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A brief history of the Australian electronic nose

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Abstract

From the early 1970s, Australian research groups attempted to understand the chemistry, physiology and psychology of the sense of smell (olfaction) in humans and animals. This work identified a clear need for cheap, rapid and portable tools for measuring and identifying complex mixtures of airborne molecules that comprise what we know as smells. Collaborative work at UNSW, Sydney University and CSIRO produced a portable array of metal-oxide conductimetric sensors, coupled with multivariate data analysis, capable of a variety of smell-sensing tasks. Their prototype devices were among the first in the world. Research with evolving designs and the rapidly improving and ever-miniaturising electronics progressed the development of four versions (Mk 1–4) of the Australian electronic nose. These found many practical applications described below. Human breath testing for disease diagnosis, such as early lung cancer, is one of many challenges for future applications. Spinning off a company (E-Nose Pty Ltd) at the new Australian Technology Park, the researchers worked with a wide range of companies, government departments, and white-knight investors. The intellectual property was recently transferred to an international company based in Sydney, iOmniscient Pty Ltd, which is currently developing an updated version (E-Nose Mk 5) with potentially increased numbers of sensors and immediate remote data analysis. The founders' legacy lives on in universities, food and wine research centres, and engineering departments, where new sensing materials and artificial intelligence (AI) approaches are offering modern insights into creating and extracting information from e-nose signals. The paper ends with a brief review of current research and directions in e-nose technology in Australia.

Introduction

A human-made artefact that works remotely like some facet of a living entity is commonly called a "bionic xxx," "electronic xxx" or "artificial xxx." Most of the mammalian senses have been reproduced in this way, either to help those who have lost that sense (e.g. bionic ear implants), or to provide an artificial analogue (e.g. electronic nose, electronic tongue). This paper will describe the development of an electronic nose and its applications in Australia. As del Valle points out: "Electronic nose devices are sensor systems *bio-inspired* in the human olfactory system" (Del Valle, 2021). Inspiration is the keyword. Researchers have made no attempt to substitute medically implantable devices to provide olfactory perception for humans suffering loss of the sense of smell. Instead, to date, the electronic nose has served as a means of analysing complex airborne molecular mixtures and identifying their source, which usually provides a name for the smell, and its strength. The need to do so was identified from aspects of food technology, environmental science, and perhaps most importantly from medical diagnostics. The Australian E-Nose® typically comprised six metal-oxide semiconducting (MOS) sensors, a far cry from the six million olfactory cells with four hundred different kinds of receptor in a person. However, all these simple machines share the enormous advantage of being cheap (compared with people and the capital equipment of an analytical chemistry lab), running 24/7, and having an ability to be connected to digital clouds and global internets for practically instantaneous results.

What is a smell? The challenges of mimicking olfactory perception

A smell, or "odour," is a perception formed in the brain from the reception of airborne molecules, usually carried by the air, in a complex molecular mixture. Chemical analysis by slow and expensive methods of gas chromatography and mass spectrometry has shown that these complex mixtures may consist of hundreds of different molecular species. The molecules carried in the air emanate from a source, by which we label the odour experience, such as "floral" (from flowers) or "putrid" (from rotting flesh). There are almost as many names for odours as there are identifiable sources. In mimicking the human nose and brain, therefore, an e-nose needs to capture sufficient numbers of molecules from an odour source and correctly identify the source by name. Even if naming the incoming odour is not required, the device can inform on: general levels of smelly and non-smelly molecules in the air, the direction from which they are coming (usually measured by wind direction), and whether the composition of the molecular mixture is changing or has reached a preset alarm level. The ubiquitous nature of smells in human existence can lead the imagination to devise innumerable applications for a device that can measure and identify smells. Solutions hang on obtaining and treating the data from the devices.

