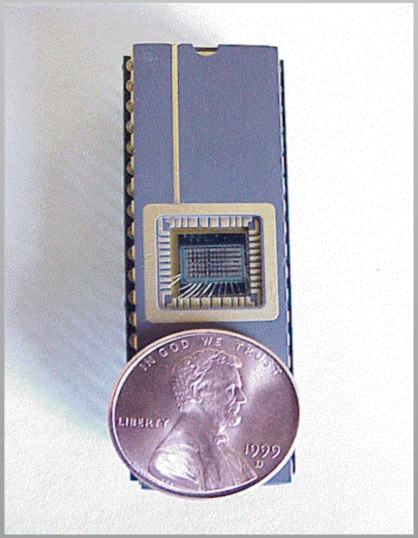
A Code in The Nose

“Olfaction: Natural and Artificial”

Rod Goodman
2008 Carnegie Centenary Professor
Edinburgh University
Scotland



Acknowledgements

This talk describes the work of many good friends and colleagues, in particular:

- *The former students and staff of my Neuromorphic Research Group at Caltech.*

- *The Chemists: Bob Grubbs (Nobel Laureate), Nate Lewis*

- *The Biologists: Jim Bower, Linda Buck (Nobel Laureate), Gilles Laurent, Gordon Shepherd.*
- *The Engineers: Owen Holland, Alan Winfield*

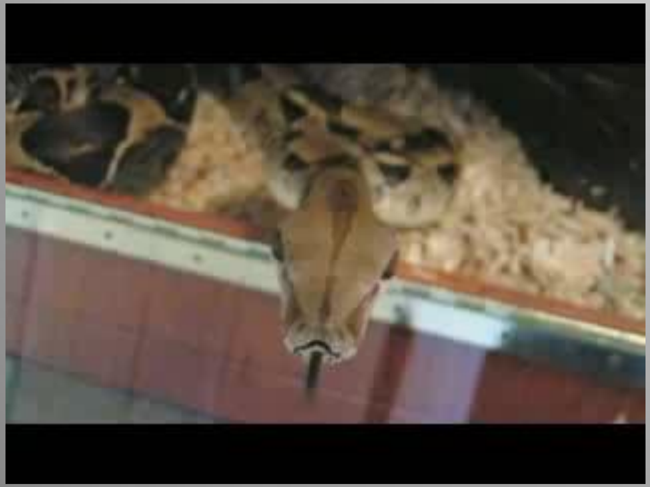
Biological Olfaction

Chemical Sensing in Biology

- Chemical sensing (chemoreception) is vital for survival in all animals.
- Used to find food, prey, mates.
- Used to recognize individuals of the same species, family members, predators.
- Used for communication.

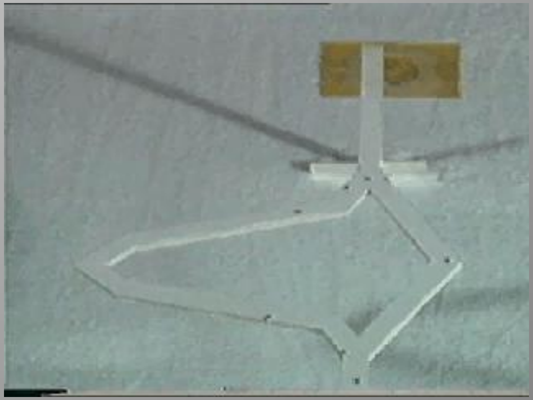
Cyrano de Bergerac

The snail has a smelly foot!



