CLAIRITY

An Air Quality Sensor Network for MIT's Campus

CEE Senior Capstone Design Project

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Overview

Project Summary

During the course of undergraduate education, students in the Department of Civil and Environmental Engineering at MIT are constantly encouraged to tackle complex problems. They are taught that an analytical mind and an ability to collaborate are qualities essential to success.

The Senior Capstone course, 1.013, tasked a group of 20 seniors with the goal of bringing the idea of a “smart city” to MIT’s campus. The concept of a smart city was formed from the desire to make urban living more efficient by harnessing the vast amounts of data created in urban environments today. The term has come to encompass technologies such as automated heating systems in buildings and trashcans that alert the city when they are full, and the opportunities in this field continue to grow as technology is further improved and developed.

In 1.013, the following mission was assigned:

Assess the exposure of the MIT population to airborne pollution through the design and implementation of a distributed air quality sensor network on MIT’s campus.

Summarizing work completed over the 2013-2014 academic year, the following report will explore:

- The reasons why this network is a valid investment of time and resources
- The technical description of the network and what is measured
- The process of scaling up a single prototype to a distributed network
- The preliminary analysis derived from the network

The CLAIRITY system utilizes a system of sensor nodes in order to accomplish these tasks. A sensor node is a unit of electronic sensors. These nodes come together as a sensor network to give a snapshot of the air quality across campus. Each of the 24 sensor nodes in the CLAIRITY network measures five pollutants: CO, NO, NO_2, O_3, and particulate matter. These measurements are being collected and stored in a central database, which is then feeding into a website which can be accessed from any computer. This website creates a way for members of the MIT community to determine their exposure to airborne pollution at various locations on campus.

Motivation

Air quality and quality of life are directly connected, as poor air quality has proven harmful to human health. According to the World Health Organization, poor air quality is one of the largest causes of premature death worldwide, and, because of rapid increases in global urban populations – especially in developing countries – is likely to become an increasingly central concern in civil and environmental engineering disciplines over the next several decades.

The knowledge attained through the course of the CLAIRITY team’s work on this project will add to a better understanding of how air quality and humans are interrelated.

Additionally, the network of 24 sensor nodes will allow for more accurate insight into the air quality at MIT. While the Massachusetts Department of Environmental Protection operates air quality monitoring stations at five locations in the greater Boston area, there is no system currently in place that provides a real-time picture of the air on MIT's campus specifically. The CLAIRITY network collects this information, logs it to a database in its raw form, applies conversion and calibration factors to turn raw data into understandable information, and then reports it to a website. This multi-step process yields a tangible result through which one could assess one's exposure to air pollution on campus.

The development of an air quality sensor network for MIT's campus facilitates a better understanding of the health risks the community faces, and ideally will address specific air quality concerns associated with a campus research university. Moreover, the network can serve as a template prototype for future air quality networks, for deployment across a diverse array of urban and rural environments in both the developed and developing world.

Network Design Considerations

With a general concept of a sensor network predetermined, the specific details of how the nodes and network would ultimately operate were left open-ended. The first step in the design process was to discuss the following details that would ultimately inform the final design of the sensor node.

Species Measured

The first design parameter to consider was the species the sensors would measure. After considering both the most commonly found air pollutants as well as the pollutants that are regulated and measured by the EPA, the following four chemical species were chosen:

- Carbon Monoxide (CO)
- Nitric Oxide (NO)
- Nitrogen Dioxide (NO_2)
- Ozone (O_3)

In addition to these four species, an understanding of particulate matter adds to the ability to explain what the average MIT community member is exposed to on a daily basis. Many sources, ranging from construction sites to cigarette smoke, contribute to particulate matter; again, particulate matter exposure can act as an indicator of negative health impacts on the MIT community. Therefore, particulate matter was added to the list of chemical pollutants, resulting in a total of five species measured by the sensor node.

Finally, in order to provide a climatic context for this data, sensors were added for relative humidity (RH) and temperature. These two streams of data provide another facet to the understanding of how the sensors operate in different conditions, and this information can be used to better calibrate the readings gathered by the sensor nodes.

Location

The second major design parameter to determine was the locations of the nodes themselves on MIT's campus. Both indoor and outdoor air quality have different implications for the MIT community. The outdoor air quality measurements, for example, require more preparation to construct a waterproof housing unit for the sensor node.

Locations were chosen based upon the constraints of the sensor nodes – such as the need for a continuous power supply or access to Ethernet – while also ensuring that a large cross-section of the campus was being monitored. Since the primary sources of the pollutants of interest are exhaust, both from automobiles and power plants, the majority of the nodes were placed outside. Cooking is the main source of the measured pollutants for indoor locations, and thus a targeted cross section of food preparation areas were chosen as locations for the nodes.

Class Organization

In order to efficiently distribute the workload of this project and capitalize on various interests and areas of expertise of the CLAIRITY team as a whole, five groups were created, each with its own tasks and goals:

The Logistics team determined the locations for each of the deployed nodes and coordinated the efforts with external stakeholders (e.g. MIT Facilities) to ensure a smooth installation process. Based on the chosen locations, suitable mounting and weatherproofing schemes were developed to ensure that the nodes remained safe.

The Hardware Team assembled and wired each node at the beginning of the term and troubleshot any malfunctioning or false-reading nodes throughout the project. This team also prepared and assembled the casing, wiring, and power configurations, which differ depending on the location of the node.

The Calibration Team designed and ran laboratory tests through which the sensors were calibrated against high-fidelity lab instruments. The ideal result is a node that reports high-accuracy air quality data at a one-hundredth of the cost of more expensive laboratory-grade equipment.

The Coding Team was responsible for writing the code to locally store the air quality data and push it to a database. In addition, this team also collaborated with many of the other teams to troubleshoot and optimize the code.

The Communications Team created a website in order to display the air quality data from the sensor network. This team also coordinated the public displays of the network data, seen throughout campus and featured in an MIT Museum exhibit during Summer 2014.

Description of Main Tasks

In the following pages, each of the five groups' work is explained in more detail. Each team section includes a brief introduction into their approach to their main objectives, as well as any major challenges they faced and suggestions for improvement. A more detailed explanation of the technical project components can be found in the "Technical Description" section of this report.

In order to organize the tasks that needed to be completed in order for the CLAIRITY network to become fully operational, the CLAIRITY team utilized InstaGantt, a free online service through the Asana project management software. This allowed the team to view completed tasks across the various categories so tasks that were strongly connected could be started in immediate succession. A copy of the final Gantt chart is attached for reference. See Appendix A2 for the Gantt charts in their entirety.

Logistics

Objectives

Successful deployment of the air quality network relied upon coordination both between teams within the project as well as between the CLAIRITY team and external stakeholders. The logistics team, comprised of five team members including the overarching project manager, was responsible for this coordination in addition to full deployment of the sensor nodes. The team's specific responsibilities included selection of deployment locations, mounting and weatherproofing methods for the nodes, installation and node monitoring after deployment.

Approach and Methods

In order to accomplish the assigned objectives, the logistics team created two sub teams, each devoted to either mounting and weatherproofing or location scouting. This better allowed the team to work within the timeline determined at the beginning of the project. After the locations were finalized, each person was designated specific locations to manage. This designation was based upon the MIT staff contact responsible for assisting with installation such that communication with the department was routed through a single team member to avoid confusion.

The CLAIRITY project manager handled inter-team coordination throughout the process. This included overseeing weekly meetings and ensuring that teams that were relying upon each other were communicating. The weekly meetings, at which one member from each team was always present, were paramount in keeping communication about progress and problems constant throughout the project.

One sub-team focused on the location scheme, and coordinated with external stakeholders to finalize the node locations and organize deployment. Meetings with various members of the MIT staff, including facilities managers, electricians and building managers were necessary to ensure that nodes were installed in locations that were non-disruptive and safe to the MIT community. The primary communication between the logistics team and facilities included walking through each potential node location and assessing its feasibility prior to installation.

The location scouting done with members of MIT facilities staff was based upon locations selected by the locations portion of the team, which looked for input from both the rest of the logistics team and other teams that worked on the project. It was the location team's responsibility to select locations based upon the sensor node capabilities in order to get an accurate view of the air quality across campus. Considerations that were made in determining locations included proximity to a constant power source, expectations for temporal and spatial variation in pollutants, Wi-Fi connectivity and serviceability. More detail on how the final locations were determined is found later in this report.

In order to successfully deploy the nodes in outdoor locations, the logistics team was tasked with creating a weatherproofing solution that would also keep rain and pests off of the sensor node while still allowing adequate airflow through the system. The weatherproofing solution had to be suitable for Cambridge weather conditions but also allow for an adaptable mounting system that could be altered based upon the location.

Challenges and Constraints

The primary constraints the logistics team faced were node capabilities and communication avenues. Specific solutions that took these constraints into account are discussed in the "Deployment Scheme" section of this report.

Node capabilities limited both the deployment scheme and weatherproofing options for the Logistics team. Selected locations had to have accessible Wi-Fi or Ethernet ports for Internet connection as well as power outlets nearby. The weatherproofing system had to allow sufficient airflow through the node and selected box without allowing rain, snow or pests through the openings. The selected box had to also allow room for a transformer to convert the AC power supplied through power outlets. in addition to the weatherproofing concerns, there needed to be sufficient clearance upon deployment for the Wi-Fi antenna to be placed outside of the polycarbonate box, which interferes with the signal, otherwise the data collected by the CLAIRITY sensors could not be sent to the database for storage.

Since communication with stakeholders outside of the core teams was necessary to ensure safe and allowable node installation, the logistics team elected members through which communication with facilities managers could be channeled. That is, each location had a team member assigned to handle the logistics of its sensor node installation. This constrained the timeframe within which the team was able to carry out certain walkthroughs and installations because communication bottlenecks began to form. The team was further constrained by the schedules of facilities contacts during node deployment, as they were only available certain days and times. After realizing the significant time constraints and daytime availability of facilities staff, the logistics team disregarded the group divisions previously installed (e.g. locations sub-team and weatherproofing and mounting sub-team). By taking away this subdivision, all members of the team gave time towards node deployment, maximizing the probability that at least one team member would be available to assist the facilities staff during the given timeframes.

Results

The logistics team was able to select 24 locations to create a comprehensive deployment scheme and successfully protect and install sensor nodes at those locations. The team was also able to develop relationships with relevant MIT Facilities stakeholders to ensure that the success of CLAIRITY will last well into the future.

Future Improvements

The continued success of the deployed nodes depends upon more robust mounting solutions and an improved method for monitoring the mobile nodes. Some nodes were secured utilizing plastic cable ties, which are insufficient for long-term deployment. Along this same vein, future work should include the development of a mounting system that does not rely on existing infrastructure to be secured. The mobile nodes, which have been placed on a Tech Shuttle and MIT Facilities vehicle, showed inconsistency in connecting to Wi-Fi and do not provide an efficient means of monitoring their locations. Without the spatial data corresponding to the sensor readings, the data is not sufficient for the purposes of the CLAIRITY project or website. Development of a better location-monitoring scheme for mobile nodes is discussed in the "Future Considerations" section of this report.

Hardware

Objectives

For the sensor system to function properly, each sensor in the network had to be able to measure the required parameters correctly and communicate results efficiently. The sensors therefore not only needed functional parts, but also good physical infrastructure to house these parts and protect them from the elements and human reach. The sensors also needed a power supply and the appropriate power distribution infrastructure. The primary objectives of the Hardware team were to:

- Obtain, design, or modify the sensor elements

- Assemble the sensor nodes
- Troubleshoot and repair sensor nodes when necessary

Approach and Methods

The design of the sensor node – including the internal elements and their special configuration relative to each other – was completed in the first stages of the CLAIRITY project; the final prototype was built through a series of design iterations that followed. In Spring 2014, the team worked to build the sensor system by duplicating the initial prototype construction process 25 times. This work included obtaining, modifying and assembling parts, creating wired connections and 3D printing the inner frame on which the various elements were affixed, among other tasks. In addition to this, an external casing to house the internal elements of the sensor was designed and 3D-printed.

On completing sensor assembly, several teams worked closely together in order to troubleshoot faulty sensors and correct sources of error due to hardware-related problems. These problems included misaligned internal elements, mismatched wire connections, and other similar issues.

Challenges and Constraints

Since other teams could not begin on their work until the sensors themselves were constructed, that meant that the Hardware team's work was critical from the very beginning of CLAIRITY. The team therefore faced the challenge of a large amount of work very early on in the project. The challenge was to maintain good balance between the speed and quality of delivery. As testing and troubleshooting continued, the team found that hardware-related work still remained urgent and critical, even after the sensor nodes were deployed across MIT.

Results

Currently, 24 of the 25 locations within the CLARITY sensor node network are fully functional. One sensor node faced several hardware issues – most notably a misaligned particle count laser. This node is still undergoing troubleshooting but will be added to the network once completed.

Future Improvements

Post-deployment, a major concern is sensor maintenance. Dust, for example, is expected to accumulate in the sensor nodes over time; this becomes a problem as it may affect the electrical components within each node. In light of this, the nodes will require servicing at regular time intervals if this deployment scheme is to be sustainable.

Another consideration is improving Wi-Fi reception through the weatherproofing boxes. Currently, there are small Wi-Fi adapters attached to the sensor nodes and deployed in the CLAIRITY network. Currently, this arrangement has the potential to expose the adapters to the elements. If the network is to avoid this issue in the future, two possible fixes can be implemented: either the weatherproof box could be made out of a different material, such that Wi-Fi can permeate it without a problem, or another Wi-Fi adapter attachment scheme could be implemented to ensure a sustainable solution.

Finally, it is possible that the nodes require a cooling system within the weatherproofing boxes in addition to the current airflow vents. The boxes tend to heat up because of the action of the transformer, which releases a significant amount of heat. So far, the nodes function properly, heat notwithstanding. But because the system has not been tested under the heat of the summer, the possible highest temperatures and their effect on node accuracy and functionality remain an uncertainty. It is however important to note that because the nodes contain a temperature and relative humidity sensor, it is possible to adjust for the effect of these on the results as long as they remain within a range that the sensors can function properly under.

Calibration

Objectives

The air quality data received can only be trusted if the sensors themselves are outputting trustworthy data. It was the Calibration team's main objective to design a series of laboratory experiments through which the electrochemical sensor readings could be better understood. Ultimately, this meant aligning the sensor readings to data collected by high-fidelity instruments in the Ralph M. Parsons Laboratory for Environmental Science and Engineering on MIT's campus. Although each electrochemical sensor and Dylos PM sensor is calibrated by its manufacturer before being sold, there can still be a significant disparity between what the sensors report and what they are actually exposed to. The Calibration team devised laboratory tests to account and correct for any such discrepancies in the data, performing analyses on the data collected in these tests to inform new calibration factors. The calibration processes detailed here refer only to the four gas-phase pollutants and their corresponding electrochemical sensors.

Approach and Methods

The first step in the process for this team was to gain an understanding of the data conversion process as a whole. The internal chemistry – either a reduction or oxidation reaction – of each Alphasense sensor results in two voltage outputs. These numbers, reported in millivolts (mV), can be converted into a gaseous concentration (in parts per billion, or ppb) using a simple equation:

$$\text{Concentration} = \frac{(OP_1 - Z_1) - (OP_2 - Z_2)}{S}$$

In this equation, OP_1 and OP_2 are the two voltage outputs that are received from the electrochemical sensors; Z_1 and Z_2 are zero offsets provided by the manufacturers; and S is a sensitivity factor – also included by the manufacturers – with units of ppb per mV. It is these zero and sensitivity values that the CLAIRITY team aimed to improve upon with their own series of calibration tests. Each sensor was run through two types of tests.

The first type of test involved known concentrations of the gas-phase species. Running two sensor nodes in the system at a time, the Calibration team pumped pre-calculated concentrations of the four pollutants into an airtight chamber and compared the reported values with what was known to be in the system. This comparison was ultimately the most important when it came to attempting to correct the factory calibration equations and better reconcile the sensor readings to the high-fidelity instrument readings.

The second type of test used ambient air from outside Parsons Laboratory. This air better reflected the real conditions these sensors would be facing once deployed. These results also allowed us to check that the sensor data varied reasonably over time. In analyzing spikes in the readings – such as during rush hour traffic or when a freight train traveled by the laboratory – it was clear that spikes in the readings were due to real-time pollution events and not due to issues with the hardware or electrochemistry of the sensors themselves.

Both of these tests required a different set-up in Parsons Laboratory, both of which are explained in further detail in the "Calibration System and Methods" section. After both tests were run on each of the 25 sensor nodes and the resulting data stored on a project-specific laptop computer, the time came to analyze the data and calculate more accurate calibration factors for the four electrochemical sensors on each node.

Challenges and Constraints

As already stated, the CLAIRITY team aimed to perform these calibration tests on each electrochemical sensor specifically. This required a substantial amount of time, given a network of 100 unique sensors. Also, the calibration processes involved another entire series of laboratory equipment – the high fidelity, research-grade instruments – with which the CLAIRITY team had to become familiar. Since these instruments were shared with other researchers in Parsons Laboratory, scheduling time to use the machines was sometimes an issue for the Calibration team. Ultimately, these challenges connect to the fact that the sensor deployment could not occur until all of the calibration experiments had been run. Once the nodes were deployed around MIT's campus, they could not then be returned to Parsons Laboratory to resume calibration tests; so the Calibration team had to complete these tests, and be confident in the data being collected, as efficiently as possible.

Besides the scheduling challenges faced during this project, the other major challenge was due to the sheer amount of data collected by the Calibration team. With 25 nodes undergoing tests at different times, it quickly became difficult to keep track of which nodes had undergone which tests and which times. While it would have been ideal to perform one species test on all nodes before moving on to the next one, this method was not feasible under the time constraints. With the research-grade instruments running almost continuously alongside the CLAIRITY sensors, it became confusing to understand what was happening to the system overall.

Results

The goal of the CLAIRITY team was to take the new calibration factors, after the nodes were run through the tests and the data was processed, and apply it in the database to the voltage readings as they were received from the network. As of May 16, 2014, all of the calibration test data has yet to be processed and analyzed completely. The analysis of this data is ongoing and is explained in greater detail in the "Data Processing and Analysis" subsection. Once the process is complete and the calibration factors have all been calculated, they will retroactively be applied through the website to ensure that the data being reported to the general public is as accurate as possible.

Future Improvements

Given that this process is yet ongoing and still requires more time and energy, the CLAIRITY team suggests that potential changes to the calibration scheme could be made to ensure that the process becomes more efficient and streamlined. These are also detailed later in the report, more specifically in the "Process Modifications" section.

Coding

Objectives

The primary objective for the coding team was to provide a code that delivers the node data from the sensors to the database for storage. The team began with a preliminary version of the code and sought to build upon it to suit the project's needs as nodes were deployed. Much of the work was done in tandem with the other teams, addressing issues and improvements as they came up throughout the course of the project.

Approach and Methods

The Coding team began with a prototype version of the code. The aim from the start of the CLAIRITY project was to make the existing code more readable and easy to modify. In addition, members of the team further familiarized themselves with Python. Immediate issues that needed to be addressed from the prototype code were the malfunctioning RH/T sensors and the lack of a database in which all of the sensor data could be stored.

Once the project began in earnest, the nature of the Coding team's work transitioned to troubleshooting. The pattern of work shifted to addressing issues found throughout deployment. Handling these issues in a timely and efficient manner meant preventing bottlenecks in the overall work in the class. While simultaneously solving problems in the code as they arose, the team also moved forward with the initial goal of creating a database to store the data.

Challenges and Constraints

The primary constraints were ensuring that any progress made regarding the code did not negatively affect any of the other teams. In particular, it had to be ensured that all the data that was collected and stored could be understood and analyzed. The method of data storage changed throughout the term, beginning with a comma separated values file (CSV) and Google Documents platform at the beginning of the term and transitioning to a database by the end. The Coding team worked closely with the Communications team on this transition, ensuring that the latter group could easily access the data collected for use in the CLAIRITY website and in data analysis. In addition, the rest of the class needed to understand the method of data storage and how to access the nodes so work could continue without hindrance.

The first major challenge was in troubleshooting the RH/T sensor on each sensor node. The issue was to understand why these sensors only logged extreme values - it was unknown whether the problem was with the sensor itself, the way the code interpreted the data, or with the printed circuit board (PCB). By testing the sensor with a breadboard version of the wiring in the PCB and the code, the problem was determined to be with the PCB construction. Collaborating with the Hardware team, the PCBs were rewired to make the temperature and humidity sensors work properly.

