

Electronic Noses Sniff Out New Markets

by Jennifer Ouellette

A nose-on-a-chip for \$5 may be a breath away

Researchers and manufacturers alike have long envisioned creating devices that can “smell” odors in many different applications. Thanks to recent advances in organic chemistry, sensor technology, electronics, and artificial intelligence, the measurement and characterization of aromas by electronic noses (or e-noses) is on the verge of becoming a commercial reality. More than 100 prototype artificial noses developed by a handful of companies currently operate in industry, and over the next 5 to 10 years, the technology will likely find a wide range of commercial applications, including medical diagnostics, environmental monitoring, and the processing and quality control of foods.

“While electronic noses were initially developed as laboratory instruments, science is now moving the technology out of the laboratory and into the workplace, enabling measurements based on smell to be made at the source,” says Steven Sunshine, president and CEO of Cyrano Sciences (Pasadena, CA), a start-up and one of several companies seeking to commercialize the technology. These companies also include Neotronics (Essex, England), Alpha MOS (Toulouse, France), Bloodhound Sensors (Leeds, England), and AromaScan (Manchester, England).

An electronic nose is a sensing device capable of producing a digital “fingerprint” of specific odors. It consists of a chemical-sensing system—usually an odor-reactive polymer sensor array—and a pattern-recognition system, such as an artificial neural network (ANN). This combination enables the device to process new odors based on patterns of aromas created by earlier experiences, which is much the same way the human olfactory system works. According to Sunshine, the human nose uses a complex system of interconnected receptors and neurons, which conduct signals directly to the brain’s limbic system. “When an aroma is sensed, the molecules from the vapor interact with numerous receptors, causing them to send a signal to the brain,” he says. “The pattern of signals is then recognized and interpreted by the brain based on prior training.”

Similarly, each sensor in an artificial nose array is designed to respond to different odors. According to

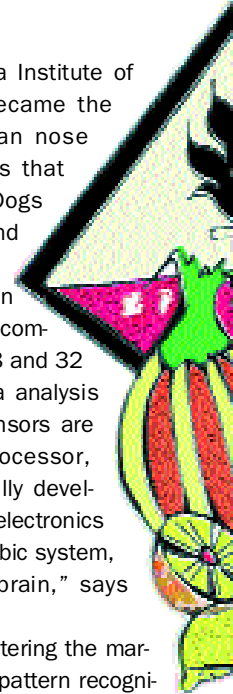
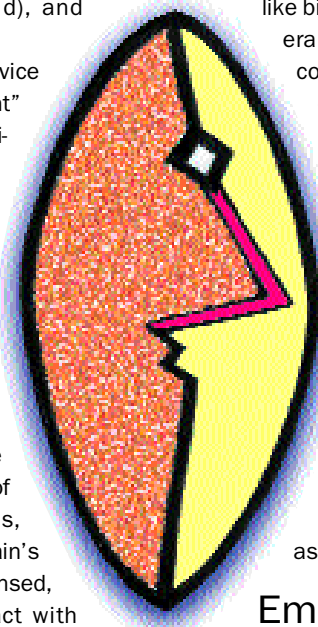
chemist Nathan Lewis of the California Institute of Technology (Caltech), whose work became the basis for Cyrano’s device, the human nose boasts about 1 million odor receptors that work in tandem to process smells. Dogs have about 100 million receptors, and hence process and distinguish among scents 100 times more effectively than the average human. In contrast, most commercial electronic noses have between 8 and 32 sensors working as receptors. For data analysis and interpretation, signals from the sensors are electronically connected to a microprocessor, which interprets the data using specially developed pattern-recognition software. “The electronics replaces the neurons in the olfactory limbic system, and the microprocessor acts as the brain,” says Sunshine.