The snake's forked tongue collects odor molecules

Insects smell with antennae

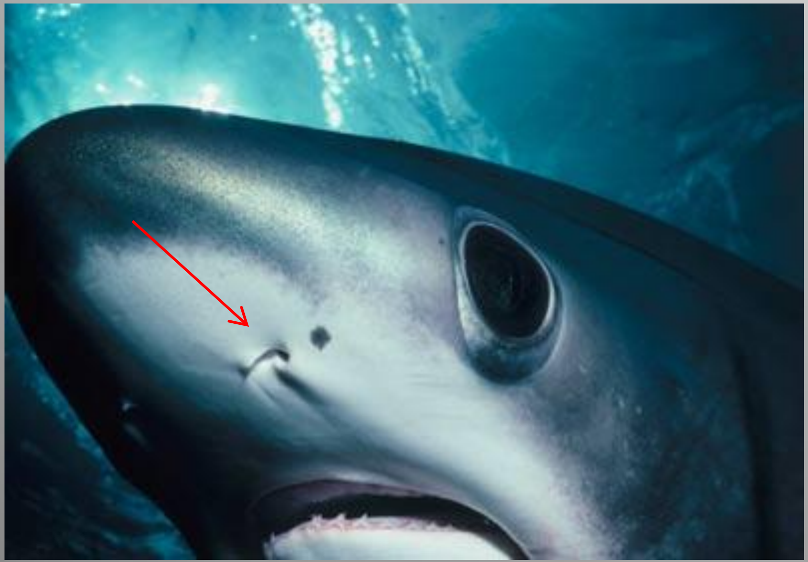


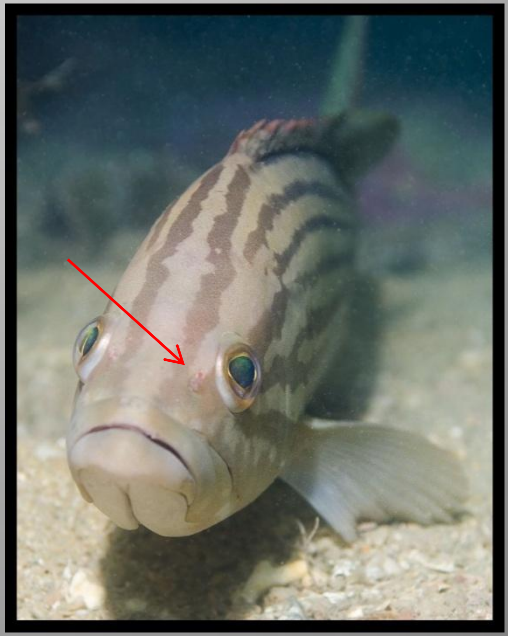
Ants follow a smell trail home

THE OLFACTORY SYSTEM AND INSTINCTIVE BEHAVIORS

Trouble Catching Fish?
– that's because fish can really smell!

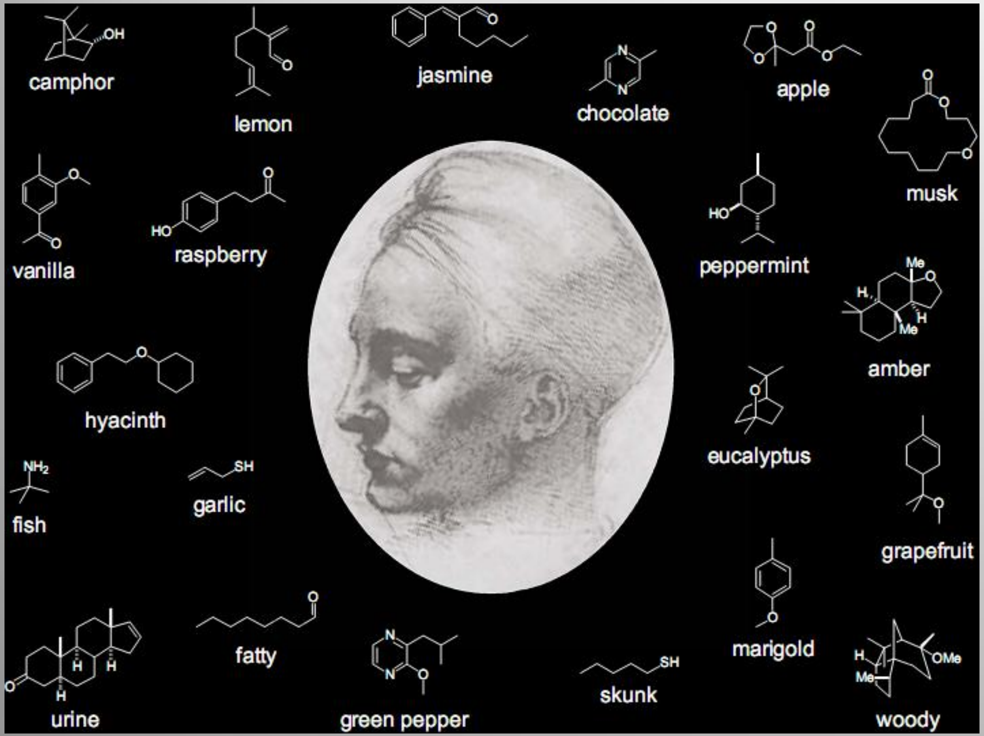
- Chemoreception (smell and taste) is very well developed in fish, especially the sharks and eels which rely upon this to detect their prey.
- Fish have two nostrils ("nares") on each side of their head, but there is no connection between the nostrils and the throat as in mammals.
- The nares lead to the olfactory rosette which is the organ that detects the chemicals. The size of the rosette is proportional to the fish's ability to smell.
- Some fish (such as sharks, rays, eels, and salmon) can detect chemical levels as low as 1 part per billion.

