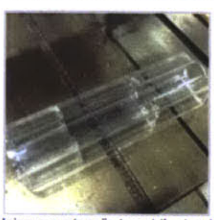




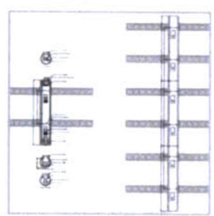
Comments (0)

## SproutsIO: Trunk Bus

Changing Places, MIT Media Lab, SproutsIO — Jennifer Broutin @ 7:52 pm Edit This


Using a custom jig to cut the trunk tubing


Cut out tubing with acrylic inserts for assembly

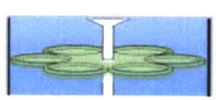
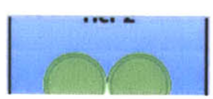

Drawing of trunk bus connectors

Comments (0)

## Android App GUI

Changing Places, MIT Media Lab, SproutsIO — collaborator @ 7:15 pm Edit This

Here is the application GUI from last week. Note, we redesigned it this morning and those changes have not been implemented.

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Appendix 3: List of plant species that the SproutsIO system is designed to grow.

- Beans: Lima, bush, pole, shell, fava, green, garbonzo
- Broccoli, Broccoli Raab
- Brussels Sprouts
- Cabbage and Chinese cabbage
- Carrot
- Cauliflower
- Chard, all types
- Chicory
- Collards
- Cucumbers
- Cress
- Dandelion, Italian
- Eggplant, European and Asian
- Endive
- Escarole
- Gourds, edible and ornamental, smaller varieties
- Herbs: basil, oregano, thyme, parsley, sage, rosemary (and various others)
- Kale
- Kinh gioi
- Kohlrabi
- Komatsuna
- Leeks
- Lettuce, all types and Mesclun Varieties
- Misome
- Mizuna
- Mustard Greens
- Ngo Gai
- New Potatoes
- Okra
- Pak Choy
- Perilla
- Peas, all types
- Peppers, all types
- Radicchio
- Radishes
- Sorrel
- Spinach
- Squash, small varieties
- Strawberries
- Tomatoes, all types, dwarf varieties
- Radishes

Appendix 4: User Interface Study Survey

# SproutsIO Player

Hello, thank you for participating in SproutsIO Player user testing. Please take a moment to answer the questions below for consideration in future system improvements (of course let me know if you like stuff too!) You will be asked to do specific and general activities on the app.

A few points:

* Please read each question and use the help text as a guide. Remember to read fully!
* Please answer every question in the order given. If you discover something new, you can come back to the question at the end.
* Suggested question time allowance will be listed with each question (the point being, don't stick on one question for too long!)

Total Questionnaire time estimate: 15 minutes

* Required

1. **What is your age?** *

   ..................................................

2. **What is your gender?** *

   ..................................................

3. **How experienced are you with growing plants?** *
   Select the answer that is most fitting to your experience (please select only one)
   *Mark only one oval.*

   ◯ Never tried it.
   ◯ In my home/office with potted plants.
   ◯ I grow in my home with potted plants, and I have gardened outdoors occasionally.
   ◯ I grow plants frequently, indoors and outdoors.
   ◯ I am an experienced grower, my family/myself has grown on a farm.

4. **Watch a brief SproutsIO intro movie (1 minute)** *
   Please see the SproutsIO intro video in the next internet tab. (If you have issue accessing, here is the direct link: https://vimeo.com/67736652)
   *Check all that apply.*

   ☐ Select once you have completed watching the video

# Lets Get Started!

You will be beta testing the mobile application experience for SproutsIO today.

5. **Play with the app and familiarize yourself. List any initial comments or questions you have briefly. (3 minutes)**
   Open the SproutsIO application on the mobile device. Enter the SHOW MY SPROUTS section of the app.

   ........................................................................
   ........................................................................
   ........................................................................
   ........................................................................
   ........................................................................