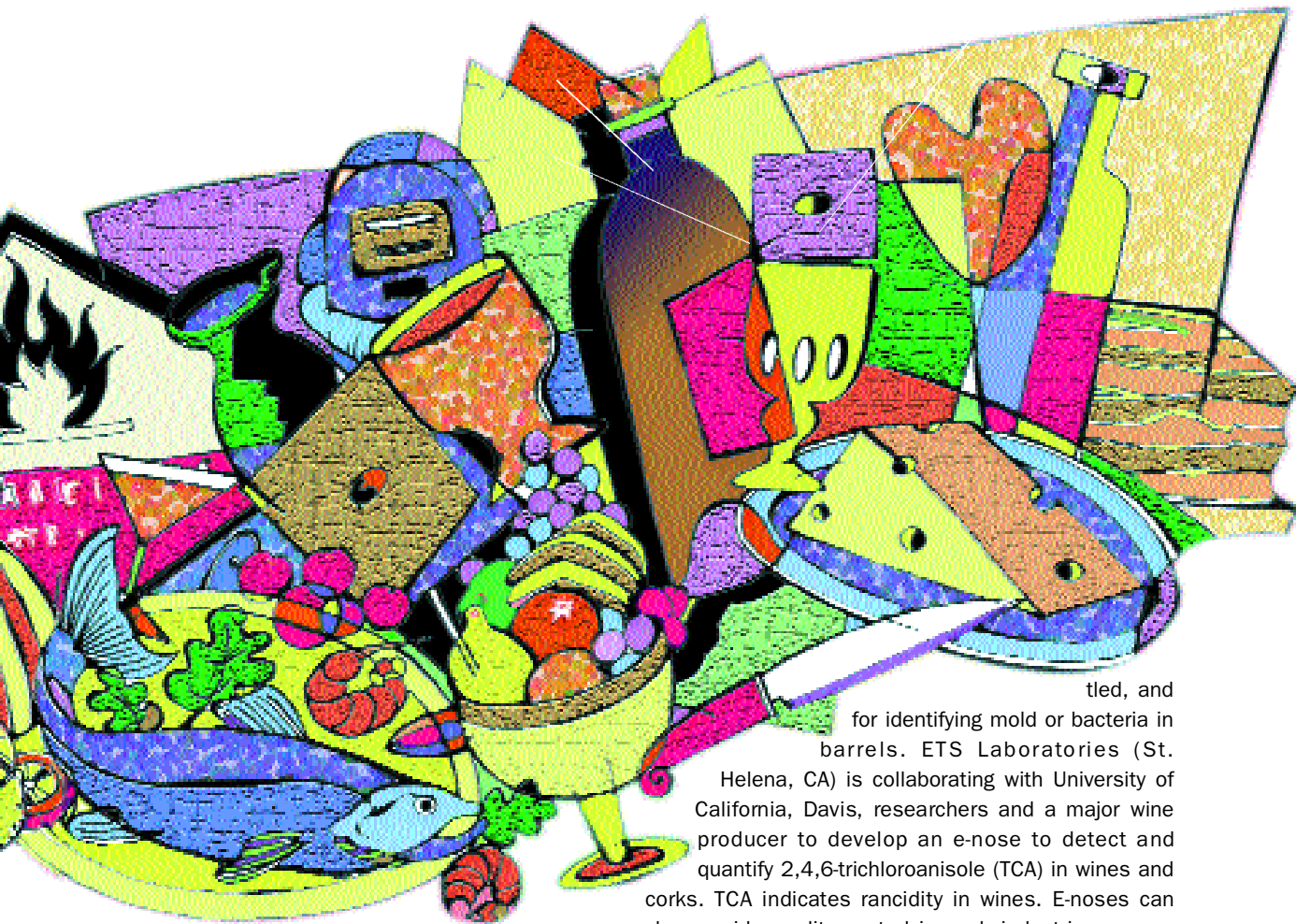
Most commercial electronic noses entering the market today employ some sort of ANN for pattern recognition (see box, p. 28). This is because ANNs employ a large number of interconnected processing elements working in unison to solve specific problems, much like biological nervous systems. ANNs are very general pattern-recognition systems that one can configure, through a learning process, for specific applications, such as identifying a chemical vapor, says Paul E. Keller, a scientist who is working with Pacific Northwest National Laboratory (PNNL) in Richland, Washington.

“In general, ANNs are well-suited to problems that people are good at solving but computers are not, including pattern recognition and forecasting,” says Keller, who once worked on developing e-nose algorithms. “ANNs, like people, learn by example. However, unlike the human capability in pattern recognition, the ANN’s capability is not affected by subjective factors such as working conditions and emotional state.”

Emerging applications

By far, the largest and most immediate commercial market for electronic noses is the food industry, where the devices can augment or replace current methods of quality control, which include gas chromatography and human experts. Gas chromatography is expensive and time-consuming, and it lacks





built-in data-analysis capabilities. Human experts are subject to such variables as fatigue, health, allergies, mood, and personal preference, which affect the reliability of the sensory evaluation. "What the electronic nose now offers is the ability to put down a descriptor for an odor or flavor in terms of hard figures," says John Hulbert, managing director of Bloodhound Sensors. And it does so with sampling times of mere seconds.