Defining a smell in terms of the data from an e-nose can become a non-trivial part of the problem. We have to validly (correctly) and reliably (repeatedly) recognise the odour's name (origin). Australian researchers made world-leading headway in the analysis of e-nose data, using the strategy of storing the incoming sets of data and then applying statistical analysis to match data from an unknown source with those held in memory. In this regard, the e-nose does what we know by introspection to be the process of recognising an odour in the human mind, by the interrogation of one's memory. So while we may use analytical chemistry to aid the identification, complete, or even partial, knowledge of the molecules involved is not necessary.

When smelling, we humans can sniff the air, usually rapidly, to determine if our judgement is confirmed or if the smell is changing or strengthening. Animals apply this method to determine the identity and direction from which the smell is coming. To mimic human smell perception, the e-nose needs a mechanism by which it can update its data within a practically useful interval, and to do so it must be able to reset its data to a base-line so that a new sample can be obtained and assessed.

What a smell is and how it is detected by the human nose helped define the challenges which the Australian researchers set out to meet, in the development of their e-nose device.

What is an electronic nose?

An electronic nose consists of an inlet system to deliver air carrying the odour to the electronic sensors, organised in an array. Each sensor usually responds strongly to a different family of airborne molecules, but can also respond to extra molecular species. The sensor array produces a measurable, patterned output (in our case voltages) responding to the components of the mixture of odour molecules. A data-processing system converts the voltages into digital form and is programmed to deliver the required information. There are electronic noses that are bench-top instruments with up to forty sensors for use, for example, in food processing plants. An example is the American Aromascan A32S with 32 conducting polymer sensors (Wilson et al., 2013). However, many exploit the portability of a few (three to six) small and low-powered sensors to widen the possible uses of an electronic nose in a variety of well-defined and specific field applications.

Electronic chemical sensors

Each electronic nose sensor provides non-specific information about the molecules it senses (Ollé et al., 2020). The principles of measurement include changes in the sensor of: conductance, temperature, optical properties, electrochemical potential, and mass (John et al., 2021). Electronic chemical sensors respond within a few seconds to properties of the airborne molecules, giving them a distinct advantage in speed of analysis over "traditional" chemical analytical tools (amounting to capital equipment in a chemistry lab) such as gas chromatography, spectroscopy, ion mobility spectrometry and mass spectrometry. The Australian e-nose took its lead from British researchers (Gardner, 1988; Gardner and Bartlett, 1994) who alerted its developers to the usefulness of metal oxide sensors for inclusion in an e-nose device. The advantages of these sensors were their reliability, speed of recovery, and non-specificity (responding to a wide range of molecular species).

Optional analytical chemical approaches to sensing include: metal-oxide semiconductors (MOS); conducting polymers for conductimetric measurements; surface acoustic wave and quartz crystal microbalance for mass measurements; and fluorescent chemical arrays for optical measurements (Barnett, 1999; Hibbert, 1999; Khorramifar et al., 2023).

Australian electronic noses have mostly used variants of metal-oxide sensors, typically those marketed by the Japanese company Figaro Electronics (*Figaro Engineering Inc.*, 2018), and known as "Taguchi" sensors, after their inventor (Taguchi, 1962). These sensors work when a gas, often a "volatile organic compound" (VOC), adsorbs on the heated sensor and reacts with the metal oxide, causing atomic vacancies in the surface which result in a reduction of electrical resistance. Typically, three to six sensors are exposed to the test atmosphere and the output (a voltage across a resistor in series with the sensor) is recorded at suitable intervals, usually seconds. See Figure 1 (overleaf) for the workings of a Mark 4 E-Nose.

Figure 1: Mark 4 E-Nose by Enose Pty Ltd showing six sensors. (Photo G Bell).

If the atmosphere being tested has unchanging levels of the sensed chemicals, the output will be essentially constant (see Figure 2a). If the device "sniffs" the atmosphere containing active chemicals, the signal will rise and then fall away back to the baseline (see Figure 2b).