6. **Turn on misting control for Tower 1. Select day(s) of week, duration and frequency of misting. (1 minute)** *
   *Check all that apply.*

   - [ ] Completed
   - [ ] Incomplete

7. **Turn on LED control for Tier 2. Select day(s) of week, and on/off time. (1 minute)** *
   *Check all that apply.*

   - [ ] Completed
   - [ ] Incomplete

8. **Select any empty pod in the system and control change plant type by selecting plant. (1 minute)** *
   *Check all that apply.*

   - [ ] Completed
   - [ ] Incomplete

9. **Search for "Trinidad Perfume Peper". Select one of these pods. (30 seconds)** *
   *Check all that apply.*

   - [ ] Completed
   - [ ] Incomplete

10. **With the "Trinidad Perfume Pepper" pod selected, what are the attributes listed? (1 minute)** *

   ........................................................................
   ........................................................................
   ........................................................................
   ........................................................................
   ........................................................................

11. **Select one of the sensor attributes. (30 seconds)** *
Note: Data is not currently being recorded.
*Check all that apply.*

- [ ] Completed
- [ ] Incomplete

12. **Sync system on the Tower level. (30 seconds)** *
Notice that the tower Sync time has updated.
*Check all that apply.*

- [ ] Completed
- [ ] Incomplete

13. **Use settings to change the name and color of Tier 1. (1 minute)** *
*Check all that apply.*

- [ ] Complete
- [ ] Incomplete

14. **Check the notifications, and add a plant to one of the new pods. (1 minute)** *
*Check all that apply.*

- [ ] Complete
- [ ] Incomplete

15. **Do you feel comfortable navigating the app? Were there any particular areas that were difficult to find - please list. (2 minutes)** *

..................................................................................

..................................................................................

..................................................................................

..................................................................................

..................................................................................

16. **Are there any particular areas that were simple and helpful for you? (2 mins)** *

..................................................................................

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17. **Would you be interested in using this app to help automate plant growing for you? (2 minutes) ***

18. **Are there any features that would help you understand the application better? (2 minutes)**

19. **Are there any features that you would like to see in future versions?**

# SproutsIO Builder

Hello, thank you for participating in SproutsIO Builder user testing.

A few points:

* Please read each question and use the help text as a guide. Remember to read fully!
* Please answer every question in the order given.

A little about SproutsIO...

Sprouts IO Microfarm introduces a new strategy for producing and consuming accessible, affordable organic produce, implemented locally and scaled globally to change the food industry. SproutsIO is a growing station that assists users to microfarm produce efficiently indoors. Here are some of the awesome features:

- Aeroponic system: Misting of water and nutrients for soil free growth
- Growth management: With environmental monitoring and automation through mobile application for optimal watering, lighting, and nutrient delivery for different plant types.
- Networked Connectivity: Multiple systems and users can connect to the system
- Pesticide Free: Indoor operation eliminates the need for pesticides
- Efficient Farming: Consumes 2% of water and 40% fertilizer required for soil farming
- Multiple plant types: Can simultaneously grow fruits, vegetables, herbs and roots
- Year round harvest cycle: Seasons and weather conditions do not affect harvest

* Required

1. **What is your age?** *

   ........................................

2. **What is your gender?** *

   ........................................

3. **How experienced are you with growing plants?** *
   Select the answer that is most fitting to your experience (please select only one).
   *Mark only one oval.*

   ◯ Never tried it.
   ◯ In my home/office with potted plants.
   ◯ I grow in my home with potted plants, and I have gardened outdoors occasionally.
   ◯ I grow plants frequently, indoors and outdoors.
   ◯ I am an experienced grower, my family/myself has grown on a farm.

4. **Watch a brief SproutsIO intro movie.** *
   Please see the SproutsIO intro video in the next internet tab. (If you have issue accessing, here is the direct link: https://vimeo.com/67736652)
   *Check all that apply.*

   ☐ Select once you have completed watching the video.

5. **Please enter the time currently - as you are about to begin building!** *

   ........................................
   *Example: 8:30 AM*

## Let's Build!

You will be beta testing the build and grow experience for SproutsIO today.