Another challenge early in the semester was an incompatibility with the SD memory cards, which locally store the node data, and the Raspberry Pi computers that operate the nodes themselves. The node prototype had the same SD card and same Raspberry Pi computing unit and worked well; in addition, if an old SD card was used and a new Raspberry Pi, or vise versa, the systems still worked, making it difficult to narrow down and troubleshoot the problem. After some research and contacting of the manufacturers, it was decided to reformat the SD cards. Although this required additional time, this was the most viable solution.

As the nodes deployed, many other issues came up for the team to address, which meant fixing problems as they arose. Part of the challenge was that problems were often brought to attention by other teams as they worked with the code, requiring a quick response to other team's issues in order to avoid causing delays in other parts of the project.

Results

The coding team was able to create a robust code to ensure successful storage and delivery of the data from the sensor nodes. Throughout the course of deployment, the team worked closely with the other groups in the class, ensuring that possible issues could be promptly addressed and code improvements could be efficiently pushed to all the nodes.

Future Improvements

Before deployment, it was difficult to anticipate all the possible upgrades that the code would need throughout the course of the project. Therefore, as full-scale deployment of the CLAIRITY project continues, it is predicted that further potential improvements will be revealed. While the code does have some security systems in place, it is anticipated that if the project were to be scaled up, additional security measures should be put in place.

One of the most recent issues brought up to the coding team was unreliable Wi-Fi on a Tech Shuttle and an MIT Facilities vehicle, two of the locations in the node deployment scheme. It is currently possible to save data while not connected to the Internet, but since these nodes are mobile, it is difficult to match node readings at a certain time to a location on campus. Moving forward, the CLAIRITY team should create a more reliable method of matching the air quality data and location data.

Communications

Objectives

The purpose of the communication team was to interface between the CLAIRITY project and the public, in order to communicate the technical outputs to both researchers and the interested community in a meaningful way. Thus, the objectives were to set up an interactive means of displaying data and to raise awareness of the project throughout the MIT community. To accomplish these goals, the team created a database and website, various informational displays, and the CLAIRITY logo.

Approach and Methods

To convey the real-time network data, several communication portals were considered, including texting and web applications. An effective communication channel was essential for conveying the data gathered by the CLAIRITY network. Ultimately, the creation of a website was chosen as the highest priority. The objectives for the website included:

- Establishing a database for collected data that the website would draw from,
- Converting the raw data into a readable and understandable form,
- Conveying the importance of the data users would see, and
- Displaying the information from the air quality sensor network in an aesthetically pleasing way.

In the website design, the team started by creating wireframe mockups to determine the site's layout and function. Next, the team divided into focusing on the front end and the back end; the front end refers to the user interface, while the back end is the structure that allows for the front end to exist. Tasks within the front end were divided even further, so that one person focused on making the interactive map, one was in charge of the graphs, and one was in charge of styling the site. The team created a generator to generate dummy data while the nodes were being built, calibrated, and deployed. The team also assigned roles for outreach: one member became the contact for the museum exhibit, and one person became the contact for campus awareness and publicity.

The team wanted to raise awareness of the CLAIRITY project around campus, by creating interactive and static displays. Originally, the communications team hoped to generate several articles in The Tech, the MIT campus newspaper, and to post a series of interactive screen displays with the website around campus. Over the course of the project, this goal was reduced to a single blurb in The Tech and two screens on campus, one in Building 48 and one in Building 1. Additionally, the communication team created and has plans to install a summer exhibit in the MIT Museum to illustrate the project.

The communication team was responsible for presenting a cohesive project to the public and therefore creating all informational material. To that end, the team developed the CLAIRITY logo to brand the project. The communication team also provided any materials used in informational displays, including node labels and signs reading "Do Not Unplug" to be placed next to the nodes once deployed. An email address, clairity@mit.edu, was also established to provide an outlet for public questions and feedback.

Challenges and Constraints

The most daunting challenge was a lack of experience in web development shared by most members of the CLAIRITY team. Initially, a fair amount of time was spent learning the basics of web development, including hypertext markup language (or HTML), Cascading Style Sheets (or CSS), JavaScript, and jQuery, and team members utilized several tutorials online, including those provided by Code Academy. With available tutorials and practice, the team was able to advance relatively quickly to a level of proficiency needed to create an interactive website.

Development time was also a constraint, since the final version of the website could not go up until the nodes had been successfully deployed. Several teams also had to work closely with each other in order to set up the database and integrate the conversion factors needed for calibration and normalization of the data.

A final and essential constraint in designing the website was taking into consideration the knowledge and interests of the intended audience. The communication team put time and effort into creating a design that would be clear to community members, even those without a background in air quality.

Results

The team created a website, clairity.mit.edu, that met all of the objectives, with displays of real-time and past data, as well as information about the project. The nodes were deployed with information stickers and the Tech published a blurb about CLAIRITY. Informational screens and the MIT Museum display will be in place by the end of May 2014.

Future Improvements

As awareness of CLAIRITY spreads, there are several improvements that could be made to the website to help serve users. Most importantly, the formatting should be edited to make it more compatible with mobile devices. Additionally, the graphing display could be improved to allow users to compare information between multiple pollutants.

Technical Description

Each sensor node is comprised of a modified Dylos particle counter, various sensors, a printed circuit board, analog to digital converter, microcomputer and power supply. These components all fit into custom cases that can then be placed into a weatherproof enclosure for outdoor mounting or mounted on a shelf for indoor locations. While most of the components can be purchased from various vendors, the combination of these components to work in unison is what makes CLAIRITY unique.

Sensor Node

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Dylos Modification

Each of CLAIRITY's sensor nodes is built on top of a Dylos, an off-the-shelf particulate matter counter. It was chosen over other particulate matter counters because of its relatively low cost and high accuracy. All Dylos elements were preserved in the CLARITY sensors, except for the back cover, which was replaced with a plastic case to house the additional sensors and circuits. A new outer cover was 3D-printed to enclose the new design. Below is a detailed discussion of the Dylos modification process and the new components added to the Dylos particle counter.

The Dylos consists of a small fan that maintains an airflow through the device, a laser beam and photodiode system that measures particulate matter, a screen that displays the results, and a power source. The Dylos reports the particle count per cubic foot of air, and it does so in two different size bins: coarse particles (diameters between 10 micrometers and 2.5 micrometers) and fine particles (diameters less than 2.5 micrometers). As air is channeled through the system, the Dylos counts particles by scattering light by the particles in the air. This scattered light is then picked up by the photodiode, which registers a voltage based on the amount of scattered light.

In the CLAIRITY nodes, a series of sensors were added to measure temperature, RH, and the concentration of four common gas pollutants: CO, NO, NO_2, and O_3. Infrastructure in the form of a 3D-printed case has also been added to the Dylos to direct incoming air through these sensors and through the particle counting system before it finally exits the device. A 3D-printed cover was also designed to house the internal components of the sensor. Furthermore, the power supply system was modified to accommodate the new electronics on the device. Below is a more detailed description of the device's new parts.

3D-Printed Cases

As mentioned above, infrastructure was built to house the new node components. The Dylos cover was replaced by a case, referred to as the “Oreo case” because of its sandwiched position, which was designed as a mount for the sensors. The Dylos fan and serial cable were removed from the original Dylos cover and placed onto the Oreo casing where fixtures were created for them.

The Oreo case was designed so as to maintain the proper functioning of the PM counter as well as guide air through the new sensors. As such, the original path of air through the laser system was duplicated exactly from the Dylos cover, while additional spatial provisions were made to channel air over the gas and temperature sensors as well. In the new design, incoming air passes over the RT, temperature, CO, NO, NO_2, and O_3 sensors before it is directed through the optical particle counter and channeled out of the system. Figure 1 shows a schematic of the airflow path.

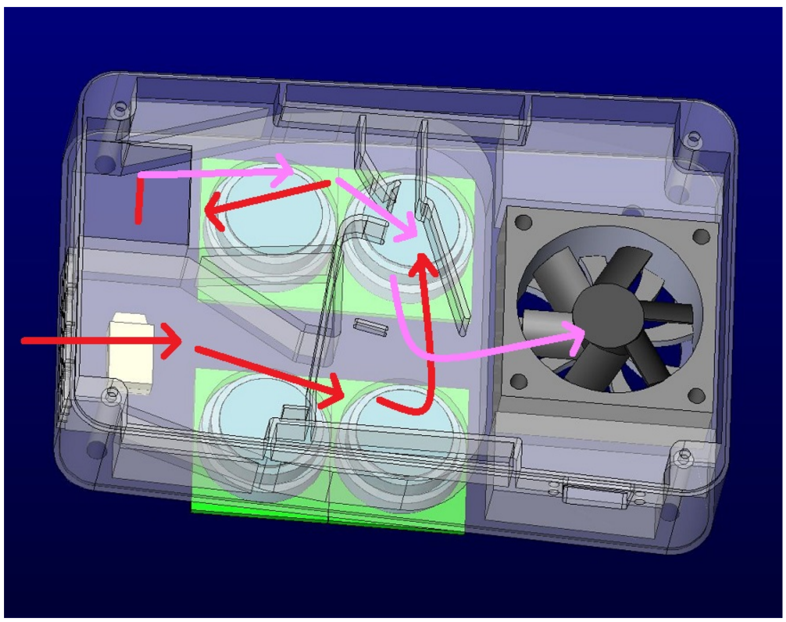


Figure 1: The red arrows indicate airflow in the lower deck, where the added sensors are situated. Pink arrows are on the upper deck and they show the flow path through the PM counter. Air then passes through the fan before exiting. For visibility, the Oreo casing has been given a transparent rendering in this image.

The Oreo case was printed in black ABS in order to facilitate proper light absorption. This is crucial for the PM counter to give an accurate reading. Where it was printed in another color, the inside surface was painted black with acrylic paint. The case snaps in position onto the Dylos system and is secured by screws and electrical tape to protect against gas leakages. The case has a very similar underside to the inside of the Dylos cover. On the flip side, it has a mount for the Raspberry Pi and the additional sensors.

An external cover was designed to snap onto the Oreo case and protect the exposed components of the node from the elements and human reach. The cover was used on the indoor nodes, which, unlike the outdoor nodes, were not housed in a sturdy weatherproofing box. The cover has a hood to facilitate air circulation as well as a circular hole for power cables to come through. As shown in Figure 2, this cover bears the MIT and MIT Civil and

Environmental Engineering logos. More detailed images of these parts can be found in the appendices.

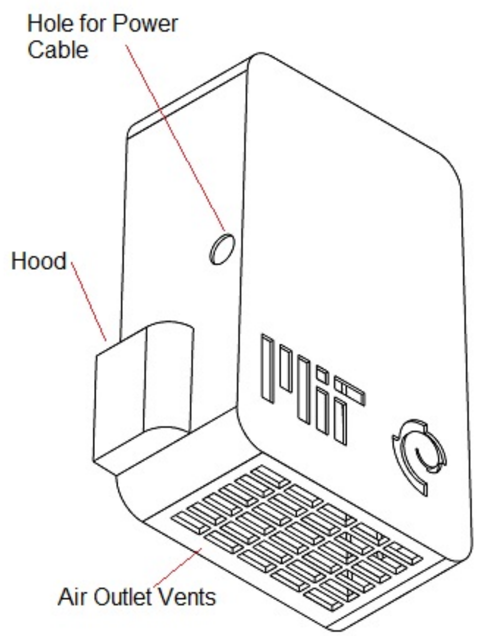


Figure 2: A 3D view of the printed cover to the CLAIRITY nodes.

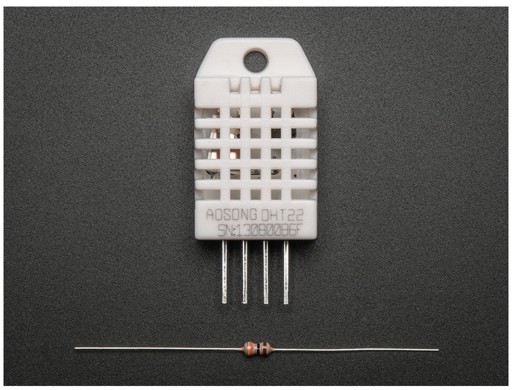
Alphasense Electrochemical Gas Sensors

Our system measures four common gas pollutants: CO, NO, NO_2 and O_3. The Alphasense sensors – as one is shown in Figure 3 – are electrochemical sensors that measure the concentration of pollutants passing through the CLAIRITY nodes. The sensors work by facilitating a chemical reaction, either reduction or oxidation, which results a voltage based on the concentration of the pollutant. This registered voltage data is reported as two voltage values, and undergoes conversion as explained in the Calibration sections of the report.

Figure 3: An image of an Alphasense electrochemical sensor; this one measures Ozone, as does one of the four on the CLAIRITY sensor nodes.

Temperature and Humidity sensor

We used the DHT22 temperature and relative humidity (RH) sensor because of its low-cost, high accuracy, and high temperature and humidity measurement range. The sensor uses a capacitive humidity sensor and a thermistor to measure the surrounding air, and spits out a digital signal on the data pin at a frequency of 0.5 Hz, or once every 2 seconds. Wire connections were created to connect the sensor to the PCB. Its four pins were extended with wires and the wires crimped and housed on the other end to bring them to snap onto the board. Figures 4 and 5 below show images of the original and altered temperature sensors.



Figures 4 and 5: The DHT22 temperature and RH sensor, both the unmodified and modified versions.

The sensor sits on the Oreo case where a gap was designed for it to dip its head into the airflow path below. To prevent air leakage, the sensor was sealed and secured into the gap with Teflon tape.

Printed Circuit Board (PCB)

The Printed Circuit Board (PCB) is a system of circuits that distribute sensor signals and power to the various components of the node. Figure 6 shows the PCB from above. It was designed particularly for this project and was printed by Express PCB. The board was modified in that the hardware team soldered resistors, capacitors and connections onto it in order to facilitate proper transfer and signal communication.

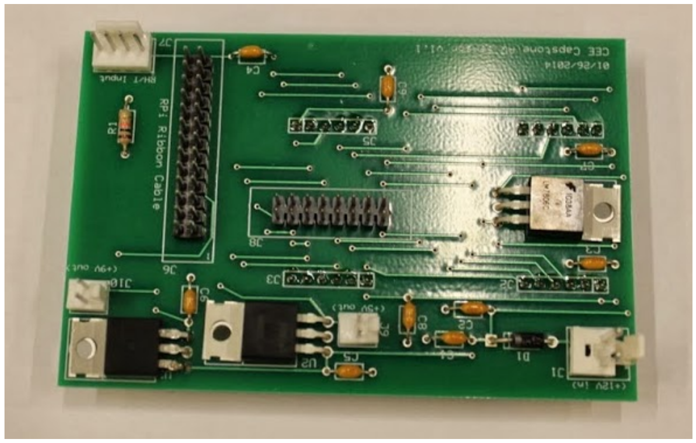


Figure 6: The Printed Circuit Board (PCB) as viewed from above.

In the hardware spatial configuration, the PCB sits on top of the four Alphasense gas sensors, each of which it is attached to through a 6-pin connection. A 28-pin connection was soldered onto the board to connect it to the ADC board.

The PCB receives 12 volts (V) of power from an external power source and directs 9V to the Dylos System, 6V to the Raspberry Pi, 6V to each of the Alphasense gas sensors, and 5V to the temperature and RH sensor. It receives raw voltage signals from the four gas sensors and transmits them to the ADC board, which converts them to digital signals before they are channeled to the Raspberry Pi. It also channels digital signals from the RH/T sensor to the ADC board. Please see Figure 7 below for a visual illustration of the movement of signals through the node.

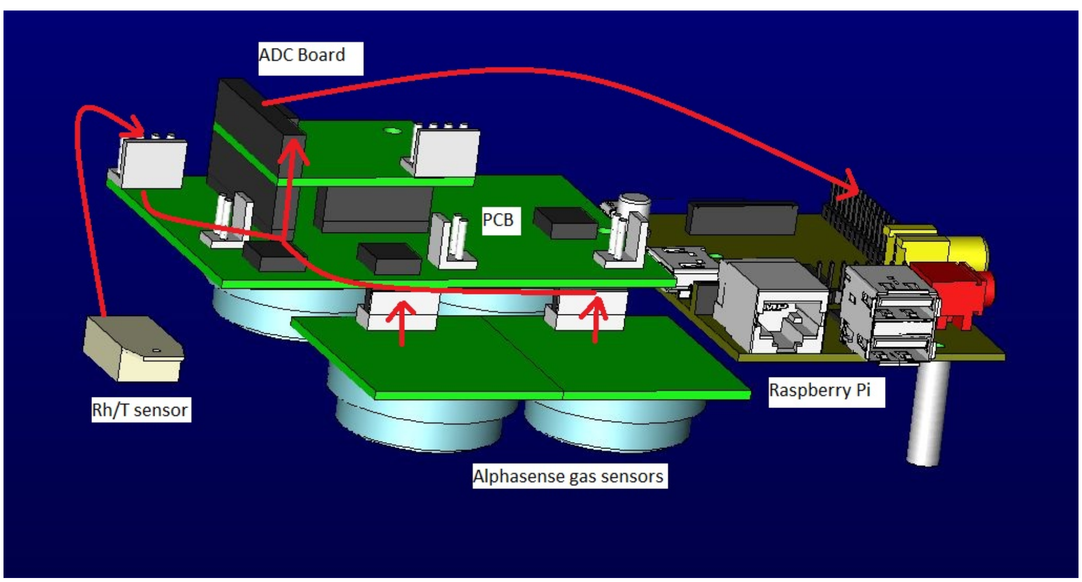


Figure 7: The arrows show the movement of signals through the node. The Dylos and printed ABS cases have been removed for visibility.

Analog to Digital Converter (ADC)

We employed the Delta-Sigma ADC from AB Electronics to take the analog data from the Alphasense gas sensors and convert it to digital data before transmitting it to the Raspberry Pi. This ADC allowed for up to 8 input ports, which made it appropriate for the

CLAIRITY project's purposes as each of the Alphasense sensors has two outputs. The ADC, as shown in Figure 8, also receives digital input from the temperatures and RH sensor, which it in turn transmits to the Pi with which it communicates through a 28-pin ribbon cable. The ADC sits on top of the PCB.

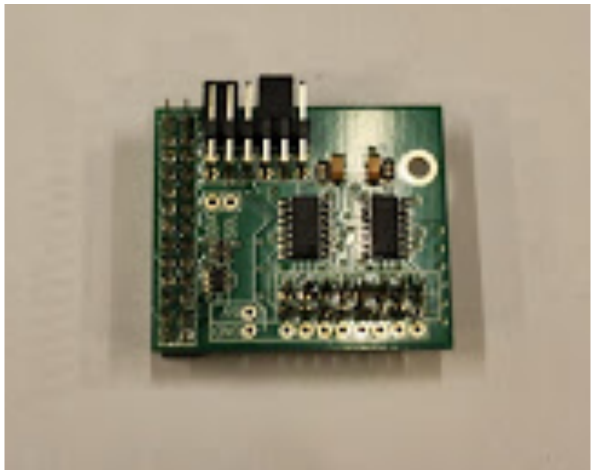


Figure 8: The Analog to Digital converter (ADC) as shown from above.

Raspberry Pi

The Raspberry Pi is the platform on which the sensors are built. It performs all the data processing and communicates to the network database through a Nano USB Wi-Fi adapter via wireless connection. Shown in Figure 9, it was chosen over other processors owing to its high processing speed and flexibility in terms of compatibility with programming languages and hardware.

It is secured onto the Oreo casing with a mount and screw. It receives power from the PCB through a micro-USB cable. As discussed above, it also receives digital data from the gas and RH/T sensors from the ADC through a 28-Pin ribbon cable. The Raspberry Pi is also connected to the Dylos through the USB-serial adapter. It stores data locally on a 4GB memory card and when connected via Wi-Fi to the network database pushes this data to a common storage area.

Figures 9 and 10: The Raspberry Pi computing unit and the customized power cord, as designed and made specifically for CLAIRITY.

As shown in figure 10 above, a power supply was created for the Raspberry Pi by stripping the other end of a micro USB adapter and crimping it to create a connection to the PCB board.

Power Supply

As discussed above, the power supply system was altered to accommodate for the changes made to the device. The internal power distribution was redesigned so that power now enters the device through the PCB. This piece in turn delivers power to the different electronic components of the device. The PCB receives 12V of DC power from an external power source and directs power to the various parts of the node as needed.