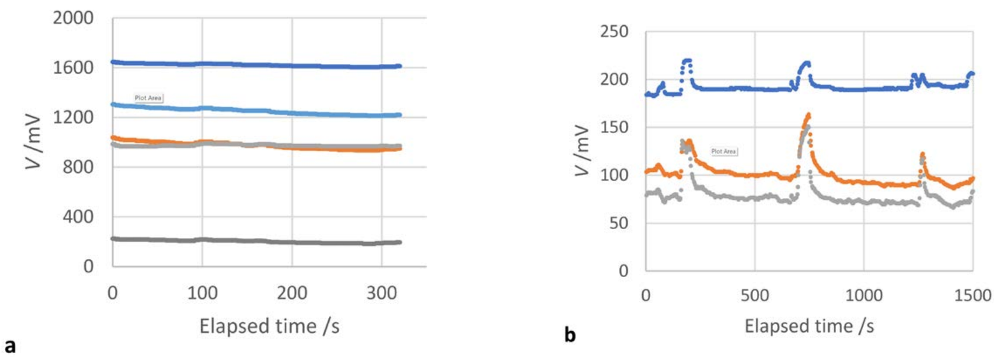

Figure 2: (a) Continuous signals from five sensors near a site in a meat works. (b) Varying signals from three sensors moving over ground with buried truffles. (Unpublished data of the authors).

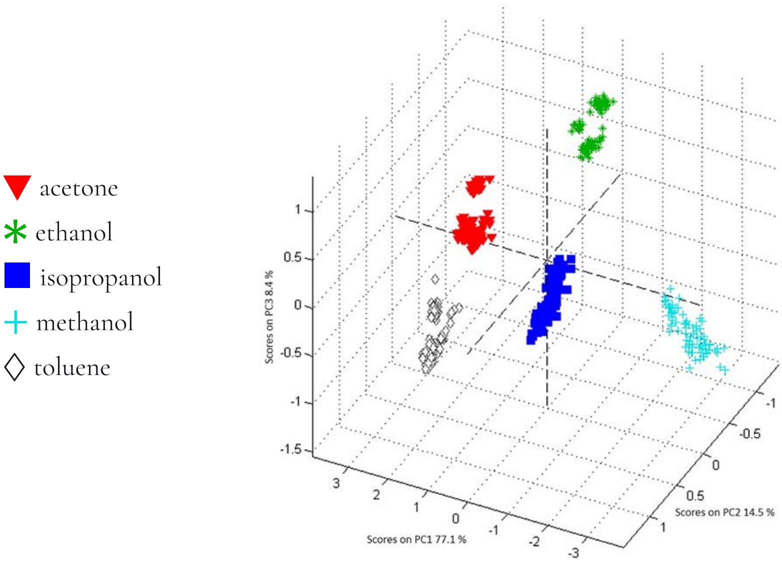

Figure 3: Discrimination among organic solvents using a five-sensor electronic nose, with principal components analysis of row-standardised data. Used with permission of Dr Surachet Phadungdhitdhada.

The response of a chemical sensor will depend on the kind of airborne chemical and its concentration. It is not possible to identify a chemical from the measured voltages alone, but by taking patterns of responses, a pattern or *fingerprint* may be obtained, to be compared against a library of previously obtained patterns from expected chemicals, i.e. odours. In the example of Figure 3, five common volatile organic solvents were successfully distinguished by a five-sensor e-nose using a simple multivariate approach (principal components analysis) on sensor data that were row-standardised to take out the effect of concentration of the target chemical. (It is coincidental that in this case there are five sensors and five targets, but, in general, the more sensors, the greater the discriminating power).

Many kinds of multivariate statistical analyses have been used to classify or quantify electronic nose data. A method that exploits Bayesian statistics to give the probability that an unknown odour is a particular target chemical was patented by E-Nose Pty Ltd in 2007 (Hibbert and Bell, 2007), and recently reviewed (Hibbert, 2024). With the current interest in AI, it is not surprising that the possibility of artificial intelligence approaches using "deep learning" artificial neural networks (LeCun et al., 2015) has already been shown to be useful in odour identification by electronic noses (Wang et al., 2023).