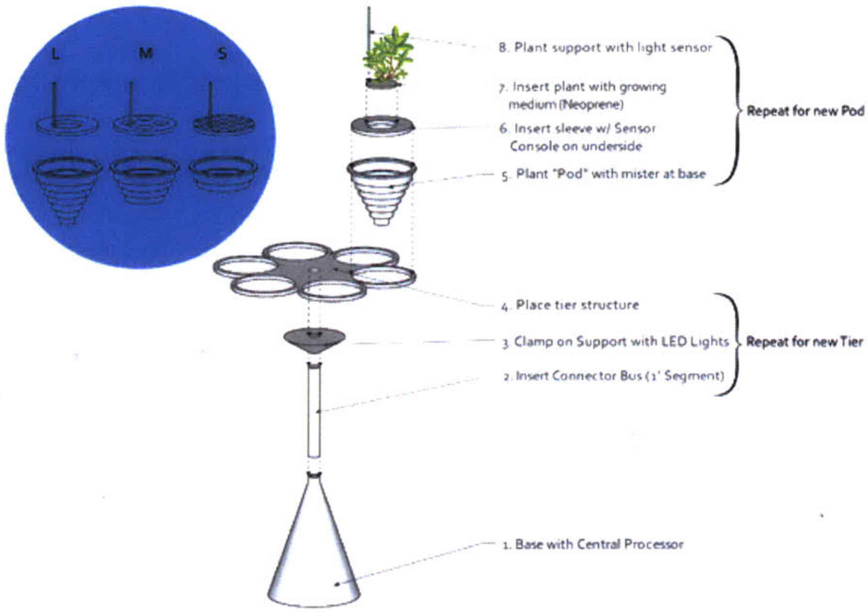
For this session, you will have the experience of putting the system together - however, some of the electronic components are not included (since they are more delicate).

In the box you will find a number of components for your use in assembly. Please be careful with the parts, while they are not super fragile, it is a prototype. That simply means if something doesn't fit right, don't force it, take a look again and see if there is a better way to assemble.

On the table you will find items for growing. There will be seeds, rockwool (fuzzy looking blocks - don't worry will explain later), water and nutrients.

After each segment of building and growing, let me know so I can mark the time and check out your awesome work!

## Hello SproutsIO :)




6. **Step 1: Place the Base** *

Note: there are no electronics included in the base presently.

*Check all that apply.*

- [ ] Select once completed

7. **Step 2: Add a Connector Bus "Trunk"** *

This should fit nicely into the base.

*Check all that apply.*

- [ ] Select once completed

8. **Step 3: Add a clamp "Collar" for support.** *
   There are 3 peices that snap together magnetically for alignment. Please note that the metal rod should go through the Trunk for support. The Collar can be spaced at 6 " intervals along the Trunk depending on plant size.
   *Check all that apply.*

9. **Step 4: Add a "Tier" onto the collar and trunk.** *
The top of the tier should be facing up, it has small plastic connectors on the top for reference. This should slide on but it may stick a little, just gently move it around so it goes through.
*Check all that apply.*

☐ Select once completed

10. **Repeat steps 2 through 4 for the next Tier 2.** *
*Check all that apply.*

☐ Select once completed

11. **Step 5: Add the third "Trunk". Then at the top of the "Tower", add the "Top" that has LED lights on it.** *
*Check all that apply.*

☐ Select once completed

12. **Step 6: Add the "Pods".** *
These are the green collapsible parts. These can be expanded to fit your plant size in the future. You can expand the pod by pulling up on the silicone (don't worry if one of the misters pops out - that is supposed to happen). A cool tip - you can remove the misters and put the pod in your dishwasher!
*Check all that apply.*

☐ Select once completed

13. **Step 7: Plug in the misters** *
Connect the mister connector from each pod to the female connector on the top of the "Tier"
*Check all that apply.*

☐ Select once completed

14. **Step 8: Add the "Sleeves"** *
There are different opening sizes for different plant sizes. For now just pick any - but in the future you can have the size correspond to your plant.
*Check all that apply.*

☐ Select once completed

15. **Step 9: Add the foam supports.** *
These help support the plants or hold the seeds in place when growing. These can be flipped up or down depending on how big your plant is. They can also be separated to make the holes larger.
*Check all that apply.*

☐ Select once completed

16. **Yay!!! You have put together SproutsIO. Please notify me so that you can record your time.** *

*Example: 8:30 AM*

## Let's Grow!

Now we will plant the system. Notice on the table there are a few items.

* Pitcher of water with nutrient solution already added (the solution is there for your reference).
* A variety of seeds for your choosing.
* Small 1/2" x 1/2" squares of rockwool.
* Bucket with Ceramic pellets.
* Small black plastic baskets.

These will all be used in beginning to plant SproutsIO.