Because of these advantages, e-noses are currently being considered for inspection and quality grading of food by odor (such as checking mayonnaise for rancidity or monitoring the ripening of cheese) and for fermentation control, automated flavor control, beverage-container inspection, and microwave-oven cooking control. Scientists at the University of Florida, working with Neotronics and AromaScan, have developed an electronic nose to ensure seafood quality. According to Maurice Marshall, one of the principal researchers, the device gave results that were in perfect agreement with FDA inspectors who participated in 43 tests on good and bad shrimp in early 1998.

Electronic noses also interest the wine industry as a way of sniffing out volatile acids before a wine is bot-

tlated, and for identifying mold or bacteria in barrels. ETS Laboratories (St. Helena, CA) is collaborating with University of California, Davis, researchers and a major wine producer to develop an e-nose to detect and quantify 2,4,6-trichloroanisole (TCA) in wines and corks. TCA indicates rancidity in wines. E-noses can also provide quality control in such industries as perfumes, household products, and pharmaceuticals, says Cyrano's Sunshine. Integrating the technology with household appliances, such as refrigerators and microwave ovens, could minimize the risk of food poisoning or ingesting spoiled food, especially for the elderly, who tend to lose their sense of smell.

Alan Gelperin of Lucent Technologies/Bell Laboratories adapted his e-nose system from an existing commercial device to distinguish between similar kinds of produce in supermarket checkout lines, such as different varieties of apples and oranges. NCR Corp. plans to introduce an ingenious device within a year that uses optics-reflectance spectra from the surface of produce items to identify them. The NCR system, however, has difficulty distinguishing between similarly colored items, such as a green pepper and a cucumber, which would be a problem if they were differently priced.

Gelperin, who works on the neurobiology of odor-memory storage, thought odor sensing could resolve the problem. He achieved 76% differentiation between similar-colored produce items under good conditions with data gathered from a single one-second sniff. Gelperin filed a patent for his device in October 1997. Although more advanced algorithms could further improve performance, Gelperin believes greater gains will likely come from improving sensor composition for the range of odorants

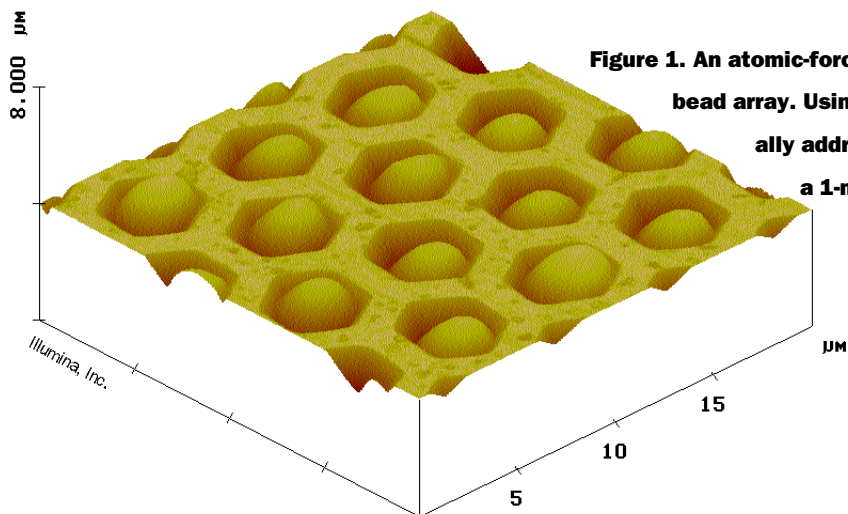


Figure 1. An atomic-force micrograph of a randomly ordered self-assembled bead array. Using etched imaging fiber bundles, thousands of individually addressable sensing elements can be secured at the tip of a 1-mm-diameter imaging bundle.

present in produce aromas, so as to provide stronger signals from more sensor channels as input to the pattern-recognition algorithms. He is also exploring other possible applications for Lucent to market, such as monitoring the odor of electronic chips—and thus their temperatures—to prevent circuitry from overheating.

“Anywhere there’s something that emits an odor that could be a useful signal, this technology could play a part,” Gelperin says. However, he warns, real barriers exist to transferring the device from the laboratory to the real world of the supermarket.

Further in the future, electronic noses may sniff body odors—such as from breath, wounds, or body fluids—to identify possible medical problems. For example, breath analysis can indicate gastrointestinal disorders, sinus problems, infections, diabetes, and liver disease. Blood and urine-odor analysis can reveal liver and bladder problems. “While smell is still used as a secondary diagnostic tool in some illnesses, the lack of a reliable and objective analytical tool has prevented its widespread usage in modern medicine,” says Sunshine. He suggests that Cyrano’s innovative hand-held e-nose could bring a resurgence in the use of smell for noninvasive disease diagnosis. The company is developing a hali-

tosis monitor in conjunction with the University of California, Los Angeles, School of Dentistry, as a means of detecting decay and bacterial infections. Similar devices could eventually be used for birth control and to determine the time of ovulation in fertility treatment.