Australian electronic noses

Research into electronic noses is now popular across the world, led by institutions in the People's Republic of China (PRC). A recent Scopus search on *electronic nose* or *e-nose* gave 11,780 documents, of which 4062 were from the PRC, more than double the next two countries (USA, 1,097 publications and Italy 1,025 publications). Australia with 230 publications is in 13th place, but much of the output from Australia is in commercial projects or a small number of patents. Publications commence in the early 1990s, some time after the inventions of chemical sensors by Taguchi (1962) and Wilkens (Wilkens and Hartman, 1964) were given an impetus by modern electronics and portable computing. Warwick University in the United Kingdom claimed (*University of Warwick*, 2016) the first commercial electronic nose (Pearce et al., 1993), which used Taguchi's metal oxide sensors.

CSIRO (Commonwealth Scientific and Industrial Research Organisation)

After World War II, the CSIRO's Division of Food Science and Technology was tasked by the Australian Federal Government with serving the Australian food industry and its need to improve the quality of food products for both the Australian domestic and export markets. Its Food Science Laboratory, in Sydney, included a group of scientists working on the chemical basis of food acceptance. Out of this emerged Graham Bell's team working on the anatomy and physiology of the sense of smell and, later, the electronic nose. In work that began in the 1980s at CSIRO, it was hoped that the physiology and anatomy of the mammalian nose and brain would lead to an understanding of human perception and chemistry of food appreciation. While work at the CSIRO's Food Research Laboratory also developed useful ways of measuring food appreciation of manufactured and fresh foods, and made a significant contribution to Australian food exports, work on the rat and mouse brain yielded new information of how specific airborne molecules became "encoded" as odour-specific *patterns* in the forebrains of these animals (Bell, 1997, 1999; Bell et al., 1987a, 1987b). The latter discoveries became an incentive for the Australian researchers to attempt to produce odour-specific patterns of data in an array of artificial electronic chemical sensors, that were at that time becoming commercially available (Barnett, 1999).

The initial aim was to develop highly sensitive and specific chemical sensors derived from nasal receptor physiology. The Nobel Prize-winning discoveries of genetic code for olfactory receptors embedded in the nasal epithelium of mammals was made by Buck and Axel in 1991 (Barwich, 2020), which opened the possibility to clone receptors for specific odour molecules, thereby creating an odour-specific man-made biosensor. After a brief collaboration with Linda Buck, it was concluded that, even if successful, the cloned biological materials in the biosensors would suffer from lack of robustness and short operating lifetime (Barnett, 1999). Since most odours of interest to the food industry, and indeed for wider use, consist of mixtures of large numbers of chemical species, the difficulty of achieving biologically-based, robust, chemical sensors proved prohibitive. Instead, the forms of this work moved to the development of an electronic nose suitable for applications in industry. The CSIRO team resolved to create an array of electronic sensors, as proposed by the Warwick University scientists (*University of Warwick*, 2016), using existing commercially available metal-oxide sensors. The paradoxical virtue of these sensors was their imperfect yet reliable specificity to families of airborne chemicals. As informed by the work of Gardner, the team started work on the statistical treatment of the complex data from the sensor array.

One of the team of CSIRO scientists, Donald Barnett, created the first CSIRO electronic nose: a sensor array housed in a small stainless-steel chamber through which gases and samples of smells could be pumped. The voltage responses from the Taguchi sensors were captured and fed to an early form of desktop computer. David Levy, formerly of the University of Natal, joined the CSIRO team and later moved to Sydney University. His expertise in neural networks as well as electronic design, was a timely contribution.

University of New South Wales (UNSW)

At around the same time as CSIRO's work, the new UNSW Chair of Analytical Chemistry, Hibbert, brought an interest in chemometrics and electrochemistry to join a thriving electroanalytical group at the University, working in flow-injection analysis, led by Peter Alexander. This resulted in publications on volatile alcohols (Di Benedetto et al., 1996) including identification of beers (Alexander et al., 1998).