The power input used for the indoor nodes is a modification of the original Dylos adapter. The endpin was stripped and the adapter modified so that the cord delivers power from an outlet to the PCB through a two-pin crimped terminal. The stripped pin was reused in that it was employed to transfer power from the PCB to the Dylos system. Crimped terminals and terminal housing were attached to the other end of the stripped pin to create a cable which attaches to the PCB on one end and to the Dylos power receptor on the other.

For the outdoor nodes, the internal transfer of power is similar to that of the indoor nodes but the external input is vastly different. Because the outdoor power supplies required weatherproofing against the elements, a weatherproofed AC power line ran from the power source into the weatherproofing box that contained the node. The nodes therefore needed a local transformer to step down incoming 110V AC power to 12V DC power. A transformer was clamped inside the weatherproofing box that received 110 V AC and sent 12 V DC to the node.

There were also some unique power configurations. The node in one of the shuttles received 12V directly from the shuttle battery. Some outdoor nodes also received power directly from emergency phone lines. These sources, as in all the nodes, entered the node through the PCB before the power was distributed and delivered to the other electrical elements of the node.

Figure 11 below shows all the node assembly parts, and Figure 12 shows an assembled node. For detailed instructions on node assembly, please refer to the assembly manual on the CLAIRITY website.

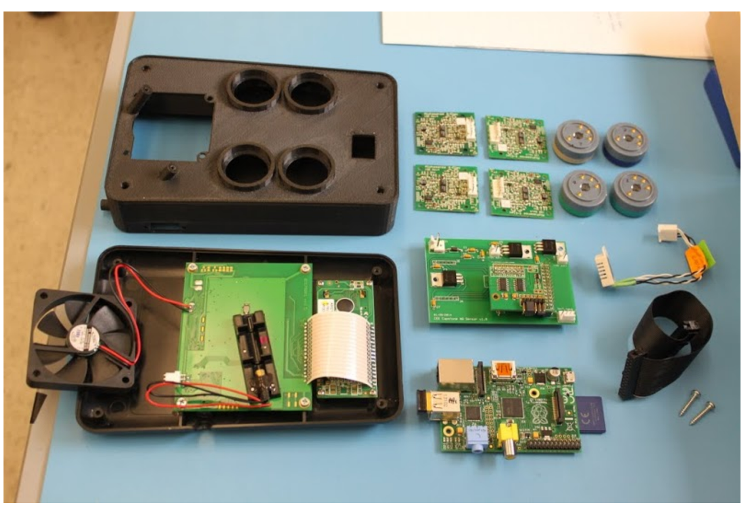


Figure 11: A CLAIRITY sensor with its components, before assembly.

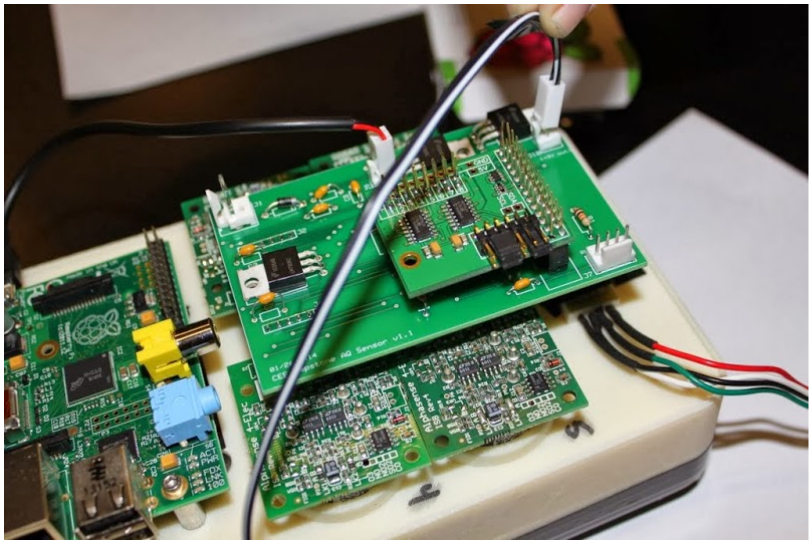


Figure 12: A fully assemble CLAIRITY sensor node, without the 3D-printed covers.

Weatherproofing

The CLAIRITY air quality network is predominantly an outdoor sensor network; there are 24 nodes in the system of which 17 are outdoors. Since outdoor locations are susceptible to wind, rain, snow and other factors, it was necessary to develop a strategy for protecting the sensor nodes. During the weather proofing process protecting the sensors from water damage, maintaining the airflow through the box and preventing insects from moving into the box were the main considerations that drove the process.

Weatherproofing began with a search for adequate waterproof boxes. The ideal box would need to provide a watertight seal, be large enough to fit the node, transformer and other components and have minimal effects on Wi-Fi signal. Most of the boxes found were metal or plastic waterproof electrical enclosures. The metal boxes posed an issue since they would most likely block Wi-Fi signal inside the box, as such plastic enclosures were pursued. Throughout the prototyping process three plastic enclosures were tested, each was a different size. Three sizes of boxes were tested: a small box (8x6x5 in.), a medium sized box (8x8x5 in.) and a large box (12x10x7 in.). The small box was eliminated from contention when it became clear that the box was not large enough to fit all of the necessary components. The large box fit all of the needed components but left a lot of free space within the box, and there was some concern that this empty space would cause air to circulate within the box instead of through it. Lack of airflow through the outlet could result in sensor readings that do not align with the true readings for the ambient air. The medium sized box was just big enough to fit all of the components and small enough to avoid air circulation within the box, so it was selected for use in deployment.

Each of the weatherproof boxes needed to have an inflow and outflow holes cut into them to allow for airflow, as shown in Figures 14 and 15. These holes were cut into each of the boxes using a CNC router. To minimize the amount of materials needed in waterproofing these holes, the node's intake was lined up with the bottom of the box. The hole cut in the bottom of the box is not very susceptible to rain and thus did not require any extra weatherproofing. The outflow hole for each box was cut into the left wall of the box, as shown in Figure 15. This hole would be susceptible to rain coming down from above the box or to wind pushing rain in from the left. The outflow holes were protected from the elements with 3D printed hoods attached to the box with waterproof foam tape. The hood is diagrammed in Figure 13.

Some boxes, such as the box protecting the tech shuttle node, had to be installed at odd angles causing both the intake and outflow holes to be vulnerable to wind and rain; in these cases hoods were attached to both holes. The opening at the bottom of each hood and the intake hole were also covered with mesh to prevent insects from moving into the boxes.

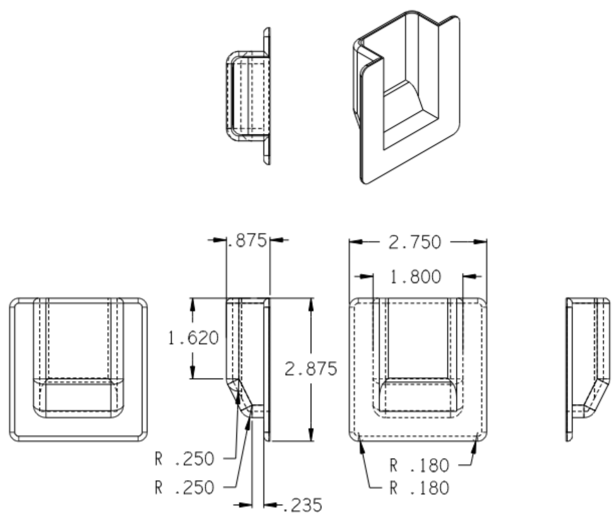


Figure 13: Schematic of the hood used to block rain from entering the weatherproof box; units are in inches.

The weatherproof box prototype was tested by holding the closed box with hoods and mesh attached beneath a running showerhead for five minutes. During testing, the box was moved around horizontally and tilted it at slight angles to simulate the possible effects of wind on rain direction. During testing, it was determined that the box maintained its watertight seal when properly closed, however the box would accumulate small amounts of water if the closer failed to tighten all of the screws completely and the box was not properly closed. To account for the possibility of human error in closing during deployment the seam of each box was sealed over with duct tape.

Figure 14: Installed weatherproof box

Figure 15: Bottom view of the weatherproof box

Mounting Detail

The deployment plan for the CLAIRITY sensor system included many locations with different infrastructure, which led to different installment challenges. Indoor nodes had easy access to power, strong Wi-Fi signal, and did not require weatherproofing. However, indoor nodes did present a mounting challenge since the main option involved attaching the node to the wall. The nodes could not be easily mounted to the wall with screws since the node itself could not be drilled into without diverting the airflow in the node or risking cracking the 3D printed parts. Fortunately, the weatherproof boxes could be easily mounted to any wall using screws and the box's mounting flanges. As a result indoor nodes in public areas, such as Café Four and the Student Center, were put into weatherproof boxes and mounted to the indoor walls using screws. Indoor nodes in less publicly accessible areas, such as Next House Dining and Burton Conner, were simply placed on inconspicuous shelves or ledges and secured into place with L Brackets, as shown in Figure 16.

Figure 16: L-brackets are secured into the wall and ledge in order to keep the indoor nodes secure.

Outdoor nodes needed to be mounted in close proximity to outdoor power sources. For the most part the possible mounting infrastructure near the necessary power sources consisted of poles and railings. The plan was to attach each of the nodes to such infrastructure using two ring clamps that are attached to the top and bottom of the box via flanges and tightened around the circumference of the pole. During deployment, however, there was a limited selection of ring clamp sizes. Some of the railings and poles were too small for the ring clamps that were available during deployment; as a result some of the nodes were zip tied in place.

Software and Data Structure

All of the coding for CLAIRITY was done in python. All the necessary software needed to be "pushed," or transmitted, to the various nodes individually. The code was carried out on the Raspberry Pi; see Appendix A5 for the final version of this code.

For the main code, all of the necessary packages were imported in the beginning. The account details for the CLAIRITY email account were also included at the beginning of the code so the node can send an email once connected to the Internet.

All the global variables to be stored in the database were then defined, which included humidity, temperature and the Dylos and Alphasense data. The values were all initialized - humidity and temperature were initialized at -9999.99 and all the Dylos and Alphasense values were initialized at 0.

After the serial port was initialized, a sensor reading function was defined. Within this function, a continuous loop was written to continually collect data. For each data reading, there was a try/except block to catch errors in reading the data. For data storage purposes, the filename was also changed everyday. After reading the data from all the sensors, the data was then written to a CSV file to be stored locally on the SD card of the Raspberry Pi. Finally, the data was also written to the database. Database writing included the database URL and the node ID to properly identify the data. In this section of the code, if the node was connected to Wi-Fi, the data was pushed to the database and the IP address of the node was sent to the capstone email. If the Wi-Fi is not connected, an error is thrown and after ten seconds the node attempts to reconnect.

Not every node had Wi-Fi connectivity once installed in its designated location. Some of the nodes ended up needing to be connected via an Ethernet connection because they were in areas with weak or non-existent Wi-Fi signal. When connected to Ethernet, each Raspberry Pi had to be registered individually to MIT Ethernet. Finally, a few nodes had no Internet connection at all via Wi-Fi or Ethernet. For these locations, data had to manually retrieved from the SD cards on the Raspberry Pi. The SD cards were retrieved, and by inserting them into a Linux based laptop, the data was loaded onto a computer and then saved to the database for later use.

Dylos, Alphasense and meteorological data functions are also defined. Each function collects the data that it is defined for. The Alphasense function is based on Delta Sigma Version 1 architecture. Due to errors with the sensors themselves, the meteorological (RH/T) data sensors sometimes crash after some time and interfere with the Alphasense request for data since they use the same i2c port. At the time of writing, the code is in the process of being updated to reboot every half hour to mitigate this issue though it is still not complete.

Calibration System and Methods

The following section will explain how the CLAIRITY calibration method was designed and implemented. It details the two kinds of tests run on the sensor nodes and displays how lab equipment in Parsons Laboratory was utilized to make this process happen.

Set-up and Testing Process

With each type of test run, the set-up was different. Known concentration tests required using tanks of the pollutants of interest, posing more of a hazard than the ambient tests, which simply sampled air from outside the building. In each scenario, a different set-up with different equipment was designed and constructed.

Known Concentration Tests

For the known concentration tests that were run in the laboratory, the CLAIRITY team first had to prepare a safe work environment. This involved modifying an electrical box with airtight Swagelok ports on each side. On one side, shown here in Figure 17, there were several lines, one allowing "clean" air from the laboratory to be pumped into the calibration chamber, and the other connected to a multi-branched manifold, each branch of which led to a tank of the gas-phase pollutants of interest.

Figure 17: Input-side of the calibration chamber; the foil-covered pipe leads to the ambient air channel from outside the laboratory. The multi-branched manifold connects to "clean" house air as well as the tanks of the gas-phase pollutants of interest.

On the other side of the chamber, here shown in Figure 18, there are more airtight connections between the calibration cell and several important instruments:

- A digital pressure gauge, which is used to maintain that the calibration cell is never over pressure; if this condition is not held, any dangerous gas that is pumped into the chamber may escape into the room, which is why the entire set-up is housed in a chemical hood as an extra precaution
- Teflon lines, which carry the air from the chamber to the high-fidelity instruments; this allows the instruments to sample the same exact air as is being analyzed by the CLAIRITY sensor nodes inside the cell
- A Wi-Fi hub, which allows the sensors inside the calibration cell to connect to wireless Internet and log data to the database

Figure 18: The output-side of the calibration chamber; lines exit from here and connect to: a Wi-Fi hub; a digital pressure gauge, to ensure the chamber is never over pressurized; and lines that carry the chamber's contents to the high-fidelity instruments after it has passed through the sensor nodes.

On the front face of the calibration cell, there are three more connections for power lines; these are used to power the sensor nodes from outside the cell. In order to calculate the known concentrations of pollutants before pumping them into the system, two variables must be known:

- The backing pressure of the gas tanks
- The airflow through the Teflon line at a certain pressure

With these two pieces of information, a simple calculation allowed the CLAIRITY team to know with a fair amount of accuracy just how much of a given pollutant was being entered into the system. This known amount was then compared to the Alphasense sensor readings and was ultimately the most important comparison when it came to performing calibration correlations plots, as discussed later in this report.

Ambient Tests

The second kind of test was less useful for calculating the calibration factors for each of the electrochemical sensors. It was, however, crucial to the understanding of how these nodes would perform once deployed. Having a pipe connection to the air outside of Parsons Laboratory allowed the CLAIRITY team to pump a large acrylic box with ambient air, a box that could contain about a dozen nodes at a time, as shown in Figure 19.

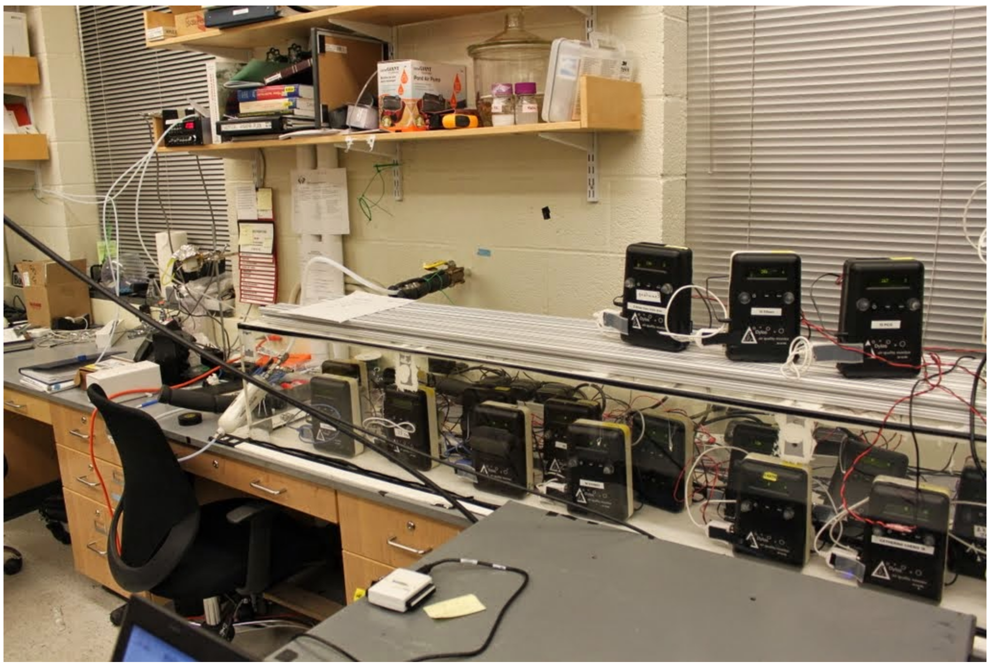


Figure 19: The acrylic ambient chamber, with several nodes collocated inside. The fixture on the wall behind the box is the pipe that connects to the air outside Parsons Laboratory.

This chamber was useful in that it allowed a glimpse of what the sensor readings would look like in the outside world. It also allowed the CLAIRITY team to check how the sensor readings compared across one another. Once collocated in the acrylic chamber, each node was analyzing the same ambient air – pumped into the box and circulated with a powerful fan. If the nodes did not read similar values, it hinted to the CLAIRITY team that there was an issue and alerted the Hardware team that there was a node that needed to be fixed.

It also allowed us to check that any spikes we saw in the readings were from actual pollution events and not simply hardware or code glitches. For example, when a freight train made its daily trip past Parsons laboratory, there was always a spike in the ambient sensor readings, demonstrating the reliability and variability of the CLAIRITY sensors in the context of real air.

These sensor readings, once collected, became a crucial part of the CLAIRITY project, informing the data analysis and calibration processes and increasing the accuracy of our network.

Data Processing and Analysis

As introduced earlier, each electrochemical reports voltage data as a way of expressing gas-phase concentrations. This data comes from two pins – labeled output one and output two – on each of the Alphasense sensors and will henceforth be denoted as OP_1 and OP_2. Each pin also has a baseline that corresponds to a zero concentration reading. This zero baseline was calculated for each sensor from a time average of data points when clean air was run through the gas chamber and the high fidelity instruments also confirmed a zero reading.

Next the data was pushed through this equation:

$$\text{Final Voltage} = \frac{(OP_1 - Z_1) - (OP_2 - Z_2)}{2.4637}$$

This operation converts the two outputs into a single voltage dataset. Note that the divisor factor of 2.4637is not typical. This correction was required for CLAIRITY due to a missed conversion at some point in the data collection process.

After a single voltage data file has been created, the millivolt reading is converted to parts per billion by dividing by a sensitivity factor. To get a value to compare CLAIRITY's calibration values to, the factory-provided sensitivity value (S) was used to calculate the "factory" concentration values.

$$\text{“Factory” Concentration} = \frac{\text{Final Voltage}}{S}$$

In order to have independent calibrations, the Alphasense voltage wave was used to calculate CLAIRITY's own sensitivity factors in units of mV/ppb.

Since the Alphasense electrochemical sensors and high-fidelity lab instrumentation both collected data points over different time intervals, it was necessary to average the data over the same time base for comparison. This was done by averaging all data points that fell within 60 second intervals for each piece of equipment, meaning no matter how many data points were taken each minute, a single average value for the same time point would be displayed. This averaging also helped to reduce electronic noise in the system.

Next, the data that forms the decay curves of the species-specific pulse is isolated and plotted, as shown in Figure 20. A correlation plot is made with the high-fidelity sensors data on the X-axis in parts per billion and the Alphasense data on the Y-axis in millivolts, as shown in Figure 21. A linear fit was applied to produce an equation of a line; the slope of this line was calculated to be the sensitivity factor for the sensor.

Equation for a line: $y=mx+b$

$$\text{Alphasense Voltage [mV]} = \text{Sensitivity [mV/ppb]} * \text{High-Fidelity Concentration [ppb]} + \text{Offset}$$

For each of the 25 nodes, this process was repeated for multiple pulses of each gas-phase species. After calculating several sensitivities for each electrochemical sensor, the reported values are calculated as an average of the resulting slope and Y-intercepts of those multiple pulses.

