ChE outreach

BUILDING AIR QUALITY SENSORS AND INSPIRING CITIZEN SCIENTISTS

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Air pollution is a significant global health and economic concern. Poor air quality accounted for 7 million deaths worldwide in 2012[1] and $21 billion in air-pollution-related health care costs in 2015.[2] Among common air pollutants, fine particulate matter ($PM_{2.5}$) – particles with diameters smaller than 2.5 μm – have the greatest adverse health effects.[1,3,4] $PM_{2.5}$ pollution is especially a concern to certain minority groups. Asians and Pacific Islanders and white Hispanics have the highest proportions living in areas with high $PM_{2.5}$ concentrations ($\geq 65 \mu g/m^3$) while whites have the lowest.[5] In addition, black (11.2%) and American Indian/Alaska native (9.4%) populations have higher asthma prevalences than that of whites (7.7%).[6] The substantial repercussions of $PM_{2.5}$ pollution have made it a critical issue for chemical engineers, who need to contribute to emission reductions through the processes and products we design.

Engineering problems that present themselves on such large scales are prime targets for distributed citizen scientist efforts, which have been shown to both provide valuable research data, and enhance citizenry's scientific literacy and engagement.[7] To be successful, however, the citizenry must first have some baseline education on the science behind these community-wide problems and the means to collect relevant data—in this case, low-cost air-quality sensors. Key limitations in the use of low-cost air-quality sensors by citizen scientists are that they are typically presented as "black boxes" with little explanation on how the sensors function and lack of engagement in marginalized communities who are more affected by poor air quality.[8] Recently, low-cost air-quality sensor networks have begun to appear, and a few incorporate $PM_{2.5}$ measurements,[9-12] creating an opportunity that allows for citizen scientists to contribute to our understanding of PM sources, spatial/temporal variations, and personal exposure. Consequently, low-cost air-quality sensors are an excellent conduit for introducing broadly important engineering concepts to our students and the public.

Several researchers have implemented air-quality curricula related to low-cost sensors in schools.[13,14] For example, researchers at the University of Colorado visited eight schools between 2013-2015 with teaching modules related to a low-cost air-quality sensor that was capable of measuring CO, CO_2, volatile organic compounds (VOCs), O_3, and NO_2. Each classroom kept a sensor for the school year and could deploy it for various projects.[13] Surveys from this program showed a general increase in student understanding of, and interest in, air quality's impact on the community and how to

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Anthony Butterfield *is an associate professor (lecturing) at the University of Utah. His research interests center around STEM community outreach, citizen scientist efforts, retention of underrepresented groups, and project-based learning, particularly as applied to first-year students. He has been awarded the GLBT Educator Award from NOGLSTP and AIChE's 2017 Award for Innovation in Chemical Engineering Education. Tony is a member of the ASEE Chemical Engineering Division's board and AIChE's Societal Impact Operating Counsel.*

Kerry Kelly *is an assistant professor in chemical engineering at the University of Utah. Her work focuses on the links between energy, air quality, and human health. Much of her research is motivated by local and regional air-quality challenges. She has a B.S. in chemical engineering from Purdue University, an M.S. in environmental engineering from the University of North Carolina-Chapel Hill, and a Ph.D. from the University of Utah. Dr. Kelly is also active in public policy. She served eight years on Utah's Air Quality Board, and she currently chairs Utah's Air Quality Policy Board.*

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Kyle Tingey *recently received his B.S. in computer engineering (December 2017) and is passionate about innovation. Mr. Tingey designed, developed, tested, and integrated a network of "hyperlocal" air quality sensors for the AQ&U project (<aqandu.org>). The project deployed 100 sensors outfitted with major hardware upgrades and clever engineering to reduce the cost of similar sensors from more than $5,000 to only $250. The AQ&U sensor development team, under the leadership of Mr. Tingey, managed these upgrades from initial concept through the deployment of these sensor across the Salt Lake Valley.*

Thomas Becnel *is a graduate student at the University of Utah. He received a Bachelor of Science degree in electrical engineering from the University of Utah. His research interests are in nanoscale attoFarad capacitive sensing techniques to be integrated into next-generation particle counters and low-cost pollution monitors.*

TABLE 1

Building block sensor components and costs. Total cost per building block sensor kit is about $40.00. When brands are noted, they are intended to facilitate purchase of a similar item, rather than a requirement.