Their work came to the attention of the public when the two scientists tested their electronic nose in the Sydney Harbour Tunnel at its opening in August 1992 (Jinman, 1992). While optimising the ventilation of the tunnel, the operators had managed to cause a compression of the tunnel exhaust fumes in the last 100 m before the northern exit. The Australian Broadcasting Corporation's (ABC) "7:30 Report" accompanied the professors and their electronic nose through the tunnel, with Hibbert remarking that the air in the tunnel was a better quality than in the CBD (Central Business District). This was until they saw the wall of white fumes in front of them. True to form, the electronic nose duly went off scale, and Hibbert was invited to say on the evening news that people would die if they ventured down the Harbour tunnel. Adjustments to the ventilation were quickly made and, on a return pass-through, the tunnels were clear.

The UNSW group attracted further attention when their e-nose was used to identify red and white wines for the ABC Science program, "Quantum." Ethanol is the primary component of alcoholic drinks. There have been many attempts to use electronic noses to classify alcoholic drinks, especially the kind, origin, and year of wines (Gonzalez Viejo and Fuentes, 2022). A trained sommelier can tell a chardonnay from a shiraz by its "nose," but could a chemical sensor? The "Quantum" segment showed Hibbert on Bronte beach in Sydney's Eastern Suburbs pouring wine into three glasses: "one for the interviewer," "one for the Professor," and "one for the electronic nose." He then waved a tube above the electronic-nose's wine glass, looked at the screen of the computer and declared, "It's a chardonnay." At the time the instrument could tell a white wine from a red wine, and the training set consisted of only half a dozen quite distinct wines, so although it made for an entertaining TV segment, science was not greatly advanced; although it was a start. The Australian Skeptics challenged the UNSW electronic-nose team to correctly identify wine of the Skeptics' choosing. The academics noted that the electronic nose could only identify wines it had already smelled and added to its database. The Skeptics were unwilling to provide a suitable training set (i.e. several bottles of different, and hopefully high-quality wines) and were satisfied by a presentation from Hibbert at their national conference. Use of an e-nose on wine was not pursued by the UNSW group, but has been attempted by other Australian scientists (Cynkar et al., 2010).

CSIRO joins UNSW at the Centre for Chemosensory Research

In 1997, several members of CSIRO's sensory research team left CSIRO and established the UNSW's Centre for Chemosensory Research. This facilitated valuable interaction with the UNSW School of Chemistry, School of Medical Science, and Departments of Anatomy and Physiology. In addition, Associate Professor David Levy had been appointed to the School of Electronic Engineering and Computer Science at Sydney University, closely located to the new Centre, and he introduced to the group Bashan Naidoo (from South Africa), Dr. Arvind Srivastava, and Master's student Winston Wu, all of whom helped develop the device and software. Together they became one of the world's most active e-nose research groups. The collaboration led to work on two fronts described in detail below: **A**. Development of e-nose hardware and software; **B**. Development of e-nose applications. Client companies brought problems for the e-noses to be tested on. The Centre offered services on various aspects of sensory science to a number of Australian and international clients, and these are discussed in section **B**.

A. Development of the E-Nose

In 2003, E-Nose Pty Ltd was launched at the Centre, as a commercial company owned by a core of shareholders from the scientific group.[1] Devices known as E-Nose Mk2, 3 and 4 (see Figure 4) were designed and tested and several patents were granted (Barnett et al., 2005a; Barnett et al., 2005b). There was a considerable amount of invention, and the electronic hardware was "tailored" to meet client expectations and functional demands, such as changing of sensors, or combining e-nose data with other technological data (wind, temperature, humidity and vision). Several printed circuit boards were designed at this time by Sydney University's Winston Wu. Communication electronics were added to Mk 4 (Figure 1), allowing the device to transmit its data on the internet, and to call its owners via the mobile phone network. Mk 3 and Mk 4 enabled the company to offer services to a number of Australian clients who needed assistance with wide-area smell issues, such as waste recycling and meat processing, whose odours were the subject of public complaints. The company was awarded *an Innovator of the Year Award* by Frost and Sullivan in 2008, Figure 4.