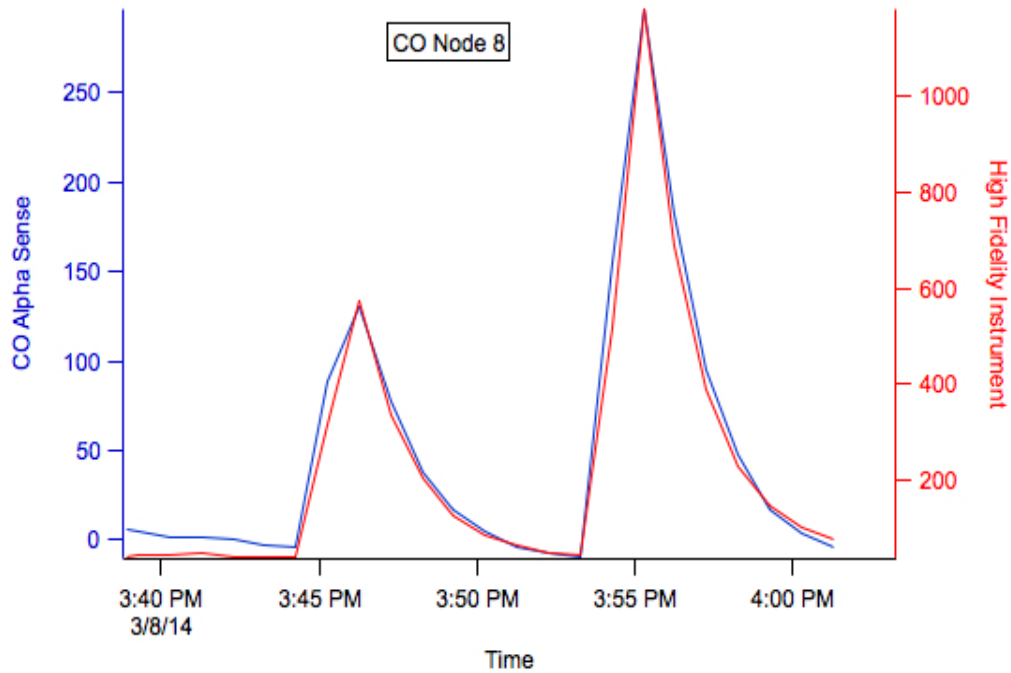


Figure 20: Decay curves of CO spikes as read by Node 8

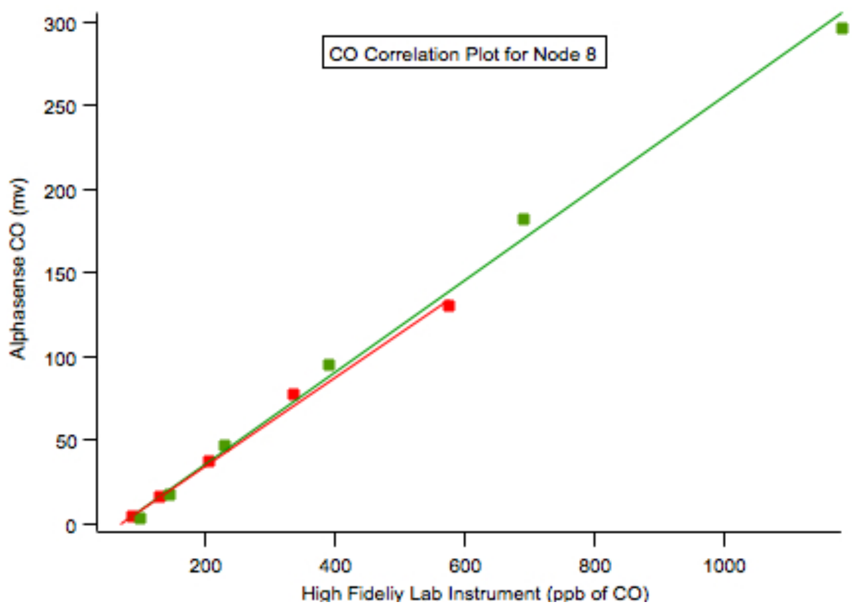


Figure 21: Correlation plot of Node 8's CO sensor and the high-fidelity CO instrument from Parsons Laboratory

Lessons Learned

As mentioned earlier in this report, the calibration process remains ongoing for the CLAIRITY network. Although the set of calibration factors is not completed yet, there are still valuable lessons learned from this portion of the project.

Firstly, the readings from the Alphasense sensors display a dependence of some kind to temperature and humidity. This dependence has not been investigated or calibrated for, but it could explain some of the anomalies in the analysis. It could be a reason for tests with very similar curves, but shifted offsets, as shown in Figure 22 below.

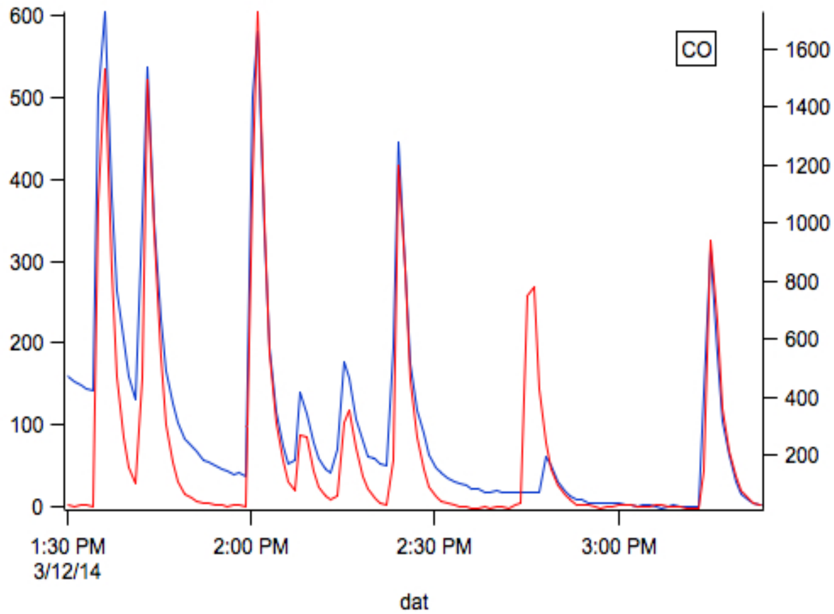


Figure 22: These curves are clearly similar, but the offset in the Y-axis could be due to the unaccounted-for dependence on temperature or RH.

Another factor that needs to be considered and accounted for is the cross-sensitivity that is evident between NO_2 and O_3. Figure 23 demonstrates this interesting effect between these two gas-phase species.

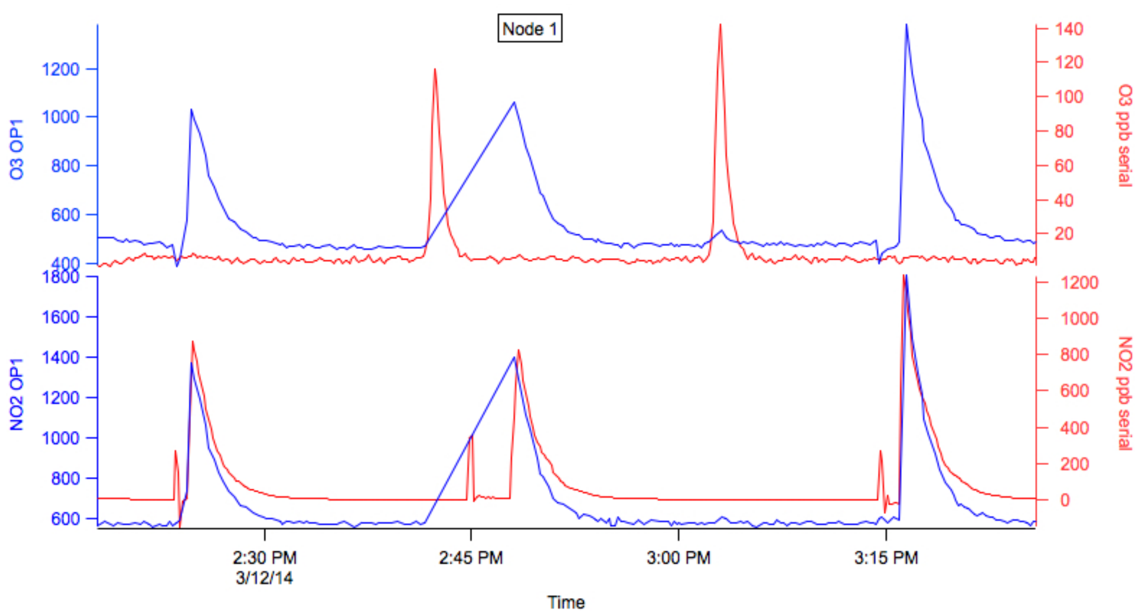


Figure 23: These plots show a cross-sensitivity between the O_3 and NO_2 in the calibration system.

Alphasense sensors have an expected start up time before the sensor gives accurate and stable readings. Some sensors baselines were still shifting while the pulse tests were occurring, as shown in Figure 24. This did not allow for accurate zeroes.

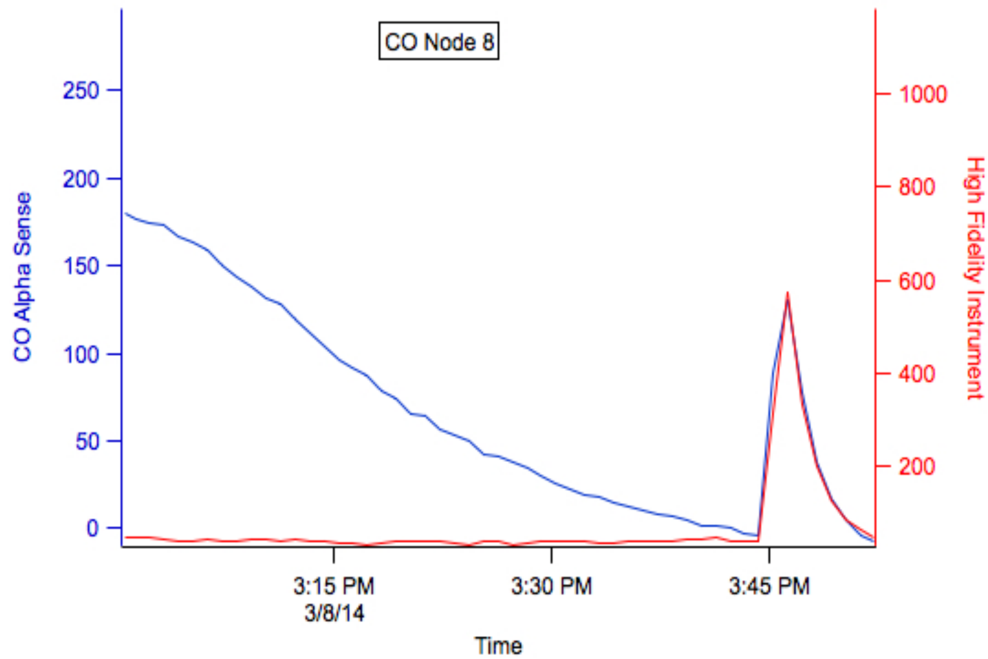


Figure 24: The blue line shows very clearly that the baseline of CO as read by the Alphasense sensor shifted dramatically, while the baseline of the lab instrument stayed at nearly zero.

Although the linear fit lines all had high correlation factors, a linear fit was not always the best option. At higher concentrations, many sensors showed a nonlinear trend, as shown in Figure 25. The removal of these one or two points from the higher concentrations drastically shifted the slope – and therefore sensitivity factor – of the same sensor. The more useful and realistic values are that of the lower concentrations, but the higher concentrations clearly do not align as well with the linear fit. Since the arbitrary exclusion or inclusion of one point can change the resulting calibration so drastically, there needs to be a hard rule for how to exclude points from the quick fit line.

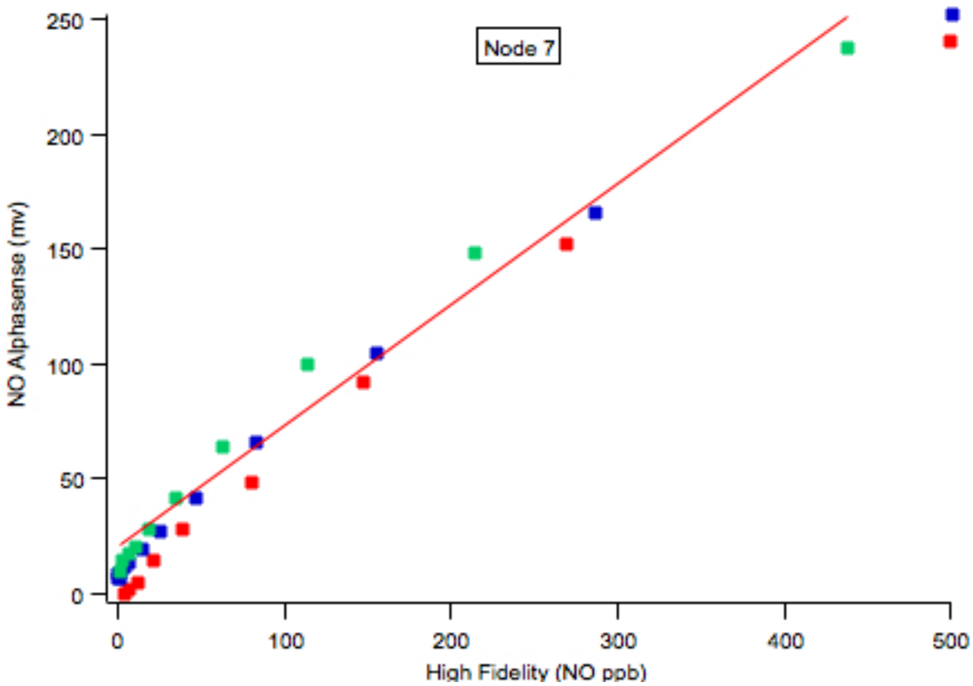


Figure 25: This plot shows that a linear fit may not be the best approximation for the data points. Near the origin, a linear fit might work, but as you increase along the X-axis, the original line's slope becomes less steep, changing the accuracy of the approximation.

Other issues included time lags between peaks and the possibility of the averaging code to flatten peaks. Both would skew the sensitivity value in similar yet incorrect ways, and both possibilities need to be better understood of the calibration is really to result in highly accurate and trustworthy data.

Process Modifications

The first major issue with the calibration process – as it was performed for CLAIRITY – was the overwhelming amount of data. The CLAIRITY team received half a million points per high-fidelity sensor in addition to the data of 25 nodes, each of which has four separate sensors to calibrate to account for each gas species. Continuous data collection from the high-fidelity sensors over the course of several weeks was not as useful as anticipated, and resulted in a large data file that was slow to process. For future calibration of the sensor nodes, the high-fidelity instruments should only record when the sensor node records. This high-fidelity section of data should then be saved directly to a node specific file. This would allow for smaller, faster, and more definite data processing. Using this method, there would no longer be a need to match where the nodes and high fidelity sensors are both recording — one of the more time consuming parts of the process.

This is the start of a necessary data organization system. The data recording would be even more useful if the high-fidelity data waves were broken down and labeled into the separate tests: zero, pulse, and ambient. Since each require different data processing, scrolling and sorting would no longer be necessary, thereby shortening the overall process further.

Communication Portal

After considering a number of options with which to communicate the CLAIRITY process and findings with the rest of the MIT population, a website was chosen as the best way to reach the project's intended audience.

CLAIRITY Website Overview

A website is essentially a document that is written in hypertext markup language, or HTML. A web page consists of two parts: a back end and a front end. As was mentioned earlier in this report, the back end contains the logic for the page and supplies the Application Programming Interface (API), which specifies how software components should interact with each other. The front end creates the visuals that appear to the user. The front end is broken down further into different sections. HTML forms the structure of the front end. Cascading Style Sheets, or CSS, is the code that is used to format the page and make it visually appealing. JavaScript is incorporated into the page in order to add dynamic elements to the page, such as graphs.

In order to construct an interactive website the CLAIRITY team had to perform the following tasks:

- Set up the frontend to display visuals and provide for a user interface.
- Determine a central server and domain name
  The Raspberry Pis would direct information to the server so the backend could locate the needed data.
- Set up the backend
  The backend refers to the programs that are executed on the server itself. In this case, it mainly provided a frontend-database interface and a nodes-database interface. Calibration of the raw data was also done here before being served.

The relationships between each portion of the website are explained visually in Figure 26.

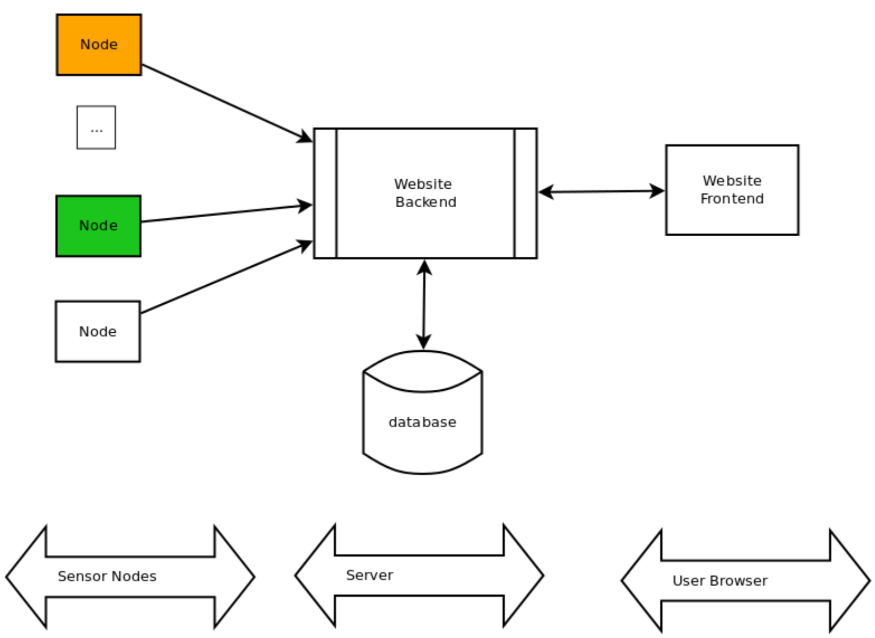


Figure 26: This diagram explains the relationships between the main components of the CLAIRITY website: the frontend, backend, database and server.

The CLAIRITY team was able to collaborate on the website by using a program called GIT and the GitHub web application. GIT is designed for code sharing. Teams can simultaneously modify code and push their edits to a common server. If different sections of the code need to be worked on, different branches can be created and modified using this online application, streamlining the process through which projects like this are completed. The code used for the CLAIRITY project can be accessed on GitHub at https://github.com/clairityproject.

Front End Construction

Visuals

The clairity.mit.edu website was built with Bootstrap, a popular front-end framework that allows for faster and easier web development, as well as dynamic CSS that responds to changes in screen size. Because Bootstrap offers a free collection of tools that already contains HTML and CSS-based design templates, it was easy to quickly design the CLAIRITY site. Bootstrap was chosen because it is compatible with the latest versions of all major browsers, a free open-source collection of tools, and could greatly accelerate the website development timeline.

Bootstrap provided a set of style sheets that provide basic style definitions for all key HTML components. The uniform, modern appearance from Bootstrap allowed easy formatting of text and table elements. The basic style sheet and JavaScript components that come along with Bootstrap were used. Bootstrap comes with several JavaScript components in the form of jQuery plugins. Some of the specific JavaScript plugins that were used on the site include Carousel (on “The Project” page) and Modal (pollutant descriptions on “How It Works” page). New style sheets were created for all of the pages to include additional styles that were not included in the Bootstrap style sheets.

The finalized site consists of several pages: a landing page, a homepage with a map, a data tab, and tabs with information on the network, the project, and the nodes. The homepage and data tab convey the data that is being collected from the nodes. The home page contains a map of MIT’s campus, and locates all of the air quality nodes on campus. The data page consists of a list of all of the node locations and pollutants. Multiple locations can be selected along with the pollutant of interest to view past data in the time scale of various time intervals. The option to download a CSV file of the data is also available. Other tabs on the website convey more information about air quality, the team, and the process of creating the network.

Map

The website homepage uses the Leaflet JavaScript Library with Google maps API to create the campus map. Cloudmade is a company that produces rendered maps and geographic related services. Originally the team used Cloudmade for the map display, but during the project Cloudmade restricted its services to large companies, prompting the team’s switch to Google maps. The team used the Styled Maps Wizard to edit the map’s colors and labels and used Leaflet markers to denote node locations, with circle markers for outdoor locations and triangular markers for indoor locations.

The homepage calls the latest data for each node from the database and then colors the node based on that node’s placement along an Air Quality Index, explained in the following paragraphs. When users hover over a marker, a Leaflet popup appears with the marker location, and when a user clicks on a marker, the latest values for that node appear on the left sidebar.