AromaScan has produced a prototype e-nose for examining wounds to detect infections and gangrene, which has been tested at South Manchester University Hospital in England. The company is also developing a hand-held unit to pinpoint the presence of common infections, such as pneumonia, by sniffing body odors. According to PNNL’s Keller, some researchers have also proposed using e-noses to provide an olfactory input to telesurgical virtual-reality systems, so that students using the systems get the smell as well as the feel of surgery. “The electronic nose would identify odors in the remote surgical environment, which would then be electronically transmitted to another site where an odor generation system would recreate them,” he says.

Environmental and security applications, such as detecting explosives, also grace the horizon. For example, AromaScan’s system can monitor human exposure to hazardous chemicals in the workplace. Cyrano is

researching vapor detection of TNT and new techniques for land-mine detection. Although Keller has since moved on to other projects, his involvement in e-nose technology resulted from PNNL’s interest in applying the device to the identification of toxic wastes and household odors, analysis of fuel mixtures, detection of oil leaks, monitoring of air quality and factory emissions, and testing of groundwater odors.

David Walt of Tufts University has developed an e-nose using arrays of fiber-optic sen-

ANN who?

An artificial neural network (ANN) is an information-processing system inspired by the way the mammalian brain processes information. ANNs are collections of mathematical models that attempt to emulate some of the observed properties of biological nervous systems.

An ANN consists of a large number of highly interconnected processing elements—essentially equations known as “transfer functions”—that are analogous to neurons and are tied together with weighted connections that are analogous to synapses. A processing unit takes weighted signals from other units, possibly combines them, and gives a numeric result. The behavior of neural networks—how they map input data to output data—is influenced primarily by the transfer functions of the processing elements, how the transfer functions are interconnected, and the weights of those interconnections.

Learning typically occurs by example—through exposure to a set of input-output data, where the training algorithm adjusts the connection weights (synapses). These connection weights store the knowledge necessary to solve specific problems.

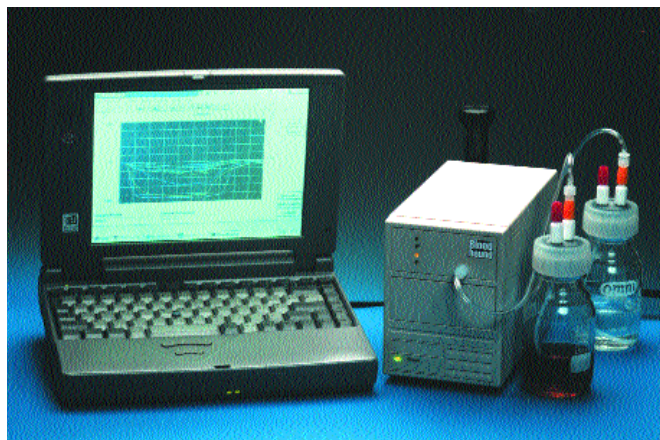


Figure 2. Bloodhound's BH 114 system uses tuned arrays of multiple gas sensors to measure and record fragrances, odors, and mixtures of volatiles as digital patterns.

sors, in which environmentally sensitive fluorescent dyes are incorporated into the polymers. The device is being further developed

to detect explosives and illegal substances, and for nucleic acid sensing for DNA sequencing and cell biology. Researchers at NASA's Jet Propulsion Laboratory and Caltech are working to apply e-noses in arson investigations—to sense the presence of flammable accelerants such as gasoline—and to use them for detecting hazardous fumes and gas leaks in refineries and on oil-drilling rigs.

In a more unusual application, Ron Lacey of Texas A&M University is developing an electronic nose with a 10-sensor array for potential use by the hog, cattle, and poultry industries to monitor and measure odor levels. Odor complaints are a common air-quality concern for agricultural operations, and environmental commissions currently rely solely on the subjective human sense of smell to make their determinations. "We're trying to determine how strong and how bad the odor is, along with the frequency of the smell and the duration—how long it lasts and when it smells the most," says Lacey.