Figure 4: E-Nose Pty Ltd Devices with Frost and Sullivan Innovation of the Year Award (2009)

B. Development of E-Nose application

Each problem set for the device required an amount of application development. This involved setting-up the e-nose/s in the "field" as required: building secure water-resistant housing, which could nevertheless "breathe" the outside air, supplying the device with appropriate power (e.g. portable batteries or connected to an uninterruptable power supply) and connected to the mobile phone network. The clients' problems were never not challenging, as can be discerned from the project summaries which follow.

B1. Wide area monitoring projects

E-Nose Pty Ltd had been working on monitoring air pollution using electronic noses since 2004, and the first sale of an industrial E-Nose was to SE Water Ltd, a Melbourne water-treatment company. Since then, the device has been developed to meet customer needs, with outright sales of around 50 devices and many service contracts for renting devices.

The company's devices were tested in several countries, including Japan, Philippines, Hong Kong, Chile, South Africa and New Zealand. Summaries of the kinds of tasks and their results, include:

a) E-Nose Pty Ltd monitored oil industry sites on Sydney Harbour and at the Port of Adelaide. Both projects concerned penetration of nearby residential areas by fugitive odours from oil or bitumen distribution plants. The device identified the sources of the odours — which came from the client's site and which did not — and how far the odour was invading community housing areas, and at what concentration. In Sydney, a monitor recorded oil industrial odours continuously for three months and was logged remotely and reported to the client weekly. The data became the basis for conflict resolution, demonstrating that

1 Brynn Hibbert, Graham Bell, Don Barnett, Brian Crowley, David Levy, Winston Wu and Arvind Srivastava.

the client companies cared about the neighbouring communities. (Clients: Shell Oil (Australia) and Shell Bitumen (Australia)).

b) Hong Kong's waste treatment facility produced odour in vast air volumes, carrying waste-treatment odours to residents. Working with local Chinese environmental consultants, E-Noses monitored odour released from a large waste-treatment operation in the New Territories, at some large apartment blocks three kilometres across the waters of Junk Bay. Continuous monitoring proceeded for one year. Data informed the HK EPD (environmental authority) about which site-sourced odours were reaching the residential towers and when. The data were used to manage operations of the waste facility and reduce the concerns of residents.

c) Biofilters are very large tanks, the size of a large swimming pool, containing plant and other materials which filter air from a smelly part of a factory (such as a meat works) to remove its smell. Waste-processing odour from biofilters in New South Wales were monitored using E-Noses. The results demonstrated which filters were saturated (no longer effective) and which needed refurbishment, to avoid community smell issues resurfacing. In addition, gas was sampled from varying depths in a biofilter and was fed into an E-Nose, thereby allowing precise assessment of the efficacy of the biofilter.

d) Long-term monitoring of the large Melbourne Resource Recovery Facility showed which parts of the site presented the biggest odour issues and that neighbouring activities (non-client) were also contributing to odour reaching a suburb, downwind. The efficacy of odour abatement methodology and various chemical sprays was demonstrated using the E-Nose, and guided the client toward the best management practice for their operations.

e) At Coffs Harbour, NSW, a large waste management facility was the subject of complaints by residents and shoppers at a local shopping mall. An odour audit by e-noses on the rooftop of a motor vehicle, at positions across the site three times during the day demonstrated which area had the highest odour and where it was emanating from. It was shown that odour increased and decreased at various points on the site according to the time of day. The contribution of the site-odour to ambient air flowing across the site was measured, and formed a basis for confidence by management in answering community concerns. After new waste-gas-combustion equipment was installed, the work was repeated and the efficacy of the investment in new equipment was evaluated.

f) Disgusting animal odours disturbing local residents in Nambucca Shire NSW: Long-term monitoring at two sites in the hills adjacent to a pig farm helped resolve a bitter dispute between residents and the farm operator. The devices provided objective measurements that tallied (independently) with diary reports kept by the residents. The Shire council used the data to quietly resolve compliance issues in what had been a highly acrimonious situation.