17. **Select some of the seeds that you like.** *
*Check all that apply.*

- [ ] Select once completed

18. **Take the a rockwool cube (fuzzy material), and insert the seed inside of the cube. You don't need to press in too far :)** *
Rockwool is a support for the roots of the plants to begin growing on. It is made out of thin ceramic fibers that hold onto water/nutrients.
*Check all that apply.*

- [ ] Select once completed

19. **Insert the rockwool into one of the crosses on the foam top.** *
Notice that these crosses open up to allow expansion. You can also break the foam tops to allow more room - that is part of the design.
*Check all that apply.*

- [ ] Select once completed

20. **Continue planting a few more as you like.**
*Check all that apply.*

- [ ] Select once completed

21. **Plant a plantlet...** *
Notice the small plants in the bowl. These are about a week old lettuce plantlets.
*Check all that apply.*

- [ ] Select once completed

22. **Add one of the small lettuce plants to the black plastic baskets.** *
There are ceramic pellets that can be added to the small black plastic baskets to hold the plant in place.
*Check all that apply.*

- [ ] Select once completed

23. **This black basket can sit into one of the large holes in the sleeves.** *
You don't need to have the foam support on the top for larger plants.
*Check all that apply.*

- [ ] Select once completed

24. **Add water/nutrients to the "Pods".** *
Pour water into the opening of the "Sleeve". You only need about an inch of water from the bottom of the mister.
*Check all that apply.*

- [ ] Select once completed

25. **Hey your Growing!!! ***
Please enter the time you complete the growing portion - let me know so I can check out your work!

*Example: 8:30 AM*

## Questions

Please give me feedback to improve the system!

26. **What were some of the stumbling blocks during assembly of the system? Were there any areas that were unclear to you? How did you figure it out if you did? ***
Please keep answers concise

27. **Did you enjoy the process? How about the length of assembly - to long/too short? ***

28. **Would you consider using this system in your home/office to grow food? ***
There is also a mobile application that will help you take care of your plants by watering and lighting remotely. Sensor information is also recorded to keep plant profiles that assist in monitoring plant growth.

29. **Do you have space in your home for this system. Do you find it a pleasing appliance to have in your home? ***

30. **Imagine that you can grow enough organic fruits and vegetables on this system (with 2 more tiers) to provide your daily fruit/vegetable intake year round. Would you be interested in purchasing this system? ***

31. **Do you purchase organic produce? And if so how much do you think you spend on organic fruits and vegetables on a monthly basis? ***

32. **If the SproutsIO system was available for purchase, how much would you spend? ***

Google Drive

# SproutsIO Lover: Daily Questionnaire

Hello, and thank you for being a SproutsIO Lover.

Each day you will receive a questionnaire that will be brief but important to submit on a daily basis!

A little about SproutsIO...

Sprouts IO Microfarm introduces a new strategy for producing and consuming accessible, affordable organic produce, implemented locally and scaled globally to change the food industry. SproutsIO is a growing station that assists users to microfarm produce efficiently indoors. Here are some of the awesome features:

- Aeroponic system: Misting of water and nutrients for soil free growth
- Growth management: With environmental monitoring and automation through mobile application for optimal watering and lighting.
- Networked Connectivity: Multiple systems and users can connect to the system
- Pesticide Free: Indoor operation eliminates the need for pesticides
- Efficient Farming: Consumes 2% of water and 40% fertilizer required for soil farming
- Multiple plant types: Can simultaneously grow fruits, vegetables, herbs and roots
- Year round harvest cycle: Seasons and weather conditions do not affect harvest

* Required

1. **How much time did you spend using the SproutsIO app today? ***

2. **How much time did you spend physically caring for your plants? ***
   Pruning, inspecting, trimming, planting

3. **How much time did you spend maintaining the SproutsIO system?**
   This includes watering, cleaning, etc.

4. **Did you encounter any specific issues with app functionality? Did you figure out how to fix it? ***

5. **Did you encounter any specific issues with system functionality?** *
   Please contact me if there are any issues/concerns

6. **Did you have any fun moments you want to share regarding your experience with SproutsIO today?** *

7. **Do you have any ideas regarding improvements for the system today?** *

8. **Did you learn anything new today about plants/food etc.connected to SproutsIO?** *