Challenges remain

One primary challenge to the application of electronic noses in real-world settings is the extreme sensitivity of the polymer sensor arrays to moisture. "Water is a very volatile compound," explains Hulbert. "We have a water-based odor system in our nose, so we don't realize it, but there's a lot of water about." Water actually has a strong smell to sensors, and its presence tends to smother the subtle qualities of a chemical vapor, making it difficult to detect odors in low concentrations. Commercial e-nose systems surmount this obstacle by incorporating separate sensors to monitor relative humidity in the sniffing environment; and the device is then calibrated accordingly.

Another difficulty is a lack of robustness and the short lifetimes of the gas sensors currently used. As sensors burn out and are replaced, they lose their memory of previously learned odors, and the replacement sensors must be retrained. "If you have a complex array with a complex pattern, and you can't replace them with an identical array set, you've lost your ability to identify the learned odors," says Walt. To address this problem, he has devised a new manufacturing method to make the sensors used in his fiber-optic electronic noses. He has

also founded a start-up venture, called Illumina (Cambridge, MA), to commercialize the technology. Walt's sensors are based on tiny polymeric microbeads, which are made in batches of some 6 billion identical beads per milliliter (Figure 1). This allows Illumina to achieve a strong response over long periods of time, because sensors in the array are replaced with others made in the same batch as the originals.

SMart Nose (Zurich, Switzerland) has developed a new generation of e-noses that allows the direct characterization by mass spectrometry of volatile organic components from liquid and solid samples. As a result, one gets a highly reproducible and precise fingerprint of each odor, without the narrow selectivity, moisture sensitivity, and short lifetimes of the gas sensors used in current devices. Hewlett-Packard recently marketed one such e-nose system, and Perkin-Elmer is also interested in bringing mass-spectrometry-based electronic noses to the marketplace. However, Hulbert points out that such systems are expensive, and their large size limits portability, making them more suitable for higher-end applications.

"It's a transition period, and I think it will be at least five years before we see broad use of electronic noses," he says. "But once we have devices that end users can employ with confidence and very little modification, we'll see a great deal of growth in this industry." Bloodhound's system is shown in Figure 2.

As with most commercial markets, the final consideration is cost. Electronic-nose systems currently cost about \$40,000 to \$50,000 apiece. However, Cyrano plans to introduce the first portable hand-held e-nose to the general market this summer (Figure 3). The company ultimately intends to develop a nose-on-a-chip, trademarked Nose-Chip, that will sell for between \$5 and \$10 each—a significant step in reducing cost. "By aggressively pursuing this technology, we will reduce both the cost and the size of electronic sensors, thus enabling the technology to be incorporated into a vast number of devices," Sunshine says. "An inexpensive and reliable nose-on-a-chip may do for smell what the camcorder has done for vision. If interest continues at its current rate, smelling devices will soon become ubiquitous to our society." □

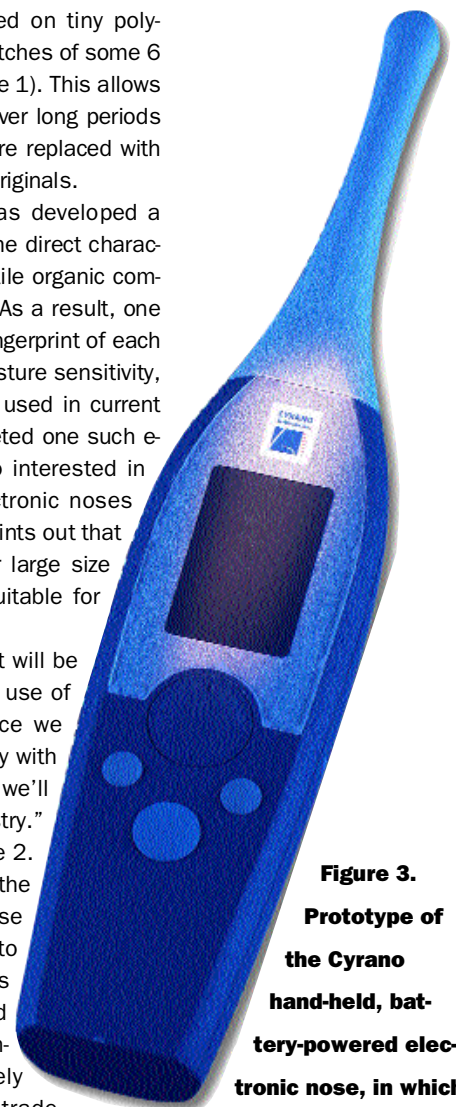


Figure 3. Prototype of the Cyrano hand-held, battery-powered electronic nose, in which vapors are pulled through the probe and across the sensor array; results are displayed on an LCD panel.