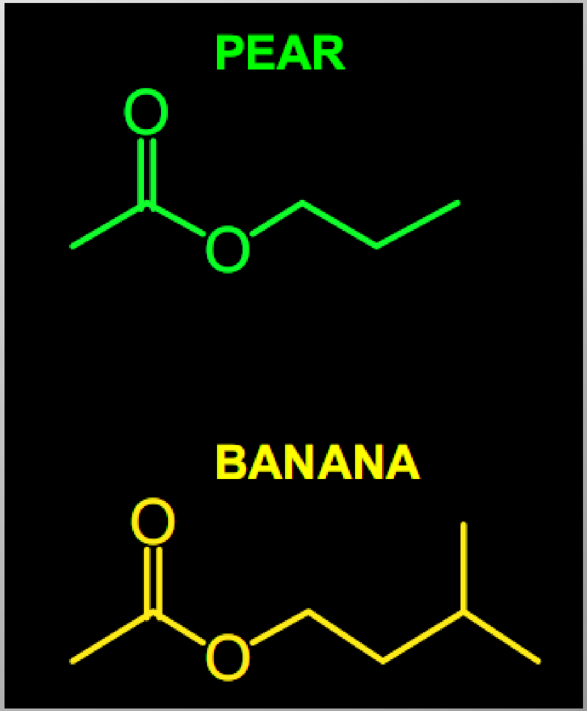




Human Olfaction

We recognize about 10,000 different odours.

