Smart nanomaterials meet smart phones

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Smart things
To be considered a smart “thing” in technology, there must be three important functions: 1) sensing (reading and sending data), 2) actuation (from the Latin actus, or to act), and 3) control. There are many different ways to apply this conceptual framework, which has led to a number of different devices used in manufacturing, transportation (self-driving and not), health care, and a host of other applications. For example, a modern cell phone has at least 10 sensors, and is capable of working as an actuator (for example, read about a method for using IBM Watson to turn your phone into an actuator here). Once this sensing-actuation function is created, it is 2/3 of the way to being a smart device. Additional control features can be implemented through algorithms that can interact with the sensing-actuation feedback loop to modulate a particular component of the device, or another device which is synced. In this regard, the modern cell phone (when transformed into a true “smart” phone) is an enabling technology that opens up the use of other smart “things” by coupling with sensors and/or actuators. These three functions operate in a network of interconnected devices, or “things” (a concept Kevin Ashton at MIT coined as the “internet of things” in 1999). Examples of how this is being applied include smart sprinkler systems, and even smart homes. For an example of our work, see the open source smart phone tool for post hoc analysis of biosensor data by Rong et al (discussed in an earlier post).

One area that has become important in nanomaterial research is the idea of using the IoT platform to directly actuate a response in the same environment where a sensor collected the data. This sense-analyze-respond logic is a type of smart system that can cross spatial scales, from the macro-scale (cell phone) to the nanoscale. While attractive, this is usually hindered by the ability to actuate a smart material with any real level of control. Nature accomplishes this in nearly every reaction that occurs, a nanoscale reaction occurs, which results in a cascade of signals that have a feedback system with a central data processing center, and a new action is created. Multiple cycles of this triad result in learning.
The definition of a smart material, on the other hand, is quite different than the standard described above. A smart material is defined as a material that has one or more properties which can be significantly changed by a, usually small, external stimulus. Examples of external stimuli include stress/strain, temperature, moisture, pH, electric fields, magnetic fields, light, or chemical compounds.

Is a material by itself be “smart”?
There are many examples of materials which can perform at least two of the functions required to be classified as “smart”. One of the classic examples is nitinol wire, which is a stimulus-response metal that is used in eye glasses (among other examples). The material will return to its original shape when bent, which is an attractive feature for eye glasses (when someone accidentally sits on them, for example). Nitinol can certainly undergo a significant physical state change (shape) with only a small change in environmental stimulus (heat), so this meets the definition used in material science for a “smart material”. See the video below from MIT for an example of nitinol in action.

There are many other examples of materials that have stimulus-response behavior as shown above for nitinol (commonly referred to as shape memory metal). For example, there are piezoelectric devices which produce voltage when stress is applied, optoelectronic materials that produce electrical current when light is applied, magnetoresponsive materials that change shape when a magnetic field is applied, and smart polymers which change shape under various environmental stimuli. This last category is the material that we work with, and we describe three different types of stimulus-response polymers (aka smart polymers) below.

Stimulus-response polymers
Stimulus-response polymers, when coated on a surface, are commonly referred to as a “nanobrush”. In sensors, these materials are highly useful since the phenomena driving the sensor signal occurs at the interface between the sensor surface and the surrounding
environment (see image below, top panel). When a nanobrush is coated on an electrode, there is an opportunity to utilize the controlled actuation feature to create a “smart sensor” (see image below, bottom panel). If a small external stimuli can be used to actuate the nanobrush (the example below swells or contracts when stimulated), we have a mechanism to control some aspects of the local sensor environment at the nanoscale. The concept is similar to that used by the pharmaceutical industry for controlled drug release. We work with nanobrushes that respond to heat (PNIPAAM and alginate), electric pulses (Nafion 117), or changes in pH (chitosan) and we use these materials in development of biosensors. See our previous discussion for why we chose nanobrushes to measure bacteria (we borrowed the idea from a squid!).

\[ \text{cations} \rightarrow \text{electrons (signal)} \]

\[ \text{anions} \rightarrow \text{electrode (carbon, metal)} \]

(Top) Fundamental principles of obtaining an electrical signal (electron) at the surface of an electrode (known as the Helmholtz theory). (Bottom) Nanobrushes allow us to engineer sensor strategies for controlling the electronic signal obtained on a sensor. When the rushes are extended, the signal is low, while the signal approaches a “clean” electrode when the brushes are collapsed.

The question looms: is this stimulus-response material “smart”? In our opinion, no (at least not by itself). The material certainly has the sensing-actuation aspects of a smart system, but the material alone lacks the control phase. In nature, there are a myriad of examples that use nanobrush structures, and the control aspect comes from the organism itself (complex networks of cells and tissues which are all interconnected with a
central processing center, such as the brain). In our engineered devices, we are building cloud based data analytical tools to process the data and then send a signal back to the sensor in order to impart a true control (or response) feedback loop. If this can be accomplished, we may achieve some level of smart sensing, as we would have the sense-analyze-respond triad within the system. We are using this smart nanobrush system to develop bacteria sensors inspired by the Hawaiian bobtail squid (link here).

Hills et al developed a mechanism for capturing bacteria in the extended nanobrush state, noted as Ex(cap), and then measuring a signal during the nanobrush collapsed state, noted as COL(meas).

Smart polymers are a critical component to these biosensors, as this is the “brush border” structure we are making as recently described by Hills et al. We did not invent the idea for selective bacteria with a brush, it is quite common in mammalian systems. The image below shows a few examples of “brush borders” found in various animal tissues (top), and the polymer “nanobrushes” we are creating in the lab. Both in nature and in our engineered system, these brushes respond to external stimuli, and are used to capture bacteria.
We use these nanobrush electrodes to measure bacteria in food samples. We are currently testing fresh produce, tomatoes, and other food products (see below for example). Our current work aims to improve the “smart” aspect of this system, and we have more questions than answers at this point.
When we couple the stimulus-response nanomaterial with a smart phone for analyzing sensor data and controlling the actuation, we converge on the early stages of a truly smart system. We published the code for the cell phone analysis in an open source journal, and it is free to anyone who wants to use it (Rong et al). We also published a user’s manual in English, Spanish, Portuguese, and Chinese in the hopes that other people would take the idea and make better technologies for the masses (it cannot be patented now that we released it). We hope that open source ideas can be used to lift many boats, not just one yacht.
Smart phone machine learning app (open source) for impedimetric biosensor data.

Smart systems are intriguing, and useful for everyday purposes. At the end of the day, our system will never attain the “intelligence” of the small nocturnal squid we are inspired by, but we continue to improve the sensing-actuation properties of the nanomaterial, and also the control aspects of the smart phone. The race between squid-inspired sensors and bacteria is officially on!