Air Quality Index (AQI)

CLAIRITY synthesized an Air Quality Index (AQI) that qualitatively describes the current level of pollution at each node. The AQI was constructed using benchmarks from the Environmental Protection Agency (EPA) and Dylos particle count thresholds. The AQI specifically uses the EPA 8-hour thresholds for ozone and 1-hour threshold for carbon monoxide, and the Dylos threshold that applies to fine particle counts in determine a composite index value for a set of instantaneous ten-second data. In other words, the AQI is updated for each node every 10 seconds.

Air quality for each of the three measured pollutants falls into separate categories, explained below in Figure 27.

	Fine Particles (particles/0.01ft^3)	Carbon Monoxide (ppb)	Ozone (ppb)
Good	0-600	0-4500	0-64
Moderate	601-2100	4501-9500	65-164
Unhealthy	2101+	9501+	165+

Figure 27: AQI thresholds and corresponding qualitative description for each pollutant accounted for.

The composite AQI for all pollutants combined is instantaneously color-coded for each node on the website and is simply the AQI of the worst performing pollutant. This categorization is appropriate because air quality is only as good as the pollutant that is, at the time, most concerning to environmental and human health.

AQI thresholds for NO_2 were not included because the EPA thresholds for NO_2 only exist at very dangerous NO_2 levels. Additionally, there were no EPA thresholds for NO. Finally, the Dylos provided threshold values for fine particle counts, but not coarse particle counts, which is why the CLAIRITY AQI accounts for only the fine particles. The team did not use EPA particulate thresholds because they measure mass concentrations of particles, while the CLAIRITY sensors solely obtain particle counts.

Graphing

The graphing function on the website uses the Highstock JavaScript Library, a variant of the popular highcharts library. The CLAIRITY team used the library's capacity to create a flexible graphing display that allows users to select nodes and pollutants of interest to view. The user can select multiple nodes and pollutants, as well as a specific time frame. In addition, the user has the option of zooming in or out the time with hour, day week, month, and all data.

Export Button

In order to increase transparency, the team wanted to make sure that users could independently take data and use it for their own projects or research goals. Raw data was therefore provided in CSV format. This file is dynamically generated from the database.

Server & Domain Name Selection

Overview

A server is a computer that responds to requests and delivers data across a computer network. The project required a server to manage the data that would be received and distributed. Options for servers included either virtual machines or physical machines. Unfortunately, the CLAIRITY team could not secure a virtual machine on MIT's XVM.mit.edu because their servers were running at full capacity. The original decision was to purchase a virtual server from a cloud service platform like Amazon. Thus, initially the team set up a server on an amazon web services machine: this service was free and was running on Ubuntu Linux 12.

Figure 28: The CLAIRITY server: Acer RL80-UR23 Desktop

Eventually, a physical server was purchased, as seen in Figure 28, which was running on the MIT network. The computer came with Windows 8, which has Secure Boot. Secure Boot prevents people from hijacking the operating system. Windows 8 was compressed into 50GB, and the other 450 GBs were used to install Ubuntu, a simpler version of Linux that is more user-friendly. The network was set up so it could identify itself on the MIT network as clairity.mit.edu. (MIT's IS&T controls the 'mit.edu' and they allowed the CLAIRITY sub-domain for the project's use). Next, server software was installed: the SSH server, MySQL server to host databases, and Nginx. The computer was physically set up in the Parsons Laboratory.

Storage

CLAIRITY's operating system has 450 MB available. While this is a relatively small size by today's standards, the team chose not to store the data on Amazon's cloud service, AWS, because of the additional monthly server costs. It is much cheaper to buy a 2TB drive and connect it via USB.

Back End Construction

Overview

The team chose Ubuntu 12.04 LTS as the operating system for the server because of its industry proven stability, ease of use and fast security update releases. The team used Nginx as the web server with gunicorn workers, which were confirmed as responsive using supervisor. For the database, MySQL server was primarily because it is free and easily integrates with Django, a web-framework that was used to implement the backend.

Django 1.6 allowed the team to abstract database interactions using its powerful Object Relation Mapper (ORM) that let us create and manipulate database tables as python classes. Django's ORM also allowed us to perform error checks on input data from the nodes by ensuring that the data saved was of the correct type. The CLAIRITY team also used a Django module called South which made database migrations very simple. This allowed us to make changes to the tables during development without having significant downtimes – normal downtimes lasted just under two minutes – preventing data loss. Please refer to the appendix for more detailed configuration files.

The server was secured using the Linux uncomplicated firewall. Communication was blocked with all ports except those the CLAIRITY team wished to utilize. While testing, the team restricted access to the MIT IP range (prefix 18) using this application as well.

Data Handling and Preparation

Endpoints were developed for the nodes to post their data in JSON (JavaScript Object Notation) format. This was not only easy to debug but common python libraries readily supported it, as JSON is a common web data transfer format.

Knowing full well that the MIT network conditions are hostile and susceptible to data hacks, the team defined an easy to verify hash function with evolving parameters and secret parameters only known to the backend and node coding teams. An attacker trying to send rogue data would be unable to do so without discovering the hash function and secret token. This allows the team to increase confidence in the integrity of the data that is collected and stored.

A JSON API was developed to allow remote requests of the data. This allowed the front-end development to be decoupled from that of the back-end and eventually provide the system an additional layer of resilience.

Voltage readings from the sensors had to be converted and calibrated before it could be presented to the user; otherwise, the user would not be able to make sense of the data. The CLAIRITY team utilized calibration factors provided by the sensor manufacturers in order to make this possible, creating the infrastructure in the website to add CLAIRITY-specific calibration factors once those have all been calculated for every node.

To improve the user experience on the website, the CLAIRITY team sped up database query times. A separate table with a single entry per node was created to make it really easy to return the latest data for use in the pollution map. MySQL's internal indexing function to index was also used for commonly queried fields. The speed improved approximately twenty fold.

Deployment Scheme

Hypothesis

CLAIRITY aims to assess the MIT community's exposure to various pollutants in the air. In determining where the sensor nodes were placed, consideration was given to the capabilities of the sensor nodes, community concerns and how pollutants disperse throughout campus.

The primary sources for the pollutants measured by CLAIRITY sensor nodes are automobile exhaust, power plant exhaust, chemical solvent vapors and smoke. As such, the CLAIRITY deployment scheme focuses on areas where these sources are prevalent. These areas include food service locations, traffic intersections and parking lots throughout MIT's campus.

One of the primary goals of CLAIRITY is to provide information to the community on real-time air quality in order to raise awareness and inform decisions in day-to-day life. As such, most of the locations selected by the CLAIRITY team are ones frequented by the MIT community. In addition to giving community members information on air quality along their normal travel route, this also means that the sensor nodes are seen by the community in order to raise awareness of the overall project.

Overall, the CLAIRITY deployment scheme covers a wide cross section of the MIT campus in order to see how pollutants are dispersing throughout the air. Utilizing the Green Building and Building 16 roofs as high elevations that can serve as a 'clean air' mark, the rest of the sensor nodes are able to give a detailed look at how pollutants are dispersed throughout campus.

Node Locations

When determining where the sensor nodes would be placed, the primary considerations were mounting capabilities and location type. The primary mounting scheme utilizes a pole or pipe to which the sensor node can be attached. This controlled where specifically nodes could be placed within a certain area. Based upon the considerations discussed above, the CLAIRITY team focused on the following types of locations for deployment:

- Roof tops
- Parking Lots/Garages
- Major Intersections
- Food Service Areas
- Community Cross Section
- MIT Vehicles
- Cogeneration Power Plant

Roof Tops

Roofs were chosen in order to have a measure spatial variation of air quality with altitude. Since the main sources of pollutants measured by CLAIRITY occur at ground level, the air should be cleaner at these higher elevations. Specifically, the two roofs selected were:

- Green Building Roof

- Building 16 Roof

Parking Lots/Garages

Parking areas throughout the campus were selected to see how actions such as idling affect air quality in specific locations. Furthermore, the distribution of parking areas across campus gives a wide distribution of sensor nodes and, as such, the cross-section the CLAIRITY team desired. At outdoor parking lots, sensor nodes were installed at the parking attendant's booth so that the node could receive constant power from within the booth. Parking areas selected include:

- Stata Center Loading Dock
- West Parking Garage
- Kresge Parking Lot
- Massachusetts Avenue and Vassar Street Parking Lot
- MIT Medical Parking Lot

Major Intersections

Traffic flow is one of the major contributors to air pollution in Cambridge. The highest density of air pollution typically occurs at busy traffic intersections. Since many streets meet at intersections, traffic flow drastically increases compared to normal street sections. Vehicles will also often engage in "stop and go" traffic at intersections, thus releasing more air pollutants than they do in continuously moving traffic. To understand the influence of intersections and traffic congestions on air quality, CLAIRITY deployed several nodes near intersections. These include:

- Sloan School of Management, near the intersection of Memorial Drive and Main Street
- Building 48, near the intersection of Main Street and Vassar Street
- The Media Lab, near the intersection of Ames Street and Amherst Street
- Building 1, near the intersection of Memorial Drive and Massachusetts Avenue

Food Service Areas

The overarching goal of indoor nodes is to sample air from different types of space usage, specifically cooking. Cooking is the primary indoor source of the gas species measured by CLAIRITY and as such the deployment scheme is focused on a cross section of food preparation techniques. Restaurant, dining hall and dormitory kitchens are all observed to see how quantity and preparation method affect air quality. The food service locations include:

- Café Four
- Stratton Student Center
- Burton Conner Suite Kitchen
- Next House Dining

Community Cross Section

Outdoor locations that are frequented by the public, areas of interest, and give spatial variation were selected to represent a varied cross-section of MIT's campus. Locations frequented by the MIT community, the Cambridge residents and/or tourists is important because these locations had the potential to show where the air quality affected the most people.

- MIT Museum
- Next House Courtyard
- Killian Court
- Walker Memorial
- Green Building Base
- Brigg's Field

MIT Vehicles

CLAIRITY recognized that the 22 stationary nodes would not cover all desired areas of the MIT campus. In view of that, two mobile nodes were also installed. The deployment of mobile nodes allows CLAIRITY to monitor air quality consistently along the vehicle's routes, adding a large set of data locations to the stationary nodes. One of the CLAIRITY's main goals is to assess how pollutants dilute in the air after emission from a source. The mobile nodes provide the network with valuable datasets for this dilution monitoring. Some of the main air pollutant sources include busy street intersections and street segments of high traffic flow. The mobile nodes give information as to which road segments and intersections around the MIT campus produce the worst air quality. Additionally, the mobile locations will also provide CLAIRITY with information as to how pollutants emitted from other major sources such as the MIT cogeneration power plant dilute across the MIT campus. The mobile nodes are located on:

- MIT Facilities Vehicle
- Tech Shuttle Bus

Cogeneration Power Plant

In order to fully utilize CLAIRITY's capabilities, a sensor node was installed in the cogeneration power plant, which is expected to be a major point source for the pollutants CLAIRITY measured. The pollutants the sensor nodes monitor are often found in the byproducts from energy production and as such, this node specifically monitors the exposure of the power plant's workers to the measured species.

Mapping Deployment

It is important to visualize the distribution of any network, both for the global perspective and for communication with stakeholders. Utilization of a map throughout the deployment process was integral to maintaining a widely distributed sensor network. The final map for the deployment scheme was then utilized on the CLAIRITY website so that the public can have a spatial reference for the air quality measurements the sensor nodes collected.

Preliminary Analysis

As of May 6, 2014, the CLAIRITY network had been operational for approximately 2 weeks, allowing the CLAIRITY team to review initial data to ensure that the sensor nodes were logging reasonable, consistent concentration values. Based upon the initial hypothesis set forth above, the CLAIRITY team performed preliminary analyses on diurnal trends with high spatial variation, the effect of cooking on indoor air quality, and a comparison of indoor and outdoor conditions.

Data Collection

Data from the sensor nodes can be used to generate plots of pollution levels over time for visual display, which could then inform data analysis. Air quality data gives insight into trends such as temperature, precipitation, road traffic patterns, and cooking patterns. While the data cannot be authoritatively correlated to these external factors – because air conditions are the product of complex human and natural feedbacks – they often do provide clear insight on such external events.

As stated earlier, this preliminary analysis is based on the first two weeks of node deployment. It is meant to provide a brief snapshot of implications the data can potentially provide into the future – from indoor human activity in a single room to comparison of trends across multiple locations across campus. While it is not meant to be an exhaustive analysis of all of the collected data, it demonstrates the power of the CLAIRITY network and pinpoints further directions for analysis.

Diurnal and Weekly Trends

The first analysis was conducted by plotting NO levels from five outdoor locations over the course of six days, as shown in Figure 29. This plot is useful in detecting macro-level trends - such as variation in outdoor pollution due to point sources rather than background pollution, correlations between weather and pollution, and daily patterns due to traffic.

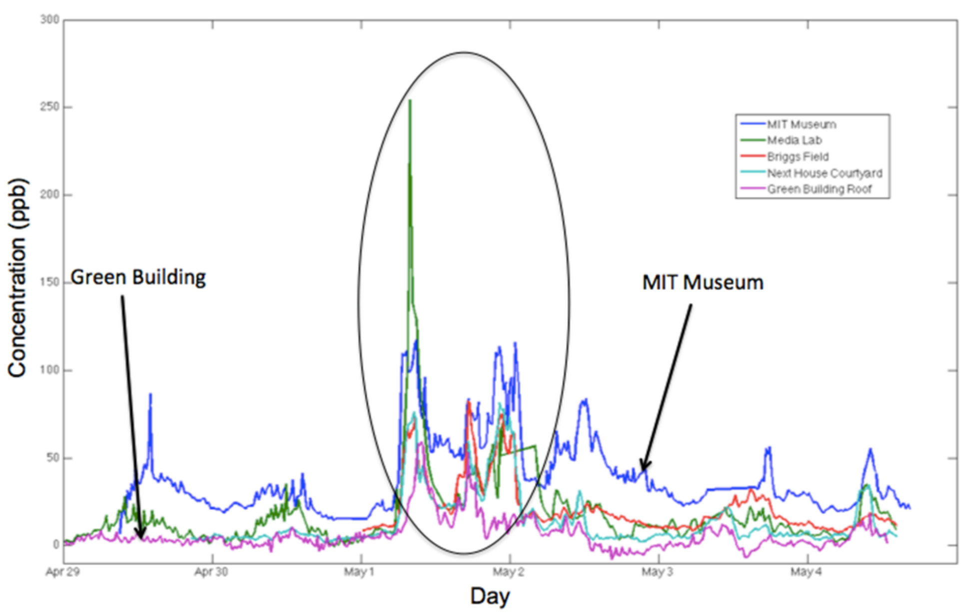


Figure 29: Plot of nitric oxide at the MIT Museum, Media Lab, Briggs Field, Next Courtyard, and Green Building Roof from April 29 to May 4. The circled region refers to a large pollution spike on May 1.

Because NO is a direct result of combustion – such as from car exhaust – and it reacts quickly before being diffusing in air, it is a relatively accurate proxy for direct source pollution. NO levels are higher during daytime, when roads tend to be more congested than at night. The Green Building Roof plot shows much less daily variability in pollution, likely because it is at a higher elevation and is therefore less exposed to car emissions. The MIT Museum node, in contrast, is located next to Massachusetts Avenue, a major road that runs through campus, which tends to be more congested than other streets in the other area. Accordingly, the MIT Museum sensor node readings suggest that this area tends to experience higher daytime pollution levels than other node locations.

There is a prominent spike in pollution on Thursday, May 1, across all of the outdoor nodes, as indicated by the circled area in Figure 26. There was a significant weather change occurring over Thursday night, when Boston became warmer, sunnier, and less windy. The halt in wind activity results in less mixing or transport of pollutants, allowing released pollution to build up near its source. There are other nonsystematic spikes in the data, which may reflect temporary and local pollution sources rather than overall pollution trends over a large area.

The consistency in diurnal pollution trends across the nodes demonstrates CLAIRITY's consistency in measuring pollution. This consistency results in the network's ability to potentially map out a pollution gradient on campus and track anomalies.

Indoor versus Outdoor

The second plot, Figure 30, explored maps CO levels over eight days in Burton-Conner and Briggs Field, two node locations that are close in proximity but differ in whether they are indoors or outdoors. This comparison is important in highlighting situations where indoor air pollution may be nontrivial, and sometimes worse than outdoor air pollution.

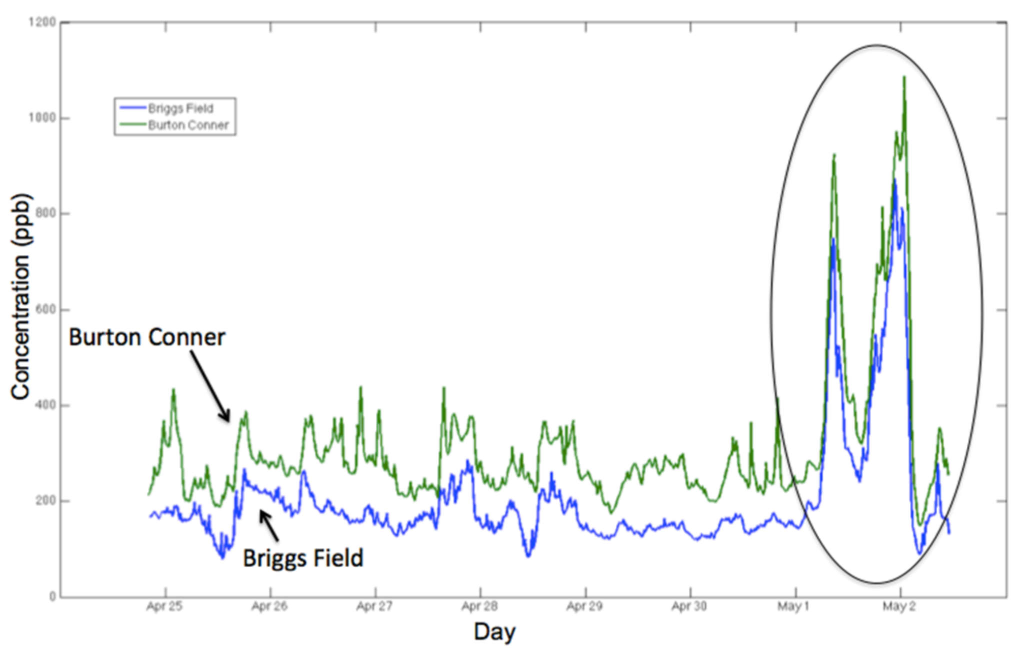


Figure 30: Plot of carbon monoxide concentrations at Burton Conner and Briggs Field - two locations close to each other - from April 25 to May 2. The circled region denotes the period of hiked pollution during the weather transition on May 1.

There appears to be a strong correlation between pollution at the Burton Conner and Briggs Field sensor nodes. This is an indication that outdoor air pollution could be a proxy for pollution in nearby buildings, likely because of building ventilation that allows for air exchange between the building and outdoors.

It is also important to note that CO levels inside Burton Conner are consistently higher than outside on Briggs Field. Common sources of indoor CO pollution include oil and gas heating or cooking. Burton Conner is not heated using a local fuel source. Instead, the dormitory uses piped heat from an external steam plant and, as such, indoor heating may not be a major indoor pollution source. However, the Burton Conner node is located in a kitchen, which indicates the node may more easily pick up pollution due to cooking.

Pollution in Dining Halls

The third analysis conducted was for particulate counts (both fine and coarse particles) in Next House Dining Hall over the course of one day, as shown in Figure 28. This analysis is significant because it demonstrates the CLAIRITY's ability to track pollution at a high temporal resolution and correlate pollution trends with external events. In this case, the external event correlated with fine particle pollution was cooking, such as the use of stoves, grills or ovens.