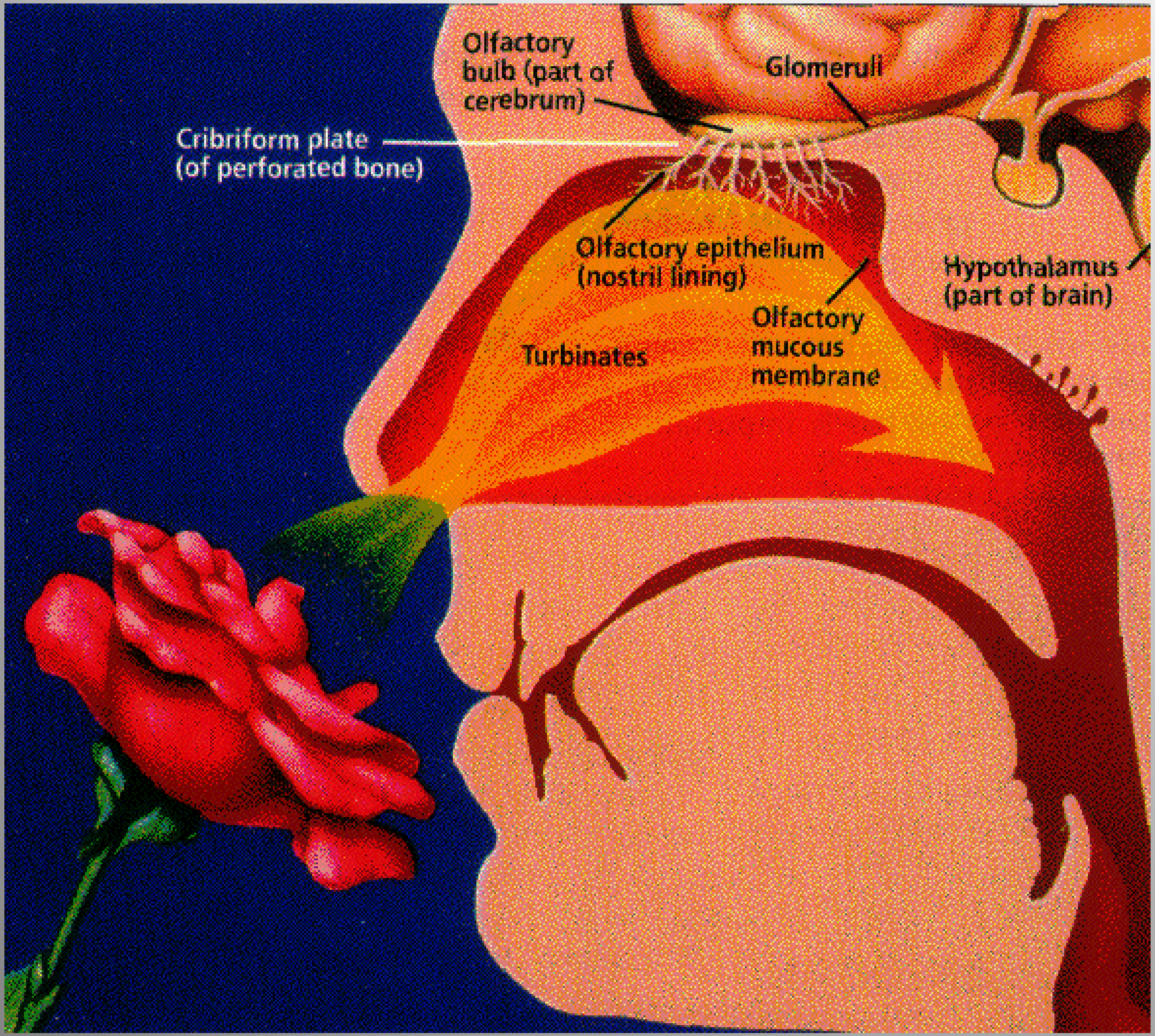




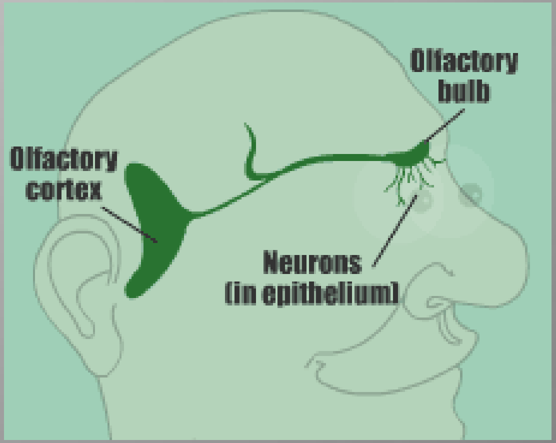
About 1% of people suffer from Anosmia – they have no sense of smell.

Chemically similar odours smell very different!

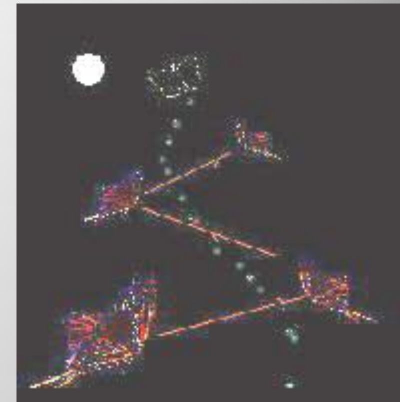
Mammalian Olfactory System



- Molecules of odorant interact with Olfactory Receptor Neurons (ORNs) in the Epithelium firing a subset of ORNs.
- ORNs project to Glomeruli in the Olfactory Bulb forming a pattern of activity.
- The Glomeruli relays this pattern to the Olfactory Cortex via the Lateral Olfactory Tract (LOT) where recognition takes place.



The "other" Smell Sense



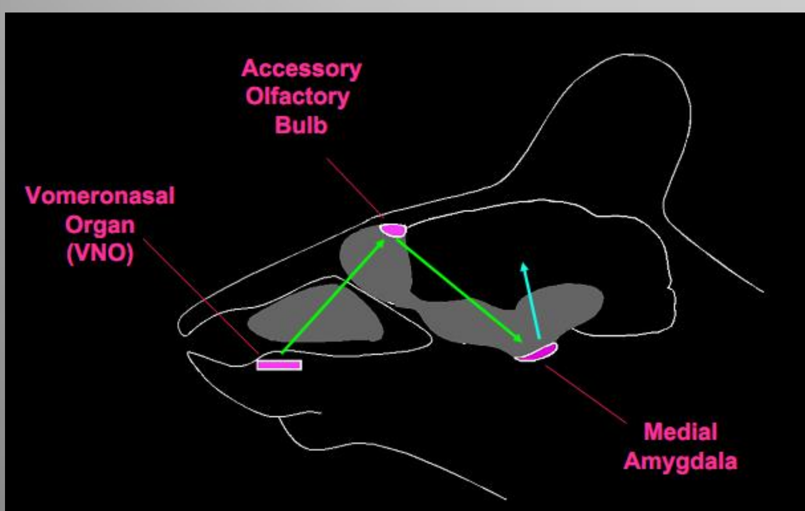
•Many insects use pheremones to signal to members of the opposite sex.

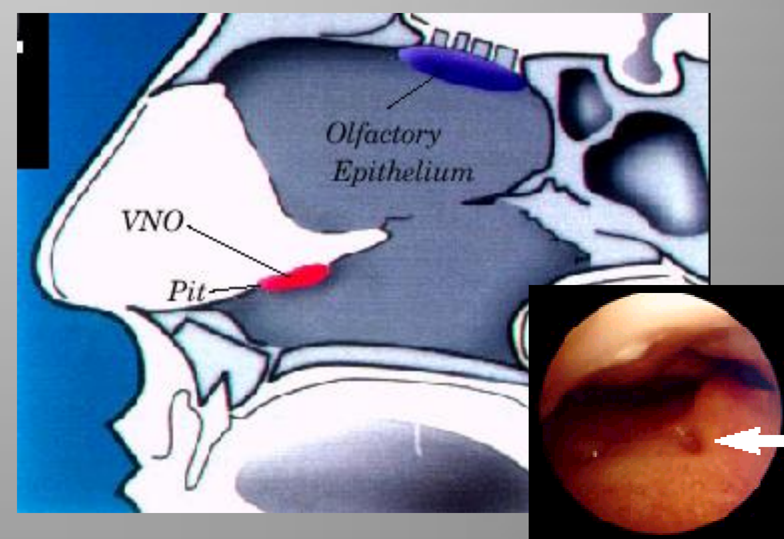
• The receptors for are very sensitive and specific. A moth can detect a single molecule of pheremone from a female a mile away!