Part	Cost per sensor ($)	Description/Source
Building-block sensor components		
Building blocks	8.25	Multicolor building blocks, compatible with major brands/Amazon
Baseplate	1.46	Strictly Briks, 6" x 6" baseplates, compatible with major brands/Amazon
LED light	0.20	Microtivity 5mm clear white LED IL051/Amazon
Photoresistor	0.17	Gikfun GL5516 LDR photo resistors for Arduino
Mini fan	4.00	Raspberry Pi DC brushless cooling fan 3.3V/5V/Amazon
Jumper wires	1.86	Phantom YoYo Jumper Wire M/F male to female 200mm length/Amazon
Detection device –The Arduino plus the Neopixel may be replaced by a multimeter.		
Neopixel	5.95	NeoPixel Stick, 5050 RGB LED with integrated drivers/Adafruit
Arduino Uno	20.00	SparkFun RedBoard, programmed with Arduino/Sparkfun
Test pollution – only one of the following needed per class. These can be used for multiple visits.		
Fog machine	35.00	Byone fog machine with wired remote control, 400-Watt/Amazon
Mist generator	11.00	AGPtek color changing 12 LED mist maker/Amazon
Baby powder	5.00	Johnson & Johnson baby powder, one 22 oz bottle/Amazon

use the technology to successfully collect and analyze data.[13] Another example was the use of CairClip sensors, which read NO_2 and O_3 levels, in Houston and Denver under the NASA-led DISCOVER-AQ Earth Venture Mission.[14] The program installed the low-cost CairClip sensors in seven schools to increase spatial coverage and time resolution of NO_2 and O_3 concentration measurements. Their results showed that some of the air-quality data collected from the citizen science sites with low-cost sensors compared favorably to measurements at nearby reference monitoring sites.[14]

This work has been developed in Utah's Wasatch Front, which periodically experiences the worst air quality in the United States[15] as the result of $PM_{2.5}$ pollution. Elevated $PM_{2.5}$ levels in the region are linked to increased incidence of asthma,[16] juvenile arthritis,[17] and mortality.[18] Furthermore, Utah's residents rank poor air quality as the number one detractor to quality of life.[19] Consequently, students and teachers in this region tend to be particularly engaged in air-quality-related learning, but the teaching module developed herein is applicable to any region due to the ubiquity of PM pollution from combustion engines and indoor particulate sources (*e.g.*, cigarettes, incense, cooking, candles).

We have developed an extensive K-12 outreach program within our Department of Chemical Engineering[20] to deliver effective hands-on learning to local schools and recruit students into chemical engineering, particularly minorities. In this work, we use our outreach methods within the context of a citizen-scientist, air-quality project to engage students with interactive learning and prepare them for sensor data collection. This module demonstrates how a low-cost air-quality sensor constructed out of inexpensive, readily available parts can be utilized in a hands-on teaching module to introduce students to the science of air-quality measurement and, specifically, how light scattering is used to measure PM concentration, which is important to a variety of chemical engineering and biochemical engineering disciplines. Specifically, the teaching module includes: (1) a low-cost sensor design made entirely of Lego®-like building blocks, (2) an electronic-interface for the building-block sensor based on a low-cost Arduino system, and (3) a set of engaging teaching activities and accompanying teaching materials. We also compare the performance of the building-block system with a more sensitive low-cost PM sensor and a research-grade analyzer. This teaching module has been extraordinarily successful in engaging students and the community as a whole in air quality and engineering solutions.

MATERIALS

Table 1 gives a breakdown of components and their costs. The building-block sensors used in this teaching module include a photoresistor, LED light, Neopixel indicator lights, and fan. These are all connected to an inexpensive microcontroller (an Arduino-like RedBoard, from Sparkfun) and housed in Lego®-like building blocks, based on student designs as shown in Figures 1 and 2A. Alternatively, a multimeter could be used instead of using an Arduino board and Neopixel to indicate the resistance of the photoresistor. The sensor, white LED indicator lights, and fan are all adhered to building-block pieces for easy assembly. A drill press or drill and vice could be used to drill holes in building blocks to install the photoresistor or LED light. These can be sealed in the building block with hot glue. The Neopixel light can also be mounted on a building block with hot glue.

Test pollution in the classroom setting is generated with an ultrasonic mist generator or fog machine. Baby powder or Gold Bond powder are also effective particulate sources (requiring additional cleanup). These test pollution sources pose little risk to the students and will not trigger a smoke detector, but smoke from combustion sources (*e.g.*, candles) could be used as well.