g) A three-month monitoring study was undertaken, using a pair of E-Noses, simultaneously, at two boundaries of a cattle feed lot, following complaints from the suburban residents and the West Echuca Primary School, Victoria. The study showed which odours were coming from the emitting sources on the feed lot, and which were not. Odours which were the responsibility of the emitter were identified, using wind direction and both quality and quantity measurements by the E-Noses, as well as duration and time, 24/7, of the high-odour events. Some relevant odours travelled only as far as the houses, while others, on the opposite wind direction, reached only the school. The information had a positive effect on odour management of the offending cattle feed lot and on community morale.

h) Fugitive emissions from sewage-pumping stations across south-east Melbourne and Port Phillip Bay were a cause for concern by environmental authorities and plant managers. An early version of the E-Nose was used to monitor these emissions from sewage-treatment plants and large areas of soil development, to determine what level of odours were likely to give rise to complaints from residences, and when the odours occurred. The Victorian EPA (Environmental Protection Agency) indicated its pleasure that these companies were acting with responsibility toward their communities.

B2. Security applications of the E-Nose

Interest has been shown in deploying e-noses to protect people from fumes, dangerous gases, unexploded devices, and to sniff-out drugs in prisons. This indicates the general interest in e-nose applications. An E-Nose was developed to control graffiti vandalism by being able to distinguish the smell of spray paint and then immediately alert an appropriate authority by means of an integrated mobile phone. Later, video monitoring was introduced to assist in the apprehension of the vandals. The E-Nose provided vital information of when the smell was detected, thereby allowing the video record of the offence to be interrogated at a precise time. The "Graffit-E-Nose™" has been used successfully by local councils in combatting graffiti vandalism (Bell, 2010; Cook, 2011).

Public exposure came with the appearance of Bell and Hibbert on the ABC program, "The New Inventors," in 2008 when they won the People's Choice award for their episode. The authors presented this novel invention which had at the time demonstrated success in apprehending graffiti vandals in Sydney and Brisbane.

B3. Breath Diagnosis: cancers and diabetes

On the academic research front, the E-Nose showed its value as a potential diagnostic tool for detection, on human breath, of both lung and breast cancer (Herman-Saffar et al., 2018; Tran et al., 2010). The latter Israeli research was performed independently of E-Nose Pty Ltd and found evidence of breast cancer using the Mk 4 device, as well as testing its performance against a leading device from the USA. The comparison showed the Australian device to be superior. This result carries a clear promise that Australian e-noses will make a significant difference to the health of populations plagued by diseases that can be treated if detected early enough. We can look forward to exciting progress in the use of Australian e-noses in early diagnosis of lung cancer and, indeed, of early diagnosis of many other cancers, such as breast, bowel and abdominal.

Early work in collaboration with Diabetes Australia showed a three-sensor E-Nose using a Bayesian classifier on a multivariate normal distribution could distinguish between non-diabetic patients (92 % correct) and diabetic patients (82 % correct), particularly if their blood sugar was elevated (88 % correct).

B4. Animal Health: sheep diseases

Australia's sheep industry has been, since colonial times, a vital part of its economy. However, like many aspects of livestock management, the human labour involved in managing ever-increasing numbers of sheep that make a viable enterprise is becoming difficult to provide, and the need for technology to aid the sheep farmer grows. The Cooperative Research Centre for Sheep Production approached the E-Nose researchers with the problem of diagnosing sheep diseases automatically, using an e-nose. A Mk 3 E-Nose was provided to the CRC, and while it remains to be successfully applied to sheep races, a resulting key study on sheep by an associated university group proved its use in detecting diseases in sheep (Cramp et al., 2009). It is anticipated that e-noses will become used in many ways in the future, by combining their power to discriminate odours and identify their sources in agricultural settings.