- Mammals (mice, rats) use these signals to trigger a wide variety of social, aggressive, and sexual behaviors.
- The Vomeronasal Organ (VNO) is the seat of this primitive olfactory reception system.

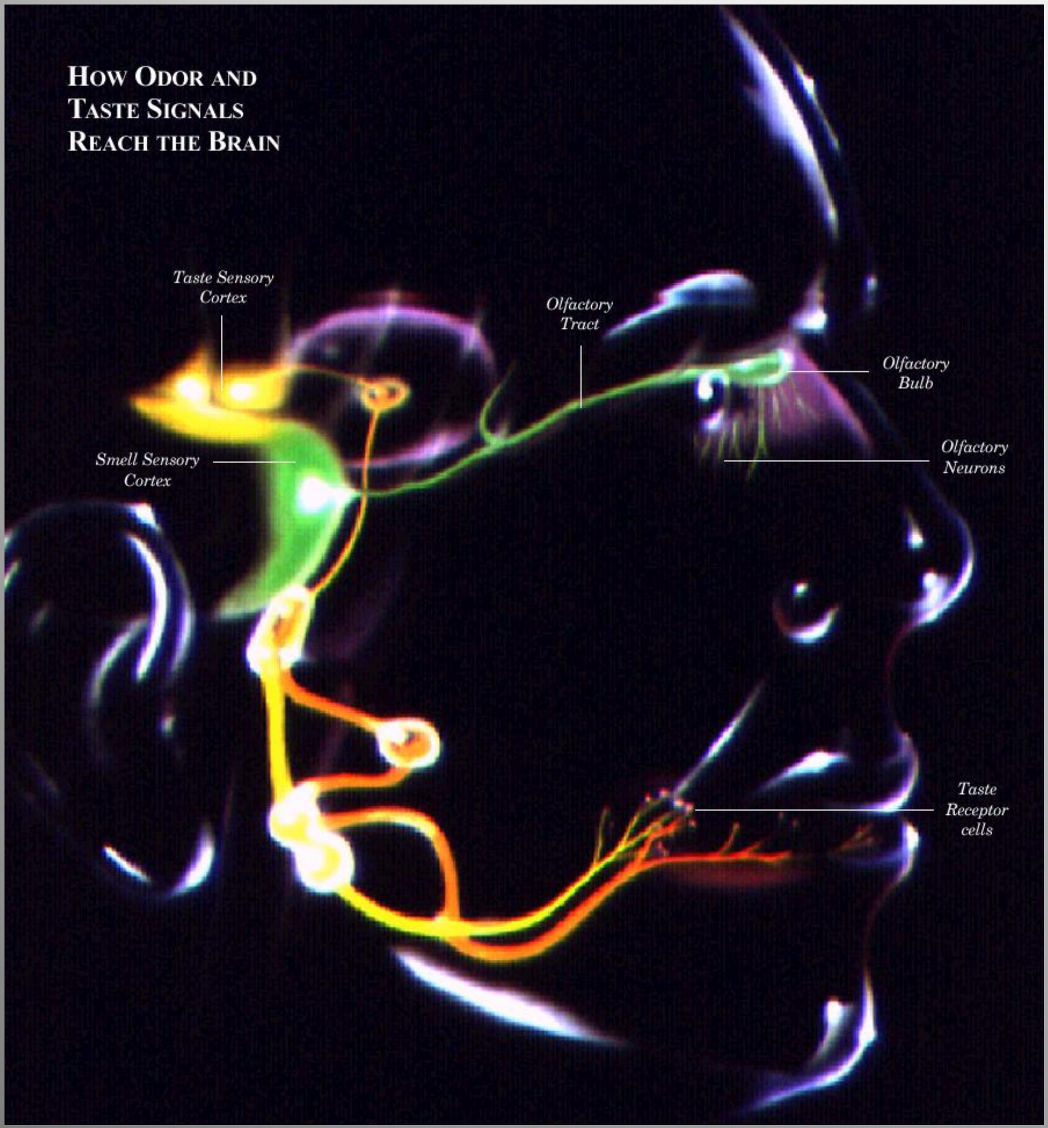
• Identified in humans, but is vestigial.

• Linda Buck and others trying to find the genes that code for these receptors, and if they are expressed or not in humans.