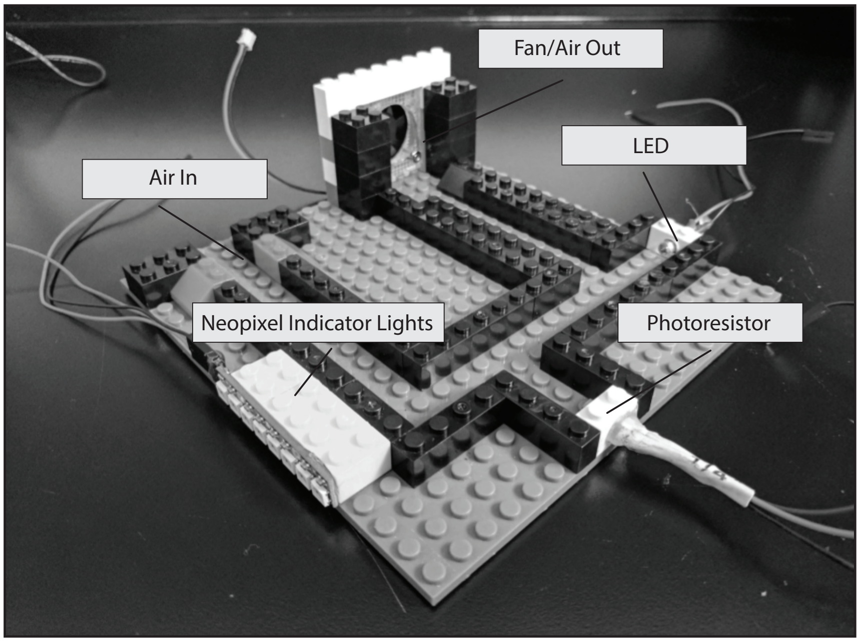
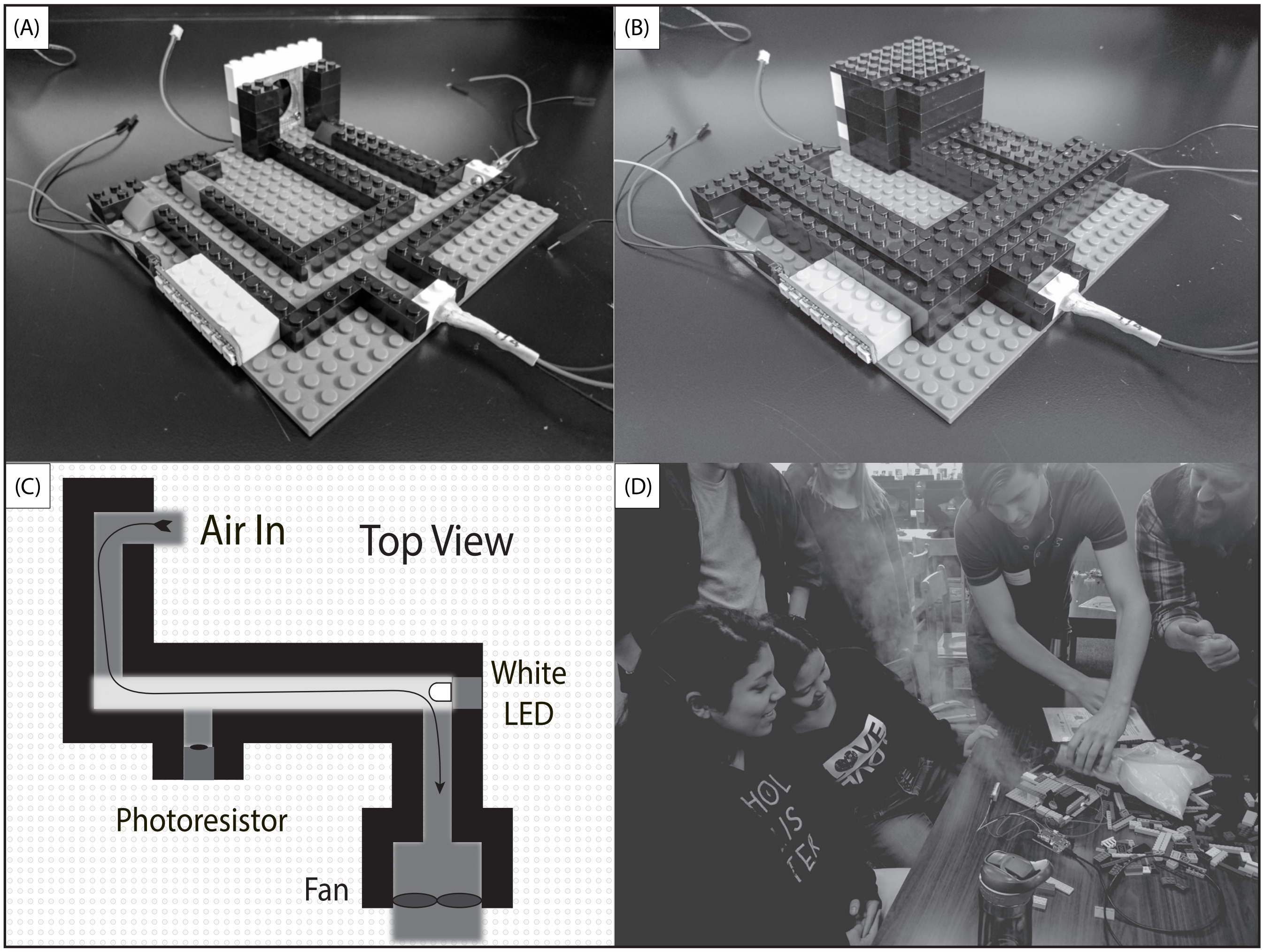