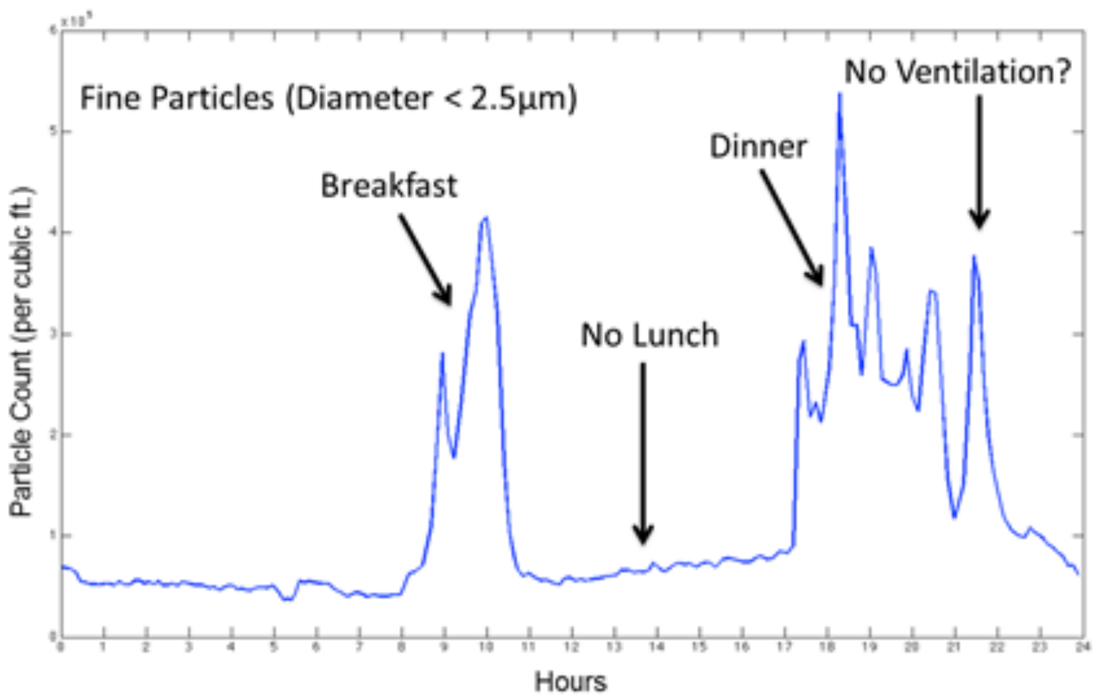


Figure 31: Plot of fine particle counts in the Next House Dining Hall on Thursday, May 1. The x-axis refers to hours of the day.

Spikes in the fine particle count occur during Next House Dining Hall's hours of operation (8-10am and 5:30-8:30pm). Cooking begins shortly before dining hours begin and continues while dining is in session. Next House does not serve lunch, hence, there is not a spike in the data at midday).

Next House Dining Hall has two "cooked to order" stations to compliment the regular buffet. These stations, which serve stir-fry and grilled food, provide primary sources of cooking-related particulates. In addition, open windows or doors leading to the kitchen provide another source of fine particulates.

The plot of coarse particulate matter in Next House Dining Hall, as shown in Figure 32, shows a similar daily trend compared to the fine particle plot. Coarse particulates are more likely due to dust or ash sources, such as foot traffic in and out of the dining hall. After 9pm, when dining closes, the coarse particle count reaches its highest peak of the day. This may be due to closing of ventilation when dining hours ended, which slows the diffusion of particles in the dining hall.

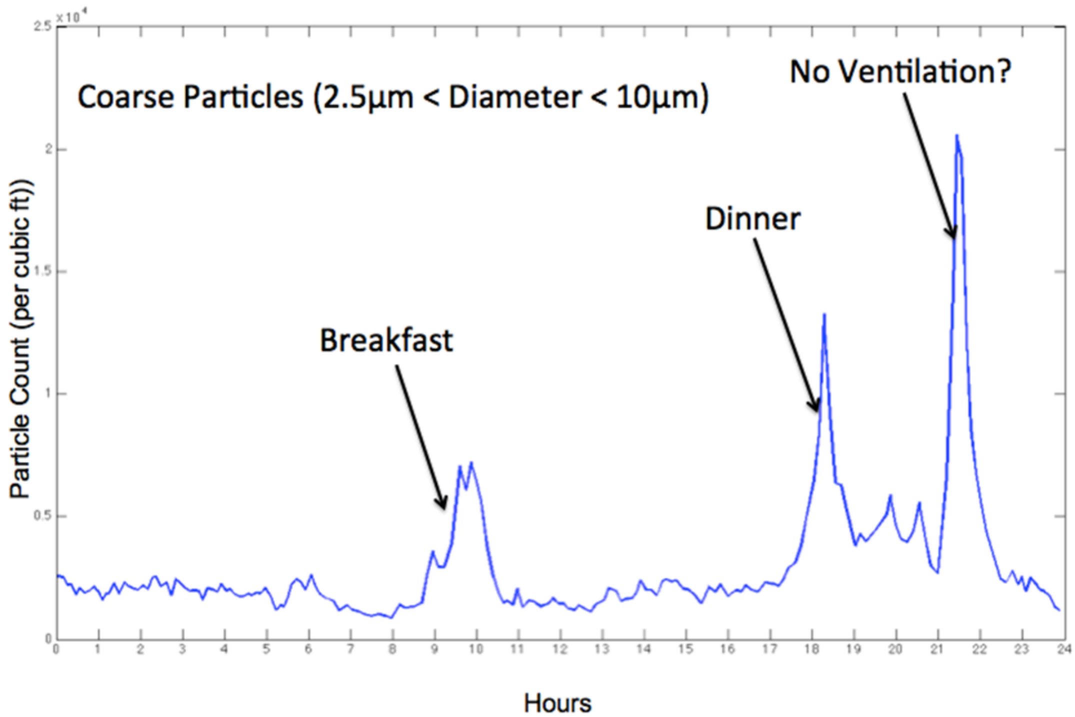


Figure 32: Plot of coarse particle counts at Next House Dining Hall on Thursday, May 1.

Discussion of Pollution Sources and Factors

The preliminary data analysis demonstrates the ability of the CLAIRITY network to provide insight on both pollution point sources such as cooking in a dining hall and overall systems pollution across multiple nodes on campus. This can be achieved because of CLAIRITY's high temporal and spatial resolution.

Systematic air pollution sources – such as daily pollution trends in Cambridge due to traffic and effects of weather change – are best captured by macro-level plots, as seen in Figure 29. These pollution sources provide a 'base' pollution level on campus, meaning that campus will always have an ambient air pollution source due to external factors beyond MIT's control.

Local sources of air pollution - such as kitchens or idling vehicles - increase the variability and presence of peaks in air quality trends, in addition to the ambient air pollution. These local sources can be understood using more localized plots, such as the comparison of Burton-Conner Dormitory and Briggs Field or Next House Dining fine particulate counts. Determining exact local point sources is less feasible without witnessing a pollution event; however, these sources become clearer when compared to time of day, such as diurnal trends correlated to rush hour traffic.

Comparison with Air Quality Standards

Data analysis indicates that air pollution in MIT tends to fall into the 'Good' category of the CLAIRITY AQI, defined previously. The CLAIRITY AQI is constructed using a combination of EPA and Dylos thresholds, which are typically applied to average pollution levels over a period of eight hours. CLAIRITY applies index values over 10 second data and consequently, the website displays "Unhealthy" index values, colored in red, during brief hikes in pollution that are not captured in the AQI measurements by the EPA. Observations of the preliminary data and color-coded representation on the CLAIRITY website's map indicate that the air on MIT's campus tends to be healthy.

Future Considerations

Recalibration and Sensor Lifetime

As with most pieces of technology, the Alphasense sensors in the sensor nodes will not perform at the same level forever. Over time, the zero baseline and the sensitivity values shift until eventually the sensor stops being reliable at all. Each Alphasense sensor has an approximate lifetime of two years, meaning that the nodes would each have to be completely replaced around that time.

In addition, the baseline shifts and changes in sensitivity can be calibrated for; this would require that nodes be brought back into the laboratory environment and run through the same series of tests as before. With this new data, the sensors can still be understood, albeit with new conversion factors to align their readings with those of the high-fidelity instruments.

Tech Shuttle GPS

In order to match the data collected through mobile deployment to location coordinates, GPS tracking information is necessary. The MIT facility vehicle has a GPS tracker installed on it. For the Tech Shuttle, a GPS tracking device of the type LandAirSea LAS-1505 Tracking Key was included in the weatherproof box. The battery-run GPS continuously collects GPS data. By comparing the timestamps of the GPS and air quality information, air quality data can be matched to GPS coordinates.

Currently, the GPS data needed to connect the air quality readings of the mobile nodes with the location sampled is difficult to obtain. Getting the GPS data from the facility's shuttle node requires the driver of the vehicle to submit a weekly work order to obtain the data and then send the data to the CLAIRITY team. This creates extra work for the driver, and delays the time frame in which the data can be displayed on the CLAIRITY website for the public to view. Getting the GPS data from the Tech Shuttle node currently requires a student to visit the shuttle fortnightly to download the data and replace the batteries in the

GPS. Both of these data acquisition options are time consuming and may be unsustainable for the long term. A potential solution would be to purchase and install a Wi-Fi enabled GPS device or a GPS device that can connect directly to the Raspberry Pi. A preliminary search into Wi-Fi enabled GPS devices yielded few feasible solutions since most of the devices are too large to fit into the current weatherproof box. However, Adafruit sells a GPS that can be connected directly to the Raspberry Pi. The Adafruit's "Ultimate GPS" package can be powered from the one of the node's USB ports and connected directly to the Pi. The GPS data would then be put onto the Pi and could be pushed from the Pi to the server via the node's Wi-Fi connection.

Conclusion

The CLAIRITY concept presented here can be expanded to studies of where pollutants originate and how they disperse over a given area. In addition, CLAIRITY gives higher resolution data than current systems, such as that utilized by the Massachusetts Department of Environmental Protection, for monitoring dangerous levels of pollutants. Furthermore, sensor networks such as CLAIRITY are the driving force in the development of smart cities across the globe.

Sensor networks such as CLAIRITY utilize data collected from urban living, which is the motivation behind Smart Cities. The Smart City concept takes data generated from day to day lives of citizens in a community in order to inform infrastructure decisions and urban development as well as educate the public on choices they can make for their personal well being. Furthermore, environmental data collected from networks such as CLAIRITY can help better inform warning systems, for such things as high pollution levels and other environmental threats, in order to keep the population safe.

With 24 nodes currently distributed across MIT's campus, the CLAIRITY network is able to monitor five major air pollutants at a relatively low cost. CLAIRITY's aim is to create a community where people are better informed about the air they breathe and can make better decisions based on this information. This can come in the form of decisions to avoid high pollution areas based on the time of day or decisions that mitigate their role in producing major pollutants. CLAIRITY offers the high-resolution data necessary to inform these decisions in a publicly accessible web portal, <clairity.mit.edu>.

Future Considerations

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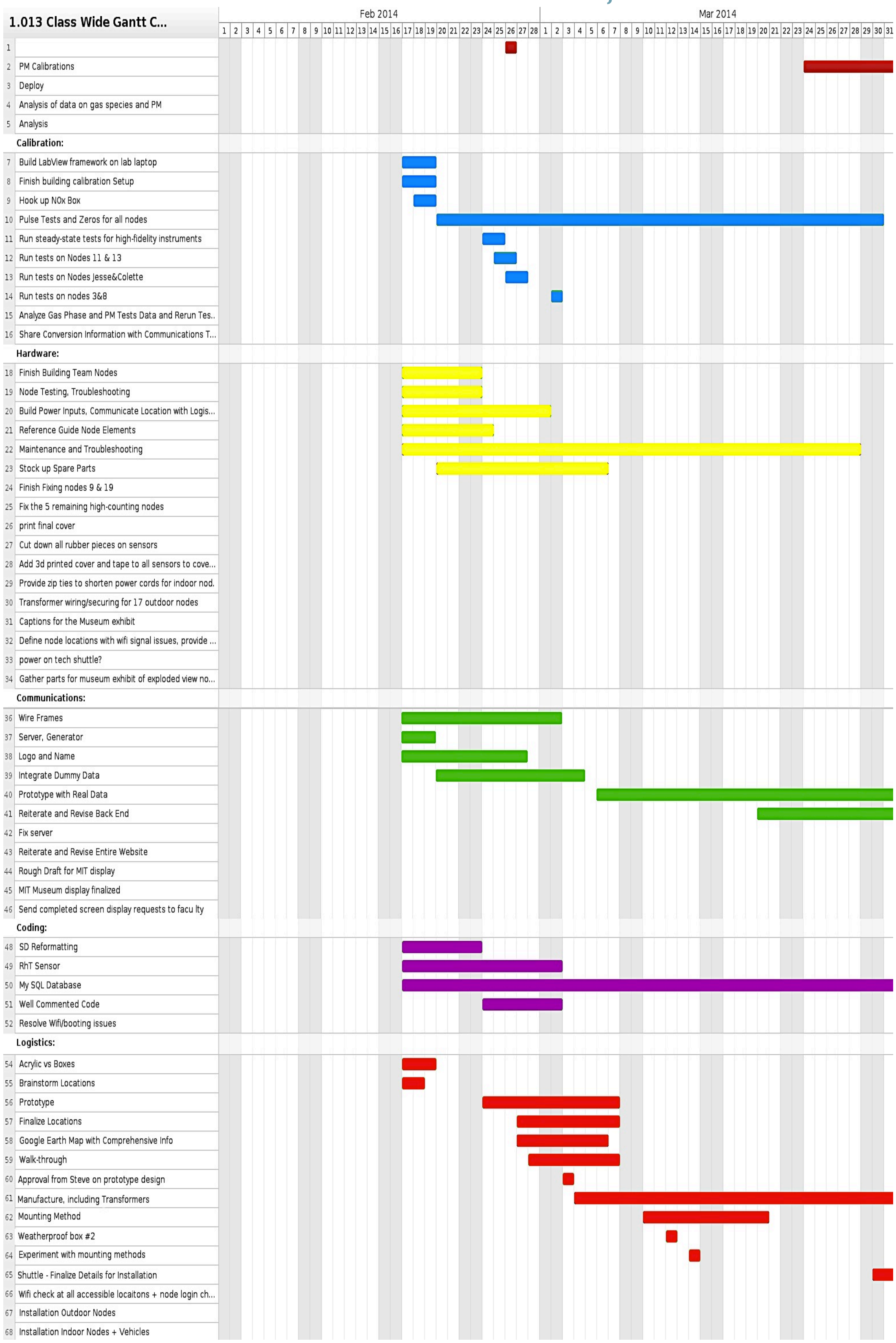
All photos courtesy of Eben Cross.