Taste, Smell, Touch and Pain



- **Most of taste is really smell.**
- **There are five tastes: Sweet, Sour, Salty, Bitter, Umami or Glutamate.**
- **The Nose is the gatekeeper for the mouth – if it smells bad don't eat it!**
- **The taste pathways connect to the limbic system (Amygdala, Hippocampus) , a region of the brain concerned with motivation, emotion, memory, and spatial navigation.**
- **The LOT also connects to the hypothalamus, which regulates many body functions, and is also involved in emotion.**
- **"Sniffing" is part of the active olfactory process so connections to the somatosensory system and cerebellum are seen.**
- **Connections to the trigeminal (pain, touch, feeling) system – e.g. menthol**

Why do we have two nostrils?

Noam Sobel, Nature 1999

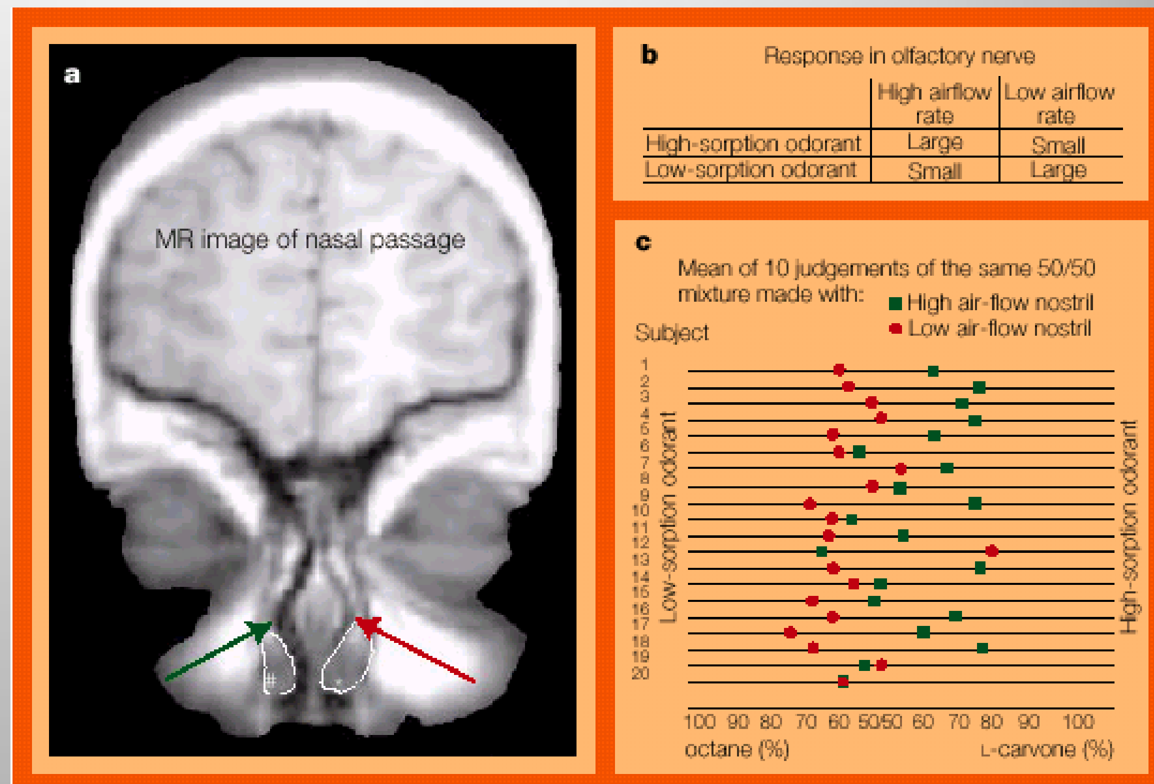
•We have a “high flow” nostril and a “low flow” nostril.

•They switch over about every hour.

•The “high flow” nostril allows low-volatility (heavy, sticky) molecules to spread throughout the epithelium, thus increasing response.

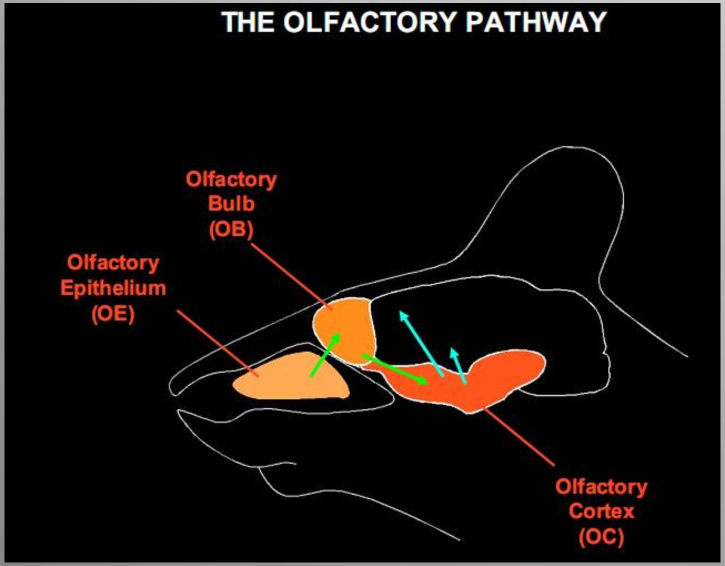
•The “low flow” nostril allows high-volatility molecules (e.g. gasoline) to be trapped before they dissipate, thus increasing response.