Figure 1, right. *Labeled cross-section of example building-block air sensor configuration.*

Figure 2, below. *(A) Unlabeled cross-section of example configuration. (B) Fully built example configuration. (C) Top down diagram of example configuration. (D) Visit at a local high school.*



METHODS

Building a Sensor:

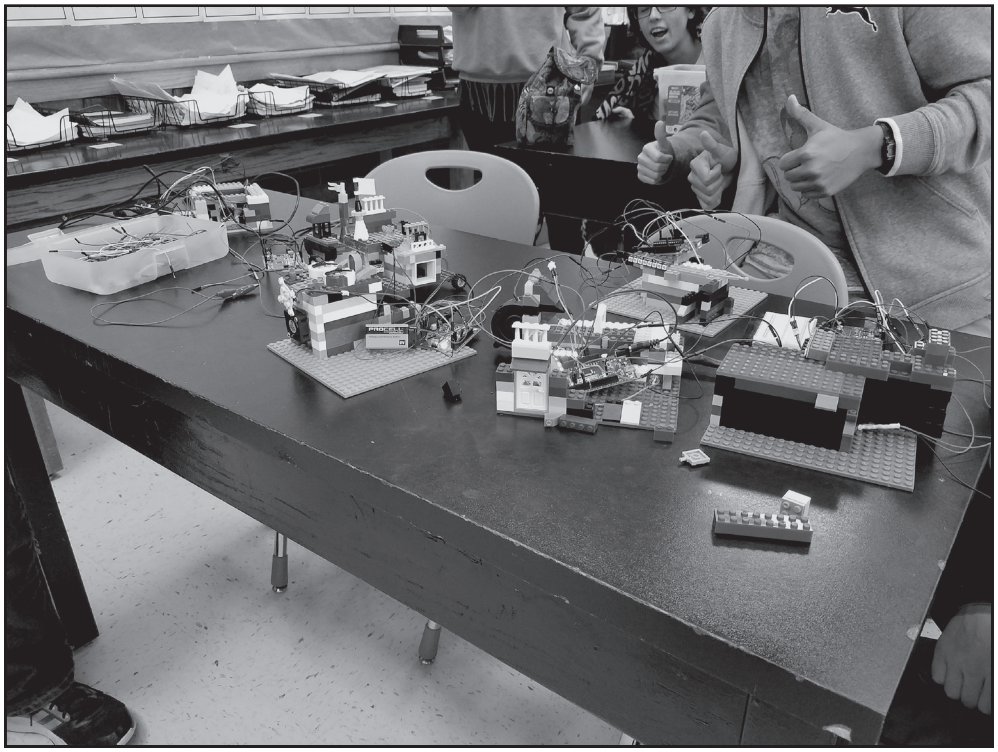


Figure 3. Table of example student configurations.

The building-block air sensor system uses a simple light-scattering apparatus to make PM measurements. Figures 1 and 2A show a cross-section of the components in an example configuration. In this effective design, air is pulled through the system by the 5V fan. As air travels down the illuminated path, light from the LED hits and scatters off of PM. This scattered light reaches the photoresistor, and the amount of scattered light correlates with the quantity of PM in the air. The photoresistor is placed on a path perpendicular and set back from that of the LED to increase sensitivity and to shield the sensor from exterior ambient light. The entire system is further shielded from ambient light with the building blocks using a U-like path. Darker building blocks also help minimize reflected ambient light in the system. The Neopixel lights provide a relative indication of PM levels to the students. Figure 2B shows a fully built design. However, many designs are possible and are left to student imagination. An example of another configuration can be seen in Figure 2C, which utilizes an S-like path instead of a U-like one. Other design options include using a blower instead of a fan to move the air through the system or even having the Arduino Board coded so that the sensor measures absorbed light rather than scattered. Figure 3 shows various working student designs.