Appendices

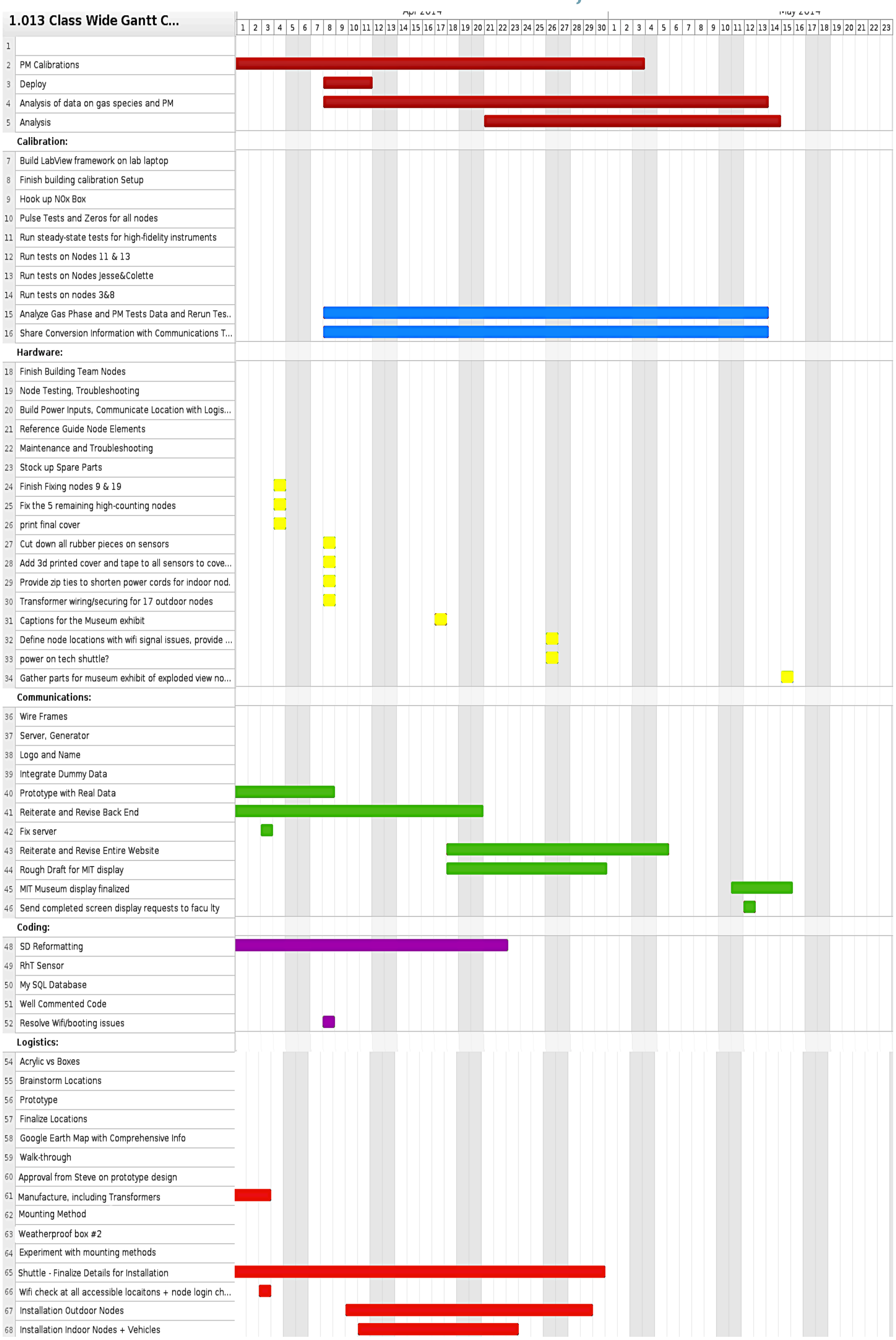
A1: Detailed Budget

	Item Description	Vendor	Part Number	Quantity	Unit Cost	Total Cost
			#	#	[$]	[$]
	COMMON NODE COMPONENTS PER NODE					
1	DC 1100 Pro Air Quality Monitor with PC interface 0.5um and 2.5um	Dylos Corporation		1	289.99	$289.99
59	Raspberry Pi, Model B, Revision,2.0	Amazon		1	42.89	$42.89
60	Prototyping Circuit Board	Express PCB		1	16.433	$16.43
61	Delta Sigma Pi 18-bit Analogue-to-Digital-Converter (ADC)	AB Electronics		1	23.27	$23.27
62	USB to Serial Cable	Amazon		1	10	$10.00
63	4GB SD card for Raspberry Pi preinstalled with Raspbian Wheezy	Adafruit		1	15	$15.00
64	4.Electrode ISB (CO)	AlphaSense		1	131	$131.00
65	Carbon Monoxide B Sensor, CO-B4-4-electrode	AlphaSense		1	81	$81.00
66	4 Electrode ISB (NO)	AlphaSense		1	131	$131.00
67	Nitric Oxide B Sensor, NO-B4-4-electrode	AlphaSense		1	77	$77.00
68	4 Electrode ISB (NO2)	AlphaSense		1	131	$131.00
69	Nitrogen Dioxide B Sensor, NO2-B4-4-electrode	AlphaSense		1	77	$77.00
70	4 Electrode ISB (O3)	AlphaSense		1	131	$131.00
71	Ozone B Sensor, O3-B4-4-electrode	AlphaSense		1	105	$105.00
72	DHT22 Temperature and Relative Humidity Sensor	Adafruit		1	12.5	$12.50
73	Edimax EW.7811Un150 Mbps nono-sized Wireless USB Adapter	Amazon		1	9.98	$9.98
74	Micro-USB cable	Adafruit		1	3.95	$3.95
75	Molex Inc. Crimp Terminals: Conn Term Female 22-30 AWG tin	DigiKey		8	0.19	$1.52
76	Molex Inc. Conn Housing 2POS .100 W/RAMP (Power source and microUSB)	DigiKey		2	0.11	$0.22
77	Molex Inc. Conn Housing 4POS .100 W/RAMP (Rh/T sensor)	DigiKey		1	0.11	$0.11
78	ABS Filament for 3D Printing Oreo Case	Amazon		12.28 [in^3]	4.62 [$/in^3]	$56.73
79	0.25" Commercial Grade Pipe Thread Sealant Tape (Part # 4591K11)	McMaster Carr		18 [in]	0.00323 [$/in]	$0.06
80	Stranded Wire, 300V AC, 22 Gauge for Rh/T sensor	McMaster Carr		24 [in]	0.0114 [$/in]	$0.27
81	Molex Inc. CONN HEADER 2POS .156 VERT TIN	DigiKey	WM4620-ND	1	0.2	$0.20
82	Molex Inc. CONN HEADER 2POS .100 VERT TIN	DigiKey	WM4200-ND	4	0.128	$0.51
83	Diodes Incorporated DIODE GEN PURPOSE 1000V 1A DO41	DigiKey	1N4007DICT-ND	1	0.1098	$0.11
84	Molex Inc. CONN HEADER 4POS .100 VERT TIN	DigiKey	WM4202-ND	1	0.303	$0.30
85	3M ONN HEADER 20 POS STRGHT GOLD	DigiKey	MHC20K-ND	1	1.036	$1.04
86	Harwin Inc. CONN HDR 1.27MM VERT AU 16POS	DigiKey	952-1385-ND	1	1.196	$1.20
87	Molex Inc. CONN HOUSING RCPT .100 2POS	DigiKey	WM2876-ND	1	0.2852	$0.29
88	Molex Inc. CONN HOUSING 2POS .156 W/O RAMP	DigiKey	WM1564-ND	1	0.152	$0.15
89	Molex Inc. CONN HSNG 4POS .100 W/RAMP/RIB	DigiKey	WM2614-ND	1	0.379	$0.38
90	Fairchild SemiConductor IC REG LDO 5V 1A TO220-3	DigiKey	LM7805CT-ND	1	0.4956	$0.50
91	Fairchild SemiConductor IC REG LDO 6V 1A TO220-3	DigiKey	LM7806CT-ND	1	0.5144	$0.51
92	Fairchild SemiConductor IC REG LDO 9V 1A TO220-4	DigiKey	LM7809CT-ND	1	0.5144	$0.51
93	Kemet CAP CER 0.1UF 50V 20% AXIAL	DigiKey	399-4454-1-ND	10	0.0792	$0.79
94	Sullins Connector Solutions CONN HEADER FEMALE 6POS .1" TIN	DigiKey	S7004-ND	3	0.4028	$1.21
95	Molex Inc. CONN TERM CRIMP 18-24 AWG GOLD	DigiKey	WM2135-ND	8	0.235	$1.88
96	FCI CONN HEADER 16POS .100 STR TIN	DigiKey	609-3220-ND	1	0.4684	$0.47
97	Molex Inc. CONN HEADER 26POS .100" STR TIN	DigiKey	WM8131-ND	1	1.931	$1.93
98	3M CONN HEADER .100 SNGL STR 36POS	DigiKey	ND	1	1.607	$1.61
99	3M CONN HEADER VERT DUAL 40POS GOLD	DigiKey	3M9465-ND	1	2.156	$2.16
100	Assman Components WSW HEATSINK ALUM ANOD	DigiKey	AE10844-ND	1	1.28	$1.28
101	Tape	McMaster-Carr	76455A14	40 [in]	0.008 [$/in]	$0.32
						$1,364.27
	INDOOR NODES					
46	Molex Inc. Insulated Bullet Terminal, 18-22 AWG, male	McMaster Carr		2	0.242	$0.48
47	Molex Inc. Insulated Bullet Terminal, 18-22 AWG, female	McMaster Carr		2	0.1978	$0.40
48	ABS Filament for 3D Printing Back Cover	Amazon		8.35 [in^3]	4.62 [$/in^3]	$38.58
49	Stranded Wire, 300V AC, 22 Gauge for power cord extension	Amazon		144 [in]	0.0114 [$/in]	$1.64
50	L Brackets for clamping	McMaster-Carr	1556A54	4	0.91	$3.64
						$44.74
	WEATHERPROOFING FOR OUTDOOR NODES					
51	YH Series Hinged Waterproof NEMA Electrical Enclosures	Polycase	YH-080804	1	49.5	
52	ABS Filament for 3D Printing Hood for weatherproofing box	Amazon		1.412 [in^3]	4.62 [$/in^3]	$6.52
53	Mesh to cover hoods - Aluminum Insect Screening, .011" Wire, 24" Wide	McMaster-Carr	1023A75	8 [in^2]	0.0034 [$/in^2]	$0.03
54	Ring Clamps - Sign Mounting Bracket, Fits 4" to 12" Diameter Poles	McMaster	1307T21	1	16.03	$16.03
55	Silicone Sealant tube	McMaster-Carr	76435T21	1	3.9	$3.90
56	Velcro - 1" Super-Adhesive-Back General Purpose Hook and Loop	McMaster-Carr	95005K355	3 [in]	0.19 [$/in]	$0.57
57	12V DC Transformer - 25W Single Output Switching Power Supply	Solidify Corp	AS25-12	1	48.3	$48.30
						$75.35
	WEIGHTGED TOTAL COST PER NODE					**$1,435.95**
	ADDITIONAL PURCHASES					
58	Custom Firmware Change	Dylos Corporation		1	400.00	$400.00
59	Acer Desktop (Black)	Amazon	RL80-UR23	1	329.99	$329.99
						$729.99

A2-1: CLAIRITY Gantt Chart and Timeline, Part 1

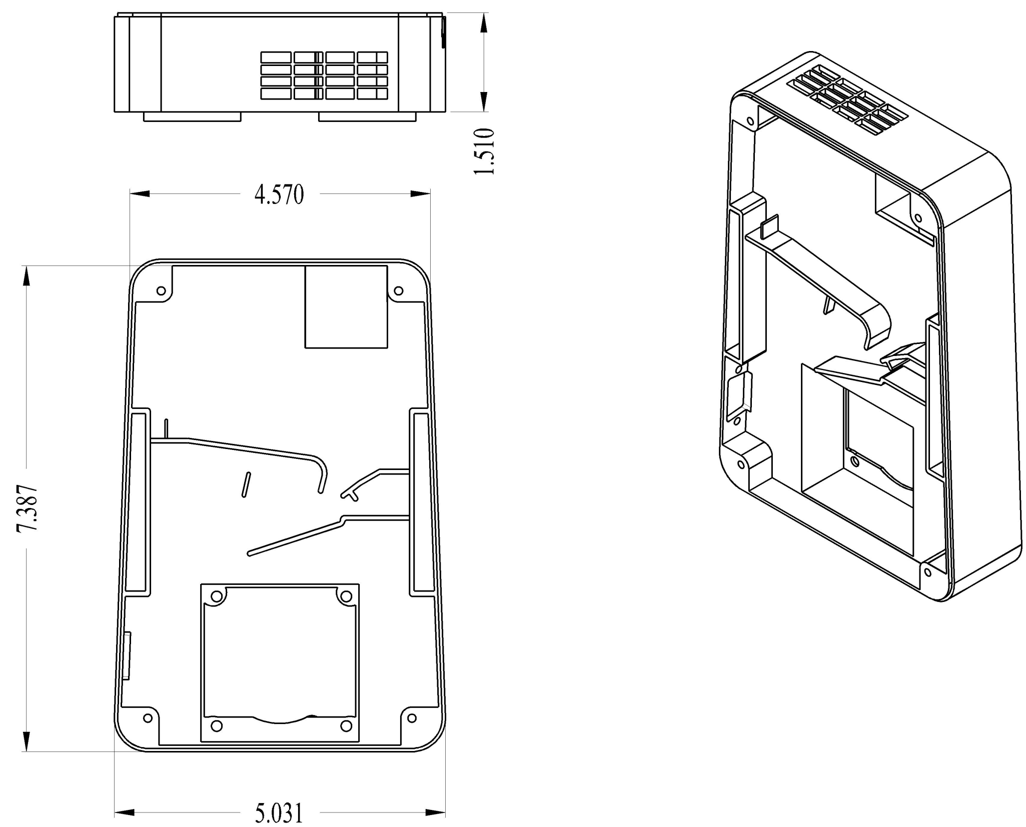


A2-2: CLAIRITY Gantt Chart and Timeline, Part 2



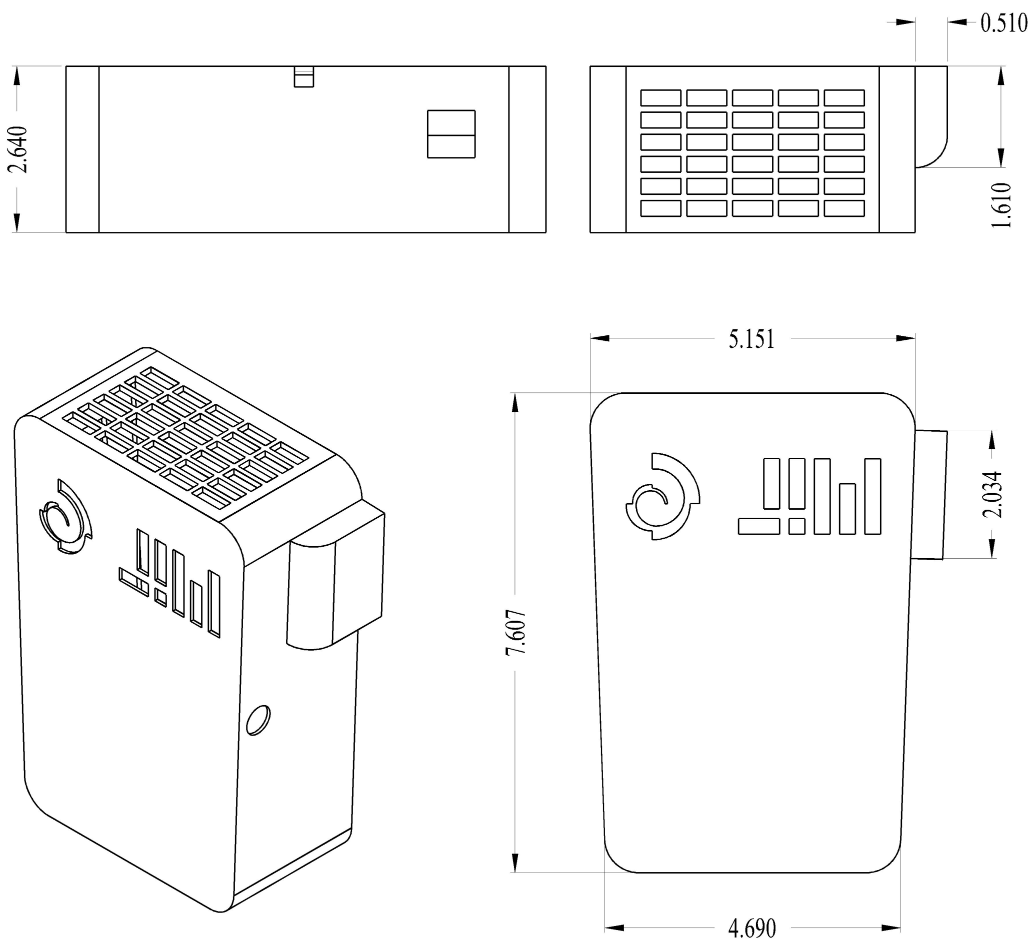
A3: Oreo Cover 3D Design

This diagram depicts the Oreo cover design in three dimensions. The units are in inches.



A4: Back Cover 3D Design

This diagram depicts the back cover design in three dimensions. The units are in inches.



A5: Final Version of Code

```
#!/usr/bin/env python3
# Contact Sidhant Pai (sidhantpai@gmail.com) to report bugs
# ======== Code will log Dylos, Alphasense Data, RH and Temp to local CSV, remote database and google doc (optional)
#final code for node
import sys

sys.path.append("/home/pi/quick2wire-python-api/")
sys.path.append("/home/pi/gspread/")

import quick2wire.i2c as i2c
import re
import json
import requests
import time
import subprocess
import re
import datetime
import socket
import gspread
import csv
from threading import Thread
from datetime import date
import smtplib

try:
	import serial
except:
	import Serial as serial

# ==========================================================================
# Google Account Details
# ==========================================================================

# Account details for google docs
email       = 'cee.capstone.2013@gmail.com'
password    = ***********
# REPORT NOTE: Password for security purposes
spreadsheet = 'NodeData13'

# ==========================================================================
# Start Code
# ==========================================================================

# Login with your Google account
#try:
#	gc = gspread.login(email, password)
#except:
#	print("Unable to log in.  Check your email address/password")

# Open a worksheet from your spreadsheet using the filename
#try:
#	worksheet = gc.open(spreadsheet).sheet1
```

```
        # Alternatively, open a spreadsheet using the spreadsheet's key
        # worksheet = gc.open_by_key('0BmgG6nO_6dprdS1MN3d3MkdPa142WFRrdnRRUWI1UFE')
#except:
#       print("Unable to open the spreadsheet.  Check your filename: %s" % spreadsheet)

# Define Global Variables
adc_address1 = 0x68
adc_address2 = 0x69
adc_channel1 = 0x98
adc_channel2 = 0xB8
adc_channel3 = 0xD8
adc_channel4 = 0xF8
i2c_bus = 1 #Version 2 of RPi

# ================ List of Global Variables to be stored in DB
global humidity
global temp
global bin_1
global bin_2
global bin_3
global bin_4
global asense_1
global asense_2
global asense_3
global asense_4
global asense_5
global asense_6
global asense_7
global asense_8
global connected_wifi
connected_wifi = 0
humidity = -9999.99 # RHT03
temp = -9999.99
bin_1 = 0 # Dylos Modified Firmware (v1.16f2)
bin_2 = 0
bin_3 = 0
bin_4 = 0
asense_1 = 0.00 # Using Delta Sigma ADC
asense_2 = 0.00
asense_3 = 0.00
asense_4 = 0.00
asense_5 = 0.00
asense_6 = 0.00
asense_7 = 0.00
asense_8 = 0.00
# ================ End of Variable List


#Initialize Serial Port for Dylos
try:
        port = serial.Serial(
                "/dev/ttyUSB0",
                baudrate=9600,
                parity=serial.PARITY_NONE,
                stopbits=serial.STOPBITS_TWO,
                bytesize=serial.EIGHTBITS,
```

```
        writeTimeout = 1,
        timeout=10)
except (Exception) as error:
    print (error)


def sensorread():
    #Continuously loop collecting all data
    while True:
        try:
            global temp
            global connected_wifi
            global humidity
            global bin_1
            global bin_2
            global bin_3
            global bin_4
            global asense_1
            global asense_2
            global asense_3
            global asense_4
            global asense_5
            global asense_6
            global asense_7
            global asense_8
            # ================== Read Dylos Data
            try:
                #print("Dylos Test")
                dylosdata()
            except (Exception) as error:
                print("Dylos Error : ",error)
            # ================== End Dylos Read


            # ================== Read Alphasense Chemical Sensors and MET values
            try:
                #print("Alphasense Test")
                alphasense()
            except (Exception) as error:
                print("Alphsense Error : ",error)
            # ================== End Alphasense Read


            # ================== Read Temp and RH Data
            try:
                temp= -9999
                humidity = -9999
                metdata()
            except (Exception) as error:
                print("MET Error : ",error)
            # ================== End Temp and RH


            # Append the data in the spreadsheet, including a timestamp
            #try:
```

```
			#	values = [datetime.datetime.now(), temp, humidity, bin_1, bin_2, bin_3, 
bin_4, asense_1, asense_2, asense_3, asense_4, asense_5, asense_6, asense_7, asense_8]
			#	worksheet.append_row(values)
			#	print("Wrote a row to %s" % spreadsheet)
			#	#print("Uncomment the worksheet command to write to google doc")
			#except:
			#	print("Unable to append data. Check your connection?")

			# Change Filename every day
			day = datetime.datetime.now()
			filename="/home/pi/sensordata/"+str(day.day)+"-"+str(day.month)+"-"+str(day.year)

			# Write to CSV
			try:
				with open(filename,'a',newline='') as fp:
					a = csv.writer(fp, delimiter=',')
					print("Current Time : ", datetime.datetime.now())
					newdata = [datetime.datetime.now(), temp, humidity, bin_1, bin_2, 
bin_3, bin_4, asense_1, asense_2, asense_3, asense_4, asense_5, asense_6, asense_7, asense_8]
					a.writerows([newdata])
					print("Wrote a row to csv")
			except (Exception) as error:
				print(error)

			# Write to database
			try:
				real_url = 'http://ec2-54-187-18-145.us-west-
2.compute.amazonaws.com/node/postdata/'
				url = 'http://localhost:8000/node/postdata/'
				node_id = 13

				values = {'node_id' : node_id,
					'temperature' : temp,
					'rh' : humidity,
					'dylos_bin_1' : bin_1,
					'dylos_bin_2' : bin_2,
					'dylos_bin_3' : bin_3,
					'dylos_bin_4' : bin_4,Fi
					'alphasense_1' : asense_1,
					'alphasense_2' : asense_2,
					'alphasense_3' : asense_3,
					'alphasense_4' : asense_4,
					'alphasense_5' : asense_5,
					'alphasense_6' : asense_6,
					'alphasense_7' : asense_7,
					'alphasense_8' : asense_8,
					'reading_time' : datetime.datetime.now().isoformat()
					}
				data = json.dumps(values)
				# print(data)
				r = requests.post(real_url, data=values)
				print("Pushed to Database")
				if connected_wifi==0:
					# Code to Send IP address to cee email
					from email.mime.text import MIMEText
					# Change to your own account information
```

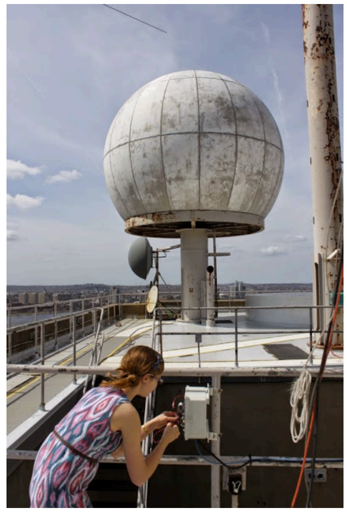
```
                    to = 'ceecapstone2013@gmail.com'
                    gmail_user = 'ceecapstone2013@gmail.com'
                    gmail_password = 'airquality'
                    smtpserver = smtplib.SMTP('smtp.gmail.com', 587)
                    smtpserver.ehlo()
                    smtpserver.starttls()
                    smtpserver.ehlo
                    smtpserver.login(gmail_user, gmail_password)
                    today = datetime.date.today()
                    # Very Linux Specific
                    arg='ip route list'
                    p=subprocess.Popen(arg,shell=True,stdout=subprocess.PIPE)
                    data = p.communicate()
                    data = str(data)
                    ipaddr = data[95:109]
                    print (ipaddr)
                    my_ip = 'Your ip is %s' %  ipaddr
                    msg = MIMEText(my_ip)
                    msg['Subject'] = 'IP For Node 13 on %s' % today.strftime('%b %d %Y')
                    msg['From'] = gmail_user
                    msg['To'] = to
                    smtpserver.sendmail(gmail_user, [to], msg.as_string())
                    smtpserver.quit()
                    connected_wifi=1
            except (Exception) as error:
                print("Unable to connect to Database. Check Connection : ",error)
                connected_wifi=0
            print(" ") # Blank Line
            time.sleep(10) # Wait 10 seconds

        except (Exception) as error:
            #Sensor Read Error
            print("Sensor Error : ", error)
            print(" ") # Blank Line
            time.sleep(1) # Wait 1 second

def dylosdata():
    try:
        dyloscnt = 0
        global bin_1
        bin_1=-9999
        global bin_2
        bin_2=-9999
        global bin_3
        bin_3=-9999
        global bin_4
        bin_4=-9999
        # Request Dylos Data
        request = bytes("R\r\n",'ascii')
        port.write(request)
        line = port.readline()
        line = str(line.strip().decode('utf-8'))
        try:
            bin_data = [int(x.strip()) for x in line.split(',')]
        except:
            #Dylos Error
```

```
                    print("Dylos Data: Error - Dylos Bin data")
                    bin_data[:]=[]
                    # print data
            if len(bin_data) >= 4:
                    bin_1=bin_data[0]
                    bin_2=bin_data[1]
                    bin_3=bin_data[2]
                    bin_4=bin_data[3]
                    print("Dylos Data: ",bin_1,",",bin_2,",",bin_3,",",bin_4)
            else:
                    bin_1=-9999
                    bin_2==-9999
                    bin_3==-9999
                    bin_4=-9999
                    print("No Dylos Data")
    except (Exception) as error:
            #Some other Dylos Error
            print(error)

def metdata():
    cnt = 0
    global temp
    temp =-9999
    global humidity
    humidity=-9999
    # Function Collects Temp and RH Data
    # Run the DHT program to get the humidity and temperature readings
    try:
            output = subprocess.check_output(["/home/pi/Adafruit-Raspberry-Pi-Python-
Code/Adafruit_DHT_Driver/Adafruit_DHT", "2302", "4"]);
    except (Exception) as error:
            print("Low-Level C Code Error")
            print(error)
    print("Collecting MET Data")
    #print(output)
    output = output.decode('utf-8')
    #output = str(output)
    #output = output[:-1]
    #print(output)
    try:
            matches = re.search("Temp =\s+([0-9.]+)", output)
            while (not matches) and cnt < 5:
                    #print(output)
                    output = subprocess.check_output(["/home/pi/Adafruit-Raspberry-Pi-Python-
Code/Adafruit_DHT_Driver/Adafruit_DHT", "2302", "4"]);
                    output = output.decode('utf-8')
                    cnt = cnt + 1
                    matches = re.search("Temp =\s+([0-9.]+)", output)
                    time.sleep(2)
            if (not matches):
                    temp=-9999
            else:
                    temp=float(matches.group(1))
    except (Exception) as error:
            print("Error in Temp data : ", error)
```

```
        # Search for humidity printout
        try:
                matches = re.search("Hum =\s+([0-9.]+)", output)
                if (not matches):
                        humidity=-9999
                else:
                        humidity=float(matches.group(1))
        except (Exception) as error:
                print("Error in Humidity Data : ",error)

        print("Temperature (C) :",temp)
        print("Humidity (%) : ",humidity)

def alphasense():
        # Based on Delta Sigma Version 1 Architecture (Current is Version 2)
        with i2c.I2CMaster(i2c_bus) as bus:
                def getadcreading(address, channel):
                        bus.transaction(i2c.writing_bytes(address, channel))
                        time.sleep(0.05)
                        h, l, r = bus.transaction(i2c.reading(address,3))[0]
                        time.sleep(0.05)
                        h, l, r = bus.transaction(i2c.reading(address,3))[0]
                        t = (h << 8) | l
                        v = t * 0.000154
                        if v < 5.5:
                                return 1000* v
                        else: # must be a floating input
                                return 0.00

                global asense_1
                asense_1=getadcreading(adc_address1, adc_channel1)
                global asense_2
                asense_2=getadcreading(adc_address1, adc_channel2)
                global asense_3
                asense_3=getadcreading(adc_address1, adc_channel3)
                global asense_4
                asense_4=getadcreading(adc_address1, adc_channel4)
                global asense_5
                asense_5=getadcreading(adc_address2, adc_channel1)
                global asense_6
                asense_6=getadcreading(adc_address2, adc_channel2)
                global asense_7
                asense_7=getadcreading(adc_address2, adc_channel3)
                global asense_8
                asense_8=getadcreading(adc_address2, adc_channel4)
                print("Alphasense Data:
",asense_1,",",asense_2,",",asense_3,",",asense_4,",",asense_5,",",asense_6,",",asense_7,",",asense_8)

sensorread()
```

A6: Location Reasoning

Green Building Roof



The sensor node on the Green Building roof is mounted on the handrail outside of the weather station shed.