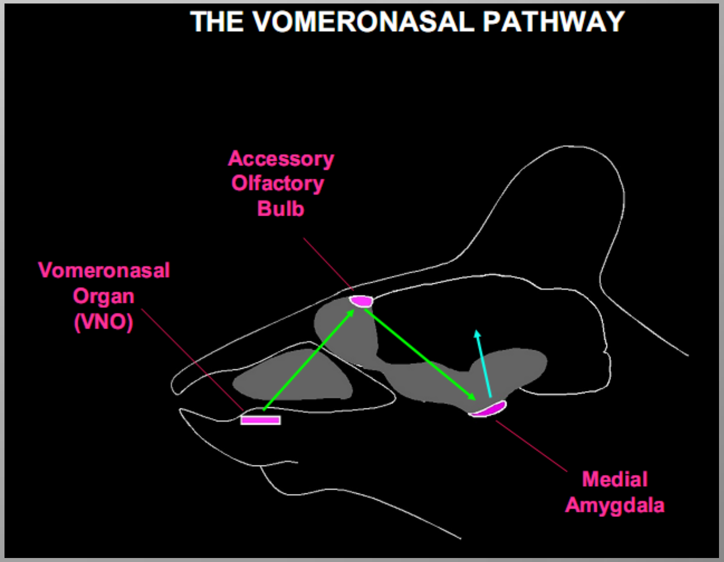
•Also some evidence for “stereo smelling”.



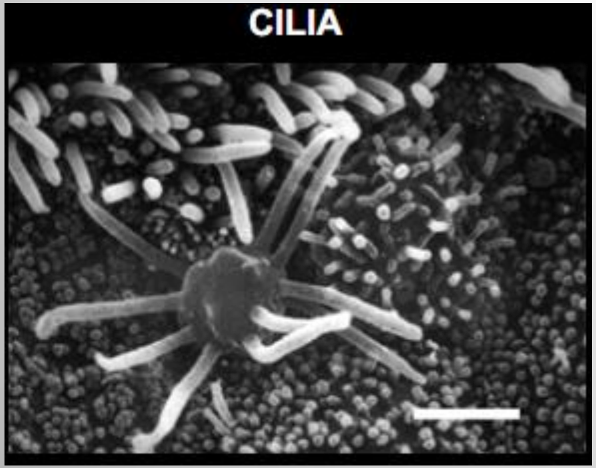
	High airflow rate	Low airflow rate
High-sorption odorant	Large	Small
Low-sorption odorant	Small	Large