Classroom Module Execution:

Students should be given some background on air quality and light-scattering sensors (our presentation and extensive module details may be found online[21]). Students form teams of two or three and receive all the needed parts to assemble their sensor. As they build their sensor, instructors should walk through the room questioning teams on their design choices and rationale. Typical student design problems include:

- *Failure to properly shield their photoresistor from ambient light: This is simple to test by passing your hand over the sensor to shade its location and observing the response. A light from a smartphone may also be useful to test for sensitivity to ambient light. An additional layer of building blocks can typically remedy this problem. Alternatively, the air entrance or exit may be allowing ambient light in, and a curve (the U-like or S-like path) may need to be introduced to the air path. Concepts of sensitivity and illegitimate experimental noise may be presented.*
- *Building tall air channels: The air channel is best kept to only one brick high where possible to maintain high particulate levels within the sensor. Here, concepts of concentration effects and even streamlines may be introduced to the students.*
- *Attempting to detect transmitted instead of scattered light: The photoresistor will not be sensitive enough to detect the small percentage change in absorbed light and must be placed perpendicular to the light path. Concepts of sensor saturation and the importance of percentage change versus absolute change in a measured property are possible teaching opportunities.*

Once a student team is finished with its design, the design should be wired to an Arduino board to power the various components. The LED is the only component requiring the 3.3V power supply, while all other components may use the 5V power supply. The photoresistor output is measured through a voltage divider with a 10 kΩ resistor, using one of the Arduino's analog pins. The Neopixel may be controlled with a digital output pin. Detailed wiring instructions, a single-page handout for students, and the needed Arduino code may be found at the AirU site.[21] Before powering on, an instructor should check student wiring.

Alternatively, if it is not desirable to use a microcontroller, the LED and fan could be powered by two AA batteries (a 3V fan would be needed, such as the General 4 cm A4010H05S). The scattered light could then be quantified using a multimeter.

Once the wiring is complete, simulated PM from the mist generator or fog machine may be used to evaluate and compare student designs. Redesigns are sometimes required to improve sensor response, but the building block components make such an iterative design a simple matter. Other design goals may be added to the module, such as minimizing material use (as measured by a scale). Typically, once the module is over, we have students present their designs and explain their design choices to the class.

We have executed this module successfully in 50-minute class periods by giving significant wiring help, but a 1.5-hour period or two class periods are preferable. We have found students of middle school age and up are capable of wiring their devices on their own; younger students are capable of building their sensors but need additional aid in wiring. This module is also useful for outreach tabling events. At such events, we bring a completed example sensor to introduce the "helping profession" aspects of chemical engineering to the public and allow interested participants to build sensors at their leisure.

TEST RESULTS

In order to illustrate the capabilities of the sensors built by the students, we conducted a series of experiments to compare the response of the building-block sensor to PM concentrations measured by a TSI DustTrak™ II 8530 (a research-grade PM instrument), and three of our own AirU sensors. Details of the DustTrak™ and the AirU devices follow. The DustTrak™ , AirU sensors, and building-block sensor were placed in a closed chamber as three different types of test particles were introduced: fog from a fog machine, smoke from seven candles, and exhaust from a 2009 125cc Yamaha Vino scooter. Three trials of each particle type test were conducted.