Other Australian electronic noses

Electronic nose research continues around Australia. The group having the greatest academic output on the use of electronic noses for food and crop monitoring is the University of Melbourne Digital Agriculture Food and Wine Group, in the School of Agriculture and Food, Faculty of Veterinary and Agricultural Sciences, led by Associate Professor Sigfredo Fuentes (*The University of Melbourne*, 2024). The group has published on, inter alia, detecting bush-fire smoke-taint in grapes and wines (Fuentes et al., 2020; Summerson et al., 2021), early detection of aphids in wheat (Fuentes et al., 2021), *Fusarium oxysporum* infection in tomatoes (Feng et al., 2022), and detection of fraudulent rice (Aznan et al., 2022). The group stresses the low cost of their electronic nose, which is often used in combination with infrared spectroscopy. Their developed instrument consists of nine MOS sensors from Henan Hanwei Electronics Co., Ltd, China (Gonzalez Viejo et al., 2020), plus temperature and humidity sensors. Classification is by artificial neural networks with a variety of training algorithms. In (Gonzalez Viejo et al., 2020) the optimum classification of beer aroma by correctly predicting 17 volatile organic compounds detected by gas chromatography-mass spectrometry was a Bayesian Regularisation algorithm.

Other Australian groups which have published on a range of electronic nose applications which are compiled in Table 1 (see overleaf).

Table 1: Other Australian groups publishing on electronic noses

Group leader	Institution	Field of work	Example study
Russell Keast	CASS Food Research Centre. Deakin University, Burwood, Victoria	Food research, Consumer Analytical Safety Sensory	Sensory studies of broccoli (Hong et al., 2022)
Antonio Tricoli	The Australian National University, Canberra, ACT	Food quality and environmental monitoring	Review of electronic nose systems (John et al., 2021)
Dusan Losic	The University of Adelaide, Adelaide, SA	Novel sensing materials for cancer diagnosis	Core-shell nanostructured hybrid composites for volatile organic compound detection (Tung et al., 2015)
Amalia Berna	CSIRO, Canberra ACT	Food analysis	MOS for electronic noses and their application to food analysis (Berna, 2010)
Daniel Cozzolino	The Australian Wine Research Institute, Glen Osmond, SA and Hobart, Tasmania	Wine classification, sensory properties of wines	Classification of Tempranillo wines according to geographic origin (Cynkar et al., 2010)
Annette G. Dent	The Prince Charles Hospital, and The University of Queensland, Brisbane, QLD	Lung cancer diagnosis	Exhaled breath analysis for lung cancer (Dent et al., 2013)
P.J. James	Queensland Primary Industries and Fisheries, Yeerongpilly and Toowoomba, QLD	Animal welfare	Detection of cutaneous myiasis in sheep using an 'electronic nose' (Cramp et al., 2009)
Richard Stuetz	The University of New South Wales, Sydney, NSW	Environmental monitoring	Monitoring techniques for odour abatement assessment (Muñoz et al., 2010)
André van Schaik	International Centre for Neuromorphic Systems Western Sydney University, NSW	Processing sensor responses	Spike-time encoding of gas concentrations using neuromorphic analog sensory front-end (Rastogi et al., 2023)

Conclusions

Spanning five decades, the invention and development of the Australian E-Nose has demonstrated noteworthy excellence. It has followed a bumpy path, contending with variable incentives from the market and funding sources. However, it is safe to say that analysis of complex mixtures of airborne odours by arrays of chemical sensors is a technology whose time has come. The Australian E-Nose has been shown to add value to human enterprises and meet needs in several contexts: industrial processes; environmental management; air pollution control; security at sites vulnerable to graffiti attack; municipal-community relations; air quality in public and private spaces; and health and welfare through new forms of rapid and cheap diagnostics. Each iteration of the E-Nose (Mk 1 to Mk4) has made improvements to the device's hardware and software in response to market demand. These have included communications technology which has been advancing with the passage of the past two decades. The Mk 5 device being developed by iOmniscient Pty Ltd will exploit new electronics and perform rapid complex data analysis using remote "cloud" technology.

In future we will see many applications bringing greater safety and security to human life, aided by electronic noses of various kinds. Miniaturization and mass manufacture, combined with ever-improving software will make possible — and indeed commonplace — many new applications in industry, the home, the hospital, the military and wherever imagination takes us. Australia has made an important contribution to this field.

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