Esselen Award Address

Chemical/Biological Sensing: Science and Real-World Applications

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The human experience is dominated by our sensory inputs of sight, touch, sight, taste, and smell. Of these, the sense of taste and smell are uniquely chemical and involve molecular recognition. We experience good smells, such as those associated with fresh flowers, and are very sensitive to foul smells, such as those associated with rotten food. The equivalent of an olfactory receptor is a chemical sensor, which is a device that translates a chemical signal into a signal that can be read electronically.

Society is properly ever more interested in the molecules we experience in our environment. When carbon dioxide levels get too high in a building, air exchanges are needed. If the air quality is satisfactory, air exchanges are not needed, and we can save energy by integrating carbon-dioxide sensors into the control system.

Incomplete combustion in a furnace can give dangerously high levels of the toxicant carbon monoxide that need to be detected by a sensor. We can't smell methane, so the gas companies add sulfur compounds with low odor thresholds for our safety.

However, people can become sensitized to different smells, a fact I know personally having worked in my youth on a pig farm. Simply put, people need chemical sensors to be made aware of their exposures and alerted to hazards in real-time. These hazards can be intermittent point sources of toxic materials. However, to detect them with conventional technologies requiring the installation of power-hungry, expensive systems in homes, offices, cars, etc. is simply not practical.

The solution is to create chemical sensors empowered by molecular material designs, that have low cost, low power, and can be used to create distributed networks. These sensors have flexible form factors and can be stuck on a wall, put in packaging, or integrated into clothing.

Although we often focus on hazards, it is also important to mention that not all smells represent threats to our safety. Specifically, there are many applications of chemical sensors that can be used purely for the betterment of society. For example, the monitoring of trace ethylene emissions from fruit represents a viable way to rapidly assess the ripeness of fruit individually, or in large batches.

Automated systems using this information can be used to optimize the supply chain and reduce waste. For example, a truck from California could have its contents evaluated in real-time to determine the relative shelf-life of its cargo. You might want to drop off that lettuce pallet in Chicago, because it has two days of shelf-life.

Stores could use gas sensors to monitor the freshness of products and create dynamic pricing to move products. Sensors that detect biogenic amines from microbial metabolism can be directly integrated into food packaging to ensure freshness. Clearly, inexpensive distributed chemical sensors are certain to improve the life for all members of society.

My approach to sensors is intrinsically very chemical and begins with an intuitive understanding of the properties and reactivity of the molecule of interest. Although I began graduate school aspiring to be a physical chemist, I evolved into someone with a very synthetic mindset and I am intrigued by chemical reactions, synthesis, and reactivity.

Molecular intuition is not enough to make high performance chemical sensors. It takes physics, nanoscience, some understanding of instrumentation, rudimentary biochemistry (for biosensors) and, importantly, an engineering problem-solving mindset.

Nevertheless, I do draw upon my molecular wet chemistry talents as being perhaps the special sauce that sets our group's approach as different from others.

I began thinking about chemical sensors as a graduate student workingon the synthetic conductor, poly-acetylene. I was amazed that the conductivity of lightly doped (oxidized) polyacetylene would change by as much as a factor of a million with exposure to some solvent vapors.

Inspired by this, I drew out a diagram of a molecular (we didn't talk nano then) wire sensor, and I still show renditions of this scheme in my lectures. I think of the wire as a

repeating sequence of variable resistors that are coupled to receptors. Binding of the target molecule (analyte) to the receptor can then cause a large increase in the resistance of the entire system.

The fact that these receptors are wired in series is important, and the analogy is that you can still get current through a million switches if they are all in the on state. However, turn one off and you break the circuit. Hence, we can get signal gain or amplification from molecular wire sensors.

We had great fun designing complex receptors with high selectivity. However in the early 1990s, as an unproven Assistant Professor, I encountered many doubters about the virtues of this molecular or nanowire architecture. Remember, this was almost ten years before carbon nanotubes and semiconductor nano-wires. So, although presently everyone thinks nanowires are a good idea, I didn't get such a pass back then.

To win over the critics, I decided to rigorously prove that molecular wires would amplify a sensor response relative to single molecule chemo-sensors. In doing so, I drew upon some of my other work in conjugated polymer photophysics, wherein we had performed the first directed energy transfer reactions in conjugated polymers.

In this case the excited states (excitons) migrate along a polymer's backbone to a low energy trapping state giving a large Stokes shift in the emission because of selective emission from a local lower energy band gap. I rationalized that exciton transport was like charge transport and could be used to amplify a signal.

Indeed, we demonstrated this amplification through quenching studies, and as a part of process we performed the most definitive measurements to date of the exciton diffusion-length in isolated conjugated polymers.

This led to an entirely new way to make high sensitivity optical (fluorescence) sensors, wherein the exciton migration can give amplification factors of more than 20,000. We then went on create sensors that could detect (smell) explosives at levels that were competitive with trained canines.

Handheld sensors based on our methods are known as FidoTM sensors and are presently produced by FLIR Systems. These systems are battery-operated portable devices with sensitivities more than 1000 times those of expensive bench top airport security systems. We continue to have had a good run with fluorescence sensors and have designed systems specific to many organic and biological targets.

Throughout my career I have always kept some focus on the use of electrical conductivity to create a sensor. My interest in these chemi-resistive sensors is much deeper than being caught up in my graduate school fascination with molecular wire sensors.

Specifically, chemiresistors based on molecular and nanowires promise to be the least expensive and lowest power electronic systems you can imagine. We have made many sensors based on conducting polymers, but have recently shifted to carbon-nanotube-based systems. Carbon nano-tubes have excellent electronic transport, have shape-persistent wire-like shapes, and are sensitive to their environment.

The challenge that most researchers ignore in this field is how to get carbon nanotubes to respond with high selectivity for an analyte of interest. It is easy to detect an oxidant or reductant, but detecting ethylene at part per million levels in a complex environment is hard. Nevertheless, with special ethylene-binding organo-metallic compounds, we found that we could create functionalized carbon nanotubes to monitor fruit ripening.

This technology is now the basis of a startup here in Cambridge, called C_2Sense, which is focused on creating sensors for food, agriculture, and occupational safety. The power of the chemiresistors is also in the fact that it doesn't take much power to move a few electrons and get a resistance measurement. In fact, we have developed radio frequency identification (RFID) sensors that cost pennies and can be inductively powered and read with a conventional smartphone. This technology clearly is ripe for mass adoption by consumers.

In our most recent adventures we have focused on highly dynamic fluid systems that respond to chemical stimuli. Specifically, we have developed a new scalable approach to complex emulsions of multiple immiscible fluids in water.

These liquid colloids behave as small lenses and can be dynamically reconfigured by the action of chemicals or enzymes. They offer a new mechanism to couple highly selective chemical processes to create sensors. There is much to do, and we haven't demonstrated trace detection with these systems. However, it is a completely different platform than has been explored before and has excellent prospects for coupling to a broad range of chemical/biochemical reactions and equilibria.

Throughout all of my adventures, I have been supported by my amazing wife, Anne, and two equally awesome daughters, Laura and Katherine. I continue to be educated in my daily interactions with scores of coworkers and colleagues with impressive intellects and insights. I am truly lucky to have been surrounded by such human kindness and support.