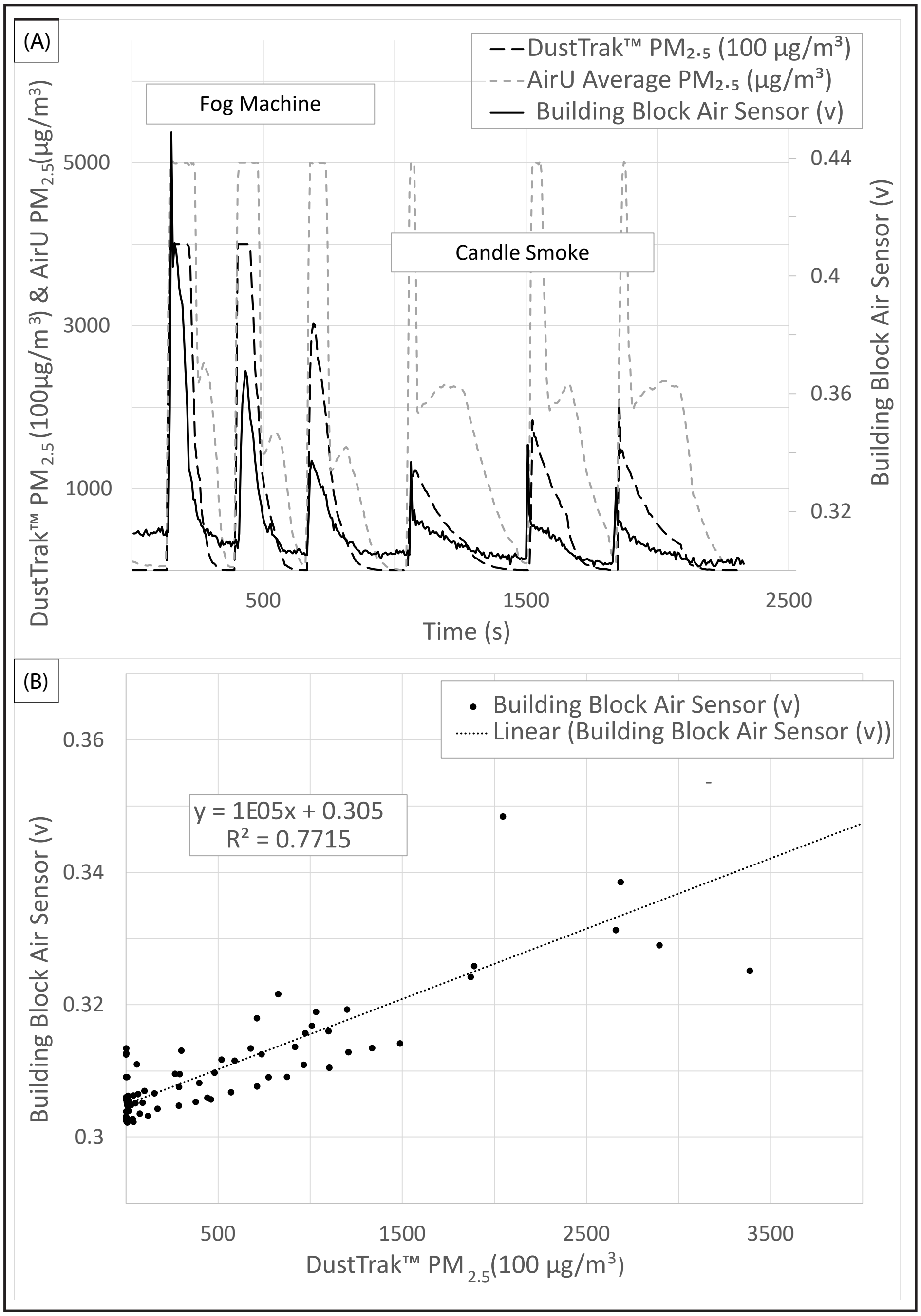


Figure 4. *(A) Time series of all sensors' PM measurements during fog and candle trials. Three trials of each where conducted, hence three peaks. (B) Building Block Air Sensor air graphed against DustTrak™ during the fog and candle trial.*

The TSI DustTrak™ II 8530 uses light scattering at a wavelength of 780 nm to estimate PM mass concentration (cost approximately \$5,000). For our trials, it was configured with a $PM_{2.5}$ size-selective inlet. The TSI DustTrak™ II 8350 has been used extensively to measure indoor and outdoor pollution levels.[22,23]

The AirU is a low-cost air-quality measurement platform designed by students at the University of Utah, as part of a

National Science Foundation grant. It incorporates a GPS and four sensors: a PlantTower PMS3003 PM sensor that detects three size cuts of particulate matter (PM_1, $PM_{2.5}$, and PM_{10}); an MiCS-4514 dual sensor that measures both CO and NO_2; an HDC1080 sensor that measures temperature and humidity; and an OPT3001 that measures the intensity of visible light. The Plantower PMS 3003 particulate matter sensor uses a laser light-scattering technique to detect airborne particles between 0.3 ~ 10 microns.[24] PM measurements are communicated over UART (9600 BAUD, 8 bits per transfer, 1 stop bit), with an average packet transmission rate of about half a second. Hold time on the sensor can be up to 1 second, however. Measured data is transmitted over UART in 24-byte packets, including the PM data (2 bytes wide each) and checksum data. Measured data is stored by the AirU platform in a microSD card. Note that the simple UART interface of the Plantower PMS 3003 sensor makes it an ideal foundation for educational settings and engaging hands-on learning in the classroom. The PM sensor can easily be incorporated with user-friendly embedded devices like the Arduino Uno[25] or the National Instrument's (NI) MyRio Embedded Device.[26] NI's intuitive software and programming environments can make pollution monitoring fun and engaging.