As the highest point in Cambridge, the Green Building Roof was selected to compare air at a high altitude to that at ground level. It is expected that the air passing over the roof is cleaner than that at lower levels because the primary source of measured pollutants is exhaust. At this location, the power cord is thread into an existing through-hole connection into a shed. After installation, a weak Wi-Fi signal was observed indicating that an Ethernet connection should be used. The primary constraint for servicing this location is that access is restricted.

Building 16 Roof

Installation of a sensor node on the Building 16 roof.

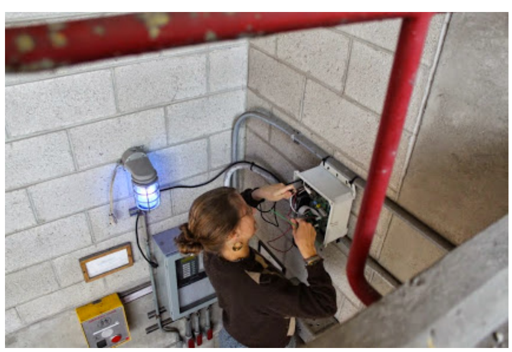
The Building 16 Roof offers a mid-level altitude to measure how pollutant concentrations change with elevation. It is expected that concentrations are higher at this location than the Green Building Roof, but lower than ground level node readings. This roof also has a reliable Wi-Fi signal allowing the node to send a continuous data stream to the central server. Similar to the Green Building roof, access to this location is restricted.

Stata Center Loading Dock

The Stata Center sensor node is installed outside of the package sorting facility.

The Stata Center loading dock was chosen for its atmosphere, as it is underground but not closed off to natural air exchange. This location is one where trucks arrive, idle during unloading and then leave throughout the day. Since vehicles are a major source of the measured pollutants, this sensor node should capture the effects of this behavior. The loading dock is also co-located with a parking garage, so the pollutant levels can be compared across several other CLAIRITY locations. This node is specifically placed outside of the package sorting facility, which follows a schedule wherein trucks are unloaded during two time intervals daily, each lasting an average of two to three hours. During the summer months, a fan circulates air throughout this area, which should be seen through lower levels of pollutants. The data from the Stata Loading dock is of particular interest to the workers who are regularly exposed to the air in the location.

West Parking Garage



Installation of the sensor node in the stairwell of the West Parking Garage.

The West Parking Garage, located on Vassar Street, was selected as a point of comparison for both the Stata Loading Dock and various parking lots in the deployment scheme. The Stata Loading Dock is adjacent to an underground parking garage whereas the West Parking Garage is an above ground structure. As such, it is expected that the pollution levels in the Stata location are higher than that in the West Parking Garage where air can more freely circulate through the various levels. The West Parking Garage should, however, show higher levels than the open parking lots selected. In order to utilize a constant power source, this node was placed in the main stairwell on Vassar Street at the ground level.

Kresge Parking Lot

The stop sign at the Kresge Parking Lot serves as the mounting location for the sensor node.

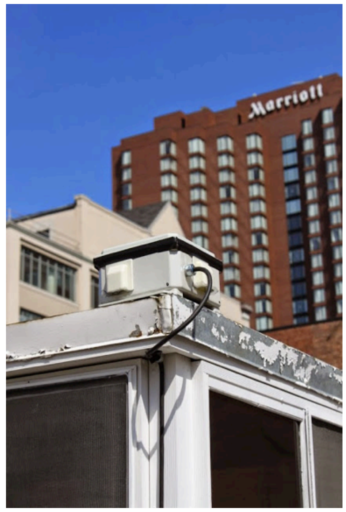
The Kresge Parking Lot was selected as one of the points of comparison for parking locations across campus. This particular lot is the most centrally located as many students pass by on their way to most dormitories on campus and it neighbors both the athletic facility and Kresge Auditorium. Limited Wi-Fi connectivity means that an Ethernet cable was threaded into the attendant's booth in order to utilize the wired network connection.

Massachusetts Avenue and Vassar Street Parking Lot

The sensor node at the corner of Massachusetts Avenue and Vassar Street is mounted on the north side of the attendant's booth.

This parking lot was selected because of the high traffic density on Massachusetts Avenue, both in terms of vehicular traffic and foot traffic coming to MIT's campus from Central Square. Furthermore, one underlying goal of this location is to see whether or not the sensor nodes show a distinct difference between a car pulling into the parking lot and one idling on Massachusetts Avenue during heavy traffic. This will show the spatial extent over which the sensor nodes are effective. The primary constraint for this location is a weak Wi-Fi signal, so the sensor node was specifically coded to connect to the "MIT Guest" network, the strongest signal.

MIT Medical Parking Lot



The sensor node at the MIT Medical Parking Lot is mounted on the top of the attendant's booth.

In addition to being a point of interest for the parking area comparison, this location was selected due to the large number of people who pass through Kendall Square. There are also food trucks that park on Carleton Street every weekday from mid-morning to the afternoon. Other sources of pollution come from the vehicle traffic through the parking lot and the proximity to the subway at the Kendall T Stop, the entrance to which is adjacent to this parking lot. The node is located on top of the attendant's booth and is attached using silicone glue due to limited mounting infrastructure in the area.

Sloan School of Management

The sensor node at Sloan is attached to a light pole outside of the entrance that faces Main Street.

The location at Sloan was chosen because traffic flow is particularly dense there with the intersection of the highly trafficked Memorial Drive and Main Street. The Longfellow Bridge that serves as a connection segment between Boston and Cambridge contributes significantly to the heavy traffic. Many delivery and facility vehicles also use these streets to supply and provide MIT, research companies and restaurants in the area with products and services. Furthermore, the MBTA Red Line that's above ground on the Longfellow Bridge switches to underground near this location. CLAIRITY is interested in understanding how the above ground Red Line influences air quality. Finally, the construction activity currently occurring at the Longfellow Bridge may also impact air quality at this location. Weak Wi-Fi outside of the building required the node to be placed close to the entrance, mounted on one of the available light poles. This node still experiences frequently dropped Wi-Fi so a stronger antenna may be required in the future.

Building 48

Node installation on an inactive steam pipe at Building 48.

Building 48 is a suitable location in connection to the Sloan location. Since the node at Building 48 also faces Main Street, it provides CLAIRITY with information on the dilution of air emissions at the intersection of Main Street and Memorial Drive. At Building 48, traffic flow is less dense compared to Sloan. While at Building 48 Vassar Street intersects with Main Street, Vassar is trafficked significantly less than Memorial Drive. Additionally, the MBTA Red line is underground at this location and does not emit air pollutants. Hence the dilution of air pollutants sourcing in the MBTA Red Line as well as in the construction activity on Longfellow Bridge can be assessed. However, the train tracks run by close to the Building 48 node, thus potentially impacting air quality. Due to limited power outlets on the outside of the building, this node utilized the emergency phone power source.

Media Lab

The Media Lab sensor node is attached to the overhang above the intake grate on Ames Street.

At the Media Lab, the road network mimics a residential area. While there is traffic flow, it is not very heavy. Most of the traffic at the intersection of Ames Street and Amherst Street occurs from MIT facility vehicles and deliveries to MIT. This location provides a good comparison to more heavily trafficked streets and busier intersections. It allows CLAIRITY to assess how the density of traffic relates to the emission of air pollutants and to understand whether heavy traffic does impact air quality significantly more than low traffic. This sensor node was positioned to face Ames Street and utilizes a power outlet in the basement. The power cord runs through the intake grate and into the basement area.

Building 1

The emergency phone at the intersection of Memorial Drive and Massachusetts Avenue provides the Building 1 node with a continuous power source.

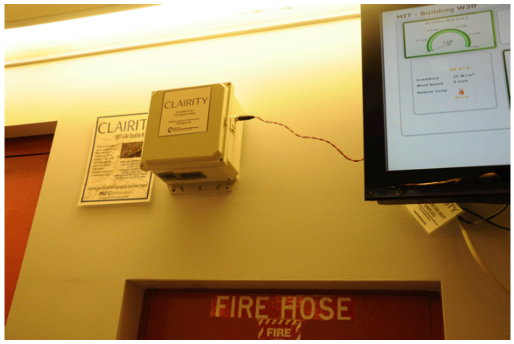
The intersection of Massachusetts Avenue and Memorial Drive at Building 1 is another busy intersection. Like Longfellow Bridge, the Harvard Bridge serves as one of the main traffic connection between Boston and Cambridge. Unlike the locations at Sloan and Building 48, the traffic at Building 1 is mostly due to traffic from cars and trucks. Neither the train nor the MBTA run by closely. This makes the intersection at good point of comparison to Sloan and Building 1 to understand how the train and MBTA affect air quality. In order to place the node as close as possible to the intersection, this location uses power from the emergency phone. Due to the distance from the building, this means that the Wi-Fi connection is weaker than anticipated and a stronger antenna may be required in the future.

Café Four

A weatherproof box was utilized for the Café Four location so that the sensor node could be mounted directly to the wall.

Café Four was selected for its proximity to the Infinite Corridor, the busiest hallway on MIT's campus. It also serves a point of comparison for the food service locations selected in that it serves food without doing in-house preparation.

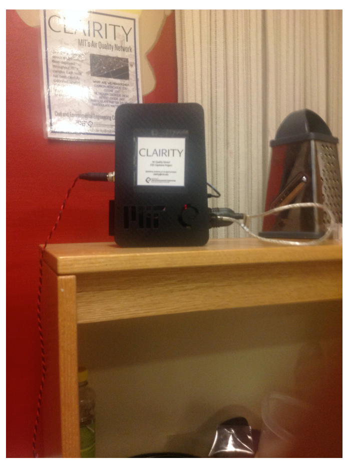
Stratton Student Center



The Stratton Student Center sensor node utilizes an outlet behind a display screen located to the right of CopyTech's entrance.

As another busy location on campus, most MIT students and other members of the community frequent the Stratton Student Center. Most of this traffic occurs during meal times throughout the day as several restaurants are near the sensor node's location. This provides CLAIRITY with information regarding how high output food production affects air quality in an enclosed space. This node is specifically placed to the right of the entrance to Copy Tech on the first floor in order to monitor an area with heavy student traffic.

Burton Conner Suite Kitchen



The Burton Conner kitchen node is in an area representative of a residential cooking environment.

Burton Conner is an undergraduate dormitory at MIT. This sensor node was placed in a kitchen shared by 7 residents. For the food service area comparison that CLAIRITY examines, this location captures a more residential cooking environment. The primary constraint for this location is that it cannot be monitored during the summer months and needs to be removed at the end of the academic year. CLAIRITY, however, does have permission to reinstall the node at the beginning of each year.

Next House Dining

The dining hall in Next House is utilized at all hours of the day as people use it for a quiet study space when the food service hours end.

This point of comparison for food service areas captures a high traffic dining area where food preparation occurs on site. This dining hall, located in an undergraduate dormitory, has two stations where food is cooked to order, utilizing grills, deep fryers and a gas range. The dining hall is open to students for breakfast, 8 am to 10 am, and dinner, 5:30 pm to 8:30 pm.

MIT Museum

The emergency light on the Front Street side of the MIT Museum provides the sensor node with a continuous power source.

This location was originally selected to compliment the exhibition featuring the CLAIRITY project during summer 2014. After selecting an outside location that had access to power, this location also became a point of interest for studying pollutants along Massachusetts Avenue. Additionally, this location has both MIT affiliates and members of the greater Cambridge community passing, giving CLAIRITY relevance to those outside of MIT. This location utilizes power from the emergency phone facing Front Street.

Next House Courtyard

The Next House Courtyard sensor node is mounted to conduit that runs near the entrance to the dormitory's kitchen.

The Next House Courtyard location was chosen in order to have a comparison between indoor air quality y of the Next House Dining Hall and the outdoor air quality of the Courtyard. The primary pollution source for the Courtyard is likely vehicle traffic on Memorial Drive and the loading dock on the Amherst Drive side of Next House. Furthermore, the sensor node is located beside the entrance and windows leading to a kitchen all residents of the dormitory have access to in order to cook for themselves. The courtyard also features a set of grills that are frequently used for large barbeque events.

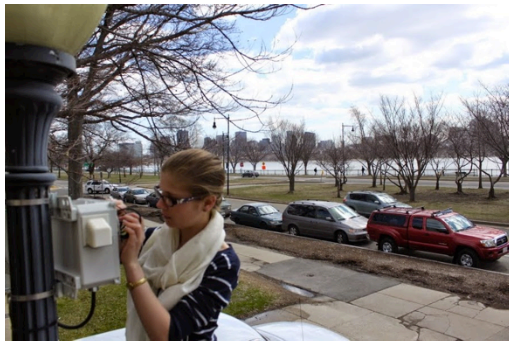
Killian Court

Connecting the Killian Court node inside of the weatherproof case.

Killian Court is an iconic location frequented by much of the MIT community as well as tourists. The freshman orientation and commencement both take place at this location. During enjoyable weather, many people frequent the grassy area. The main potential pollutant source is vehicle traffic on Memorial Drive, which passes directly in front of Killian

Court. This location was selected primarily for its iconic nature in addition to the frequency with which community members pass through the court. This node was placed on a light pole by the entrance to Building 3 in order to increase visibility by campus tour groups that pass directly though the area.

Walker Memorial



Memorial Drive is in close proximity to the Walker Memorial sensor node.

Walker Memorial is another location frequented often by MIT students. Additionally, there are tennis courts adjacent to the sensor node's location, which faces Memorial Drive. As such, Walker Memorial was selected to not only be a point of interest for community members, but also to monitor how pollutant concentrations vary along Memorial Drive, a street that frequently experiences heavy traffic. In order to best monitor the pollutants from traffic on Memorial Drive, this node was placed on a light pole to the right of the main entrance.

Green Building Base

The Green Building Base sensor node is attached to conduit on the East Campus dormitory facing the Green Building.

The main goal of this location is to compare spatial variation in altitude between the Green Building Roof and at the base. MIT Campus Tours pass by this location twice a day, making it a location to which both students and members beyond the MIT community are regularly exposed. This location is further removed from Memorial Drive than the Walker Memorial sensor node allowing CLAIRITY to see how pollutants from heavy traffic times disperse spatially. Due to limited mounting infrastructure on the Green Building, this node was specifically placed on conduit on the East Campus dormitory, facing McDermott Court and the Green Building.

Brigg's Field

A light pole on the southeast corner of Briggs Field serves as the mounting location for the sensor node.

The Briggs Field node is centrally located next to the du Pont Tennis Courts, Henry Steinbrenner Stadium and Track, Barry AstroTurf Field, and Briggs Field. Many athletes, who during practice intake air at high rates, spend time in this area. The node is also located near Amherst Street, where many of the undergraduate dorms are located. This is node is especially near Burton Conner, a dormitory in which another sensor node is located. This will allows a direct comparison of the indoor and outdoor air at locations due to the close proximity. The pollution sources for the Briggs Field node are the Kresge Pits, where there are frequently grilling events, and vehicles from Memorial Drive, Amherst Street, and the Kresge Parking Lot.

MIT Facilities Vehicle

Since the MIT facility vehicle and the Tech Shuttle typically drive along different traffic routes, having both vehicles covers more areas of the MIT campus. The MIT facility vehicle mainly drives around the MIT main campus and passes by different MIT department and research buildings to which the Tech Shuttle route does not connect. This sensor node was placed on vehicle number 99.

Tech Shuttle Bus

The sensor node on the Tech Shuttle is attached to the ThermoKing unit on the roof.

The Tech Shuttle drives along streets marking MIT's boundaries, including Amherst Street and Vassar Street. The Tech Shuttle is most frequently used as a way for MIT students to commute from MIT residences to main campus. Since the route traverses the perimeter of the campus, this sensor node is especially useful in seeing how pollutants disperse. The sensor node was placed on the ThermoKing on shuttle number 1601. In order to achieve a stronger Wi-Fi connection, a longer antenna may need to be thread through the roof and into the shuttle.

Cogeneration Power Plant

The Cogeneration Power Plant on the MIT campus is a unique location because it's industrial, low-traffic, and a closed site, with only about 30 employees using the facility daily. The chemical species measured by CLAIRITY are expected byproducts of electricity and heat generation processes and as such this location was selected to monitor to what extent this occurs. The sensor node was placed within the facility on the second floor that has boilers. This node will serve the purpose of looking at the pollutant levels for facilities staff in this type of location. This location does not have a network connection and as such the data needs to be retrieved manually. Additionally, this location has restricted access and supervision is required while servicing the node.

A7: Contact Information for Node Servicing

The following contact information is provided in case nodes are removed from a location or additional access other than what is publically available is needed.

Parking Lot Attendants' Booths and MIT Tech Shuttle

Dean-Ray Carthy
MIT Transportation
drcarthy@mit.edu

West Parking Garage and MIT Facilities Vehicle

Joseph D'Entremont
MIT Department of Facilities
Supervisor, Grounds and Services
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Next House Nodes

Next House Dining, Next House Courtyard
Jason Doucette
House Manager, Next House Dormitory
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Stratton Student Center Node

Michael Foley
Campus Activities Complex
Associate Director of Operations
mfw@mit.edu

Café Four Node

Thayer Donham
Campus Planning
Senior Planner
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Stata Center Loading Dock

Susan Bolster
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Supervisor, Mail Services
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MIT Museum

Susan Timberlake
MIT Museum Affiliate
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All Other Outdoor Nodes

Steve Gilligan
MIT Department of Facilities
Senior Electrical Supervisor

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Cogeneration Power Plant

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