Figure 4A shows the time-series PM concentrations for the three different types of sensors when exposed to the fog and candle smoke. The fog and candle results show that all sensors respond at similar times to the test PM. They also show that the DustTrak™ saturates at 400 mg/m^3 while the AirU Sensor saturates at around 5.0 mg/m^3. For comparison purposes, the U.S. EPA's National Ambient Air Quality Standard for $PM_{2.5}$ is 0.035 mg/m^3 (24-hour average). Figure 4A also shows that the AirU sensors had two peaks instead of just one, unlike the DustTrak™ and building-block sensor (Figure 4A). These dual peaks may be due to inconsistent flow patterns in the test chamber or proprietary data conditioning. All of these observations may be used to introduce concepts of sensor saturation, data filtering, and such to better prepare citizen scientists to take care of their research sensors.

The scooter results differ slightly. None of the sensors reached saturation, and the DustTrak™ and the AirU sensors peaked in a consistent way. However, the building-block sensor did not respond. This is probably due to the scooter exhaust not containing enough PM for the building-block sensor to take accurate measurements. Such data may be used to discuss concepts of sensitivity and response time, and illustrate to the students the need for more sophisticated sensors than the sensors built with building blocks.

When plotting the building-block sensor readings against the AirU readings, a linear correlation is seen. Although there is not as strong a correlation as when the building-block sensor is plotted against the DustTrak™ as seen later on (Figure 4B), there is still a notable association between the building-block sensor and AirU readings. The weaker, but still notable, correlation between the readings may be due to the DustTrak™ being a research-grade instrument or the proprietary data conditioning of the AirU.

This module demonstrates how a low-cost air-quality sensor constructed out of inexpensive, readily available parts can be utilized in a hands-on teaching module to introduce students to the science of air-quality measurement and, specifically, how light scattering is used to measure PM concentration, which is important to a variety of chemical engineering and biochemical engineering disciplines.

A scatterplot of the DustTrak™ and building-block sensor readings shows a strong linear correlation (Figure 4B, R^2=0.772); the saturated measurements for the fog and candle trial were omitted in this plot. This data suggests that our building-block sensor was able to read reasonable relative measurements of pollution, and it may be used to highlight to students that the devices they build are capable of approaching the performance of equipment that costs thousands of dollars.

OUTREACH RESULTS AND DISCUSSION

To date, we have used this module in more than 30 classrooms (more than 1,000 students), and at several community STEM tabling events. Our outreach program visits more than 1,000 students in their classrooms each year, and this module has become our most requested since its development. In addition, we have also partnered with Breathe Utah, a local nonprofit organization, with this teaching module reaching an additional 100 classrooms and more than 3,000 students thus far.

Because this work involves minors, we have limited ability to collect student information and feedback. The parental consent needed to use a survey tool would prevent our outreach visits to most local K-12 teachers. However, allowable data was collected from several sources.

This module was used at a college summer camp for high school girls. From the 25 campers, there were zero negative comments; 65% of the campers ranked the activity as Great, with the remainder ranking it as Good. Student comments include:

- *"I never considered being a chemical engineer before now, but you really opened my eyes to that field."*
- *"I always thought chemical engineering was a scary thing, but now I know it's actually really cool! I am also glad that green technology is involved."*
- *"Thanks for the great activity and education. I'm considering being a chemical engineer."*

Student free-form reflections on the activity were collected for two classes at one local high school: a biotechnology class and an ELL (English Language Learner) science class (Figure 2D). All students regarded the activity as a whole positively. Of the comments, 90% could be classified as positive. A majority of the students (70%) mentioned their appreciation for learning something new about air quality (several also positively mentioned learning more about circuits). Slightly more than 70% also positively mentioned using hands-on building and creativity. Other major positive themes included interacting with the university outreach team (particularly faculty), working in their team, and the connection of the activity to addressing a community health problem. All of the negative comments (10% of total) referred to some form of confusion about how to get their sensor working, as may be expected with open-ended design outreach modules. Improving this balance between student creativity and confusion is discussed in the Lessons Learned section of this paper.

These student reflections support the anecdotal observations of the researchers who visited these hundreds of students: Students seem particularly engaged by learning more about an engineering problem that directly affects their lives and the hands-on building. While some students may feel confused, very rarely does the module end without every student group having built a working sensor. There has been effectively 100% participation in each classroom, and positive feedback from educators. Of the schools we visited in the 2016/2017 academic year, we have been invited back to approximately 82% of them in the 2017/2018 academic year, and at least three teachers have incorporated this activity into their yearly core instruction.

This module was created in partnership with a team of women interns from the Academy for Mathematics, Engineering, and Science (a local Title 1 high school), and reaching underrepresented groups was a key focus from the start. Aside from its successful use at our summer camp for high school girls, we have seen additional evidence that this module has had a disproportionately positive impact within underrepresented groups. While we are limited in our ability to survey students about their inclusion in an underrepresented category, we have collected school district data for each visit to approximate our impact. While the surrounding county is home to 16% underrepresented ethnic minorities for our department (non-Caucasian and non-Asian),[27] the schools visited by this work are, on average, double that value (30%).[28] We have found the module to also be useful for reaching non-English speaking students and have used it in two ELL science classrooms with the help of translators and without needed additional time (approximately 35% of the student responses from the local high school visit mentioned above required translation from Spanish to English).

This module has also been useful in making inroads into a wide variety of community events. Due to air quality's impact on the reservation community, we were invited to use the activity during the Northern Arapaho Environmental and Natural Resource Conference. The module was also effectively used at the West Side Communities Breathe Clean Air Festival, and the Environment and You, West Side Festival, both with the help of Spanish-speaking outreach students. Finally, our outreach team was invited to have a booth at the Salt Lake City Pride Festival, during which this module was used to engage LGBTQ youth. Due to the broad community impact of poor air quality, this module has even become the focus of local and national media attention for its engagement of students.[28,29]

LESSONS LEARNED

As the first of a number of teaching modules focused on air quality developed by the Department of Chemical Engineering at the University of Utah, several lessons were learned. First, it is useful to provide a number of spare parts as some parts may break or become lost due to successive uses by students. Extra care can be taken to prevent breakage by hardening the wires using hot glue or other sealants. We color-coded the wires in order to help the students with the wiring; all ground wires are black, all supply voltages are red, and everything else is a consistent other color. We strongly suggest color-coding the wires as it made things much clearer to the students, giving more time for the students to be creative with their sensor designs. It will also save time if the parts are organized in separate bins (*e.g.*, male/male wires separated from female/female and female/male wires). It is important to check the wiring before students power their device. The students commonly will reverse power and ground which can lead to damaging some of the components. Lastly, it is important to train the faculty and outreach student leaders prior to executing the teaching module by having each outreach leader read the accompanying teaching module and assemble a device of their own.

In terms of the demographics, we found that the teaching module is ideal for middle school and high school students. However, we have successfully deployed this teaching module in elementary schools as well, as long as the wiring is done for the students. Roughly one facilitator per 10 students is enough to keep the students on track and engaged with building their sensors.

CONCLUSIONS

Too few K-12 students (or laypersons) realize that chemical engineering is a very important helping profession, one that can allow the chemical engineer to have a significant positive impact on an entire community. While our outreach efforts often highlight the cutting-edge science or even material wealth to be found in a chemical engineering degree, it is important to present a diverse picture of what it means to be a chemical engineer. It is, for example, strongly suspected that one reason for the low numbers of women in engineering may be due to the misperception that engineering is not a helping profession.[30-32]

This work presents an outreach teaching module that emphasizes the ways in which a chemical engineer and citizen scientist can help address a crucial public health and economic problem. Air quality is an important concern around the globe, and is especially concerning within the Salt Lake Valley. Air pollution is a prime target for citizen-scientist and chemical engineering outreach efforts.

The primary goal of our building-block air sensor teaching module is to make the science of air quality sensing more accessible—and less of a "black box"[8]—to the community, notably underrepresented groups, so that they can more confidently enter a larger citizen-scientist program and contribute to our own understanding of air quality. Another goal was to introduce young students to basic engineering concepts as well as to encourage them to become chemical engineers. Using a simple light-scattering sensor constructed out of low-cost parts and housed in Lego®-like building blocks, this teaching module has been a successful example of a hands-on teaching activity that excites students and the public.

This teaching module is the first component of a set of teaching modules developed by the Department of Chemical Engineering at the University of Utah that will teach K-12 students about air quality, how air quality is measured, and the significance of citizen science. After gaining core concepts from this teaching module, the K-12 class will become responsible for a more-sensitive air quality sensor, called the AirU, that will be placed in and outside of their respective schools. The network of these more-sensitive sensors will reduce time and spatial disparities in air quality sensing across the Salt Lake Valley.

ACKNOWLEDGMENTS

This material is based in part upon work supported by the National Science Foundation under Grant Numbers NSF 1646408 and 1642513. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

We would like to thank the students of the Academy for Math, Engineering & Science and West High School, who helped develop and hone this teaching module: Colin Pollard, Keenan Lins, Katie Nolan, Piper Stevens, Vaishnathi Thiraviyarajah, Annika Young, and Emma Dean.

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