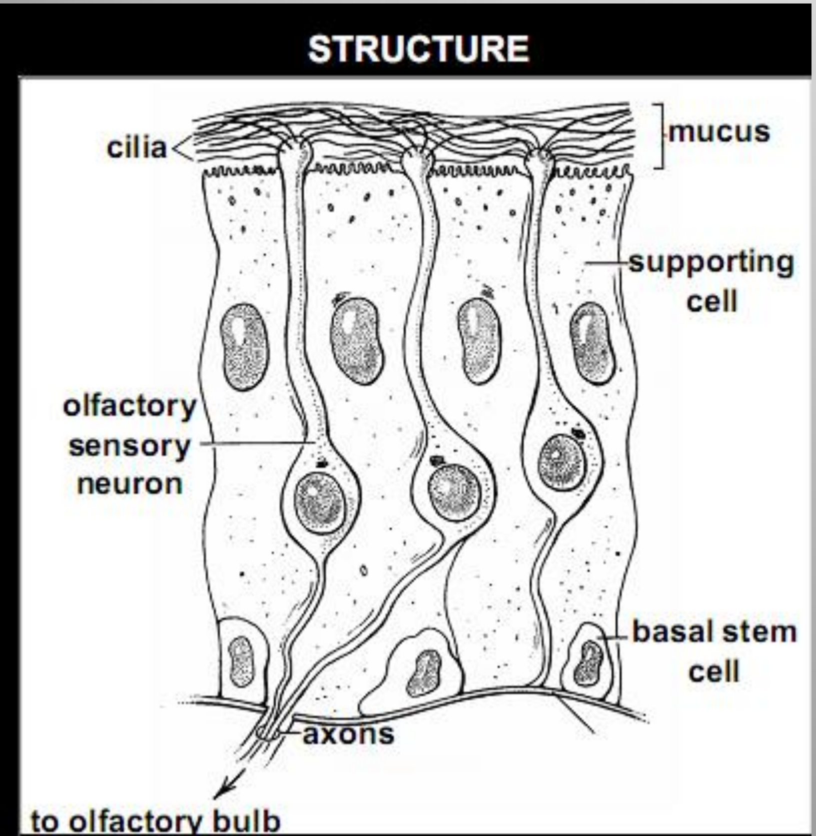
A Code in The Nose





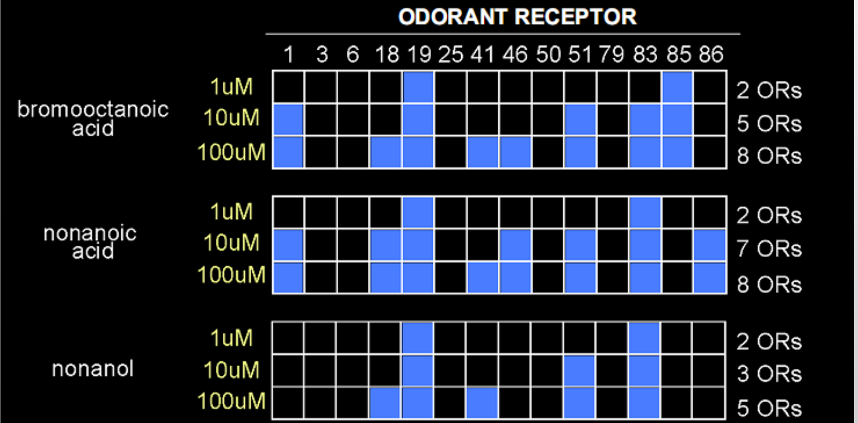
Olfactory Receptor Neurons (ORNs)



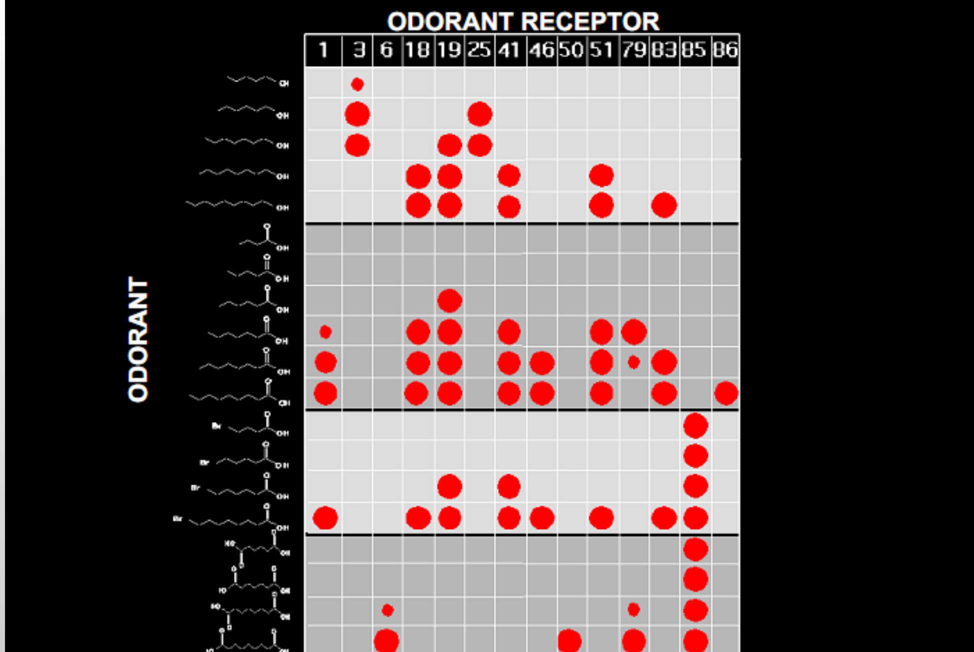


- Mammalian olfactory systems have large numbers of ORNs in the epithelium (~40M humans, ~100M dog).
- There are ~1000 ***different*** ORN genes (~3% of the genome) of which ~400 are actively expressed. (We smell in ~400 different "colors").
- Sensors are ***broadly*** tuned:
    - Single receptor recognizes multiple odorant molecules (ligands).
    - A single odorant is recognized by multiple receptors.
    - Up to 10% are firing for any given odorant.
- Individual olfactory receptor neurons are replaced approximately every 40 days by neural stem cells residing in the olfactory epithelium. (neurogenesis).
- There are special receptors highly tuned to things that smell really bad! Such as amines Cadaverine, Putrescine (dead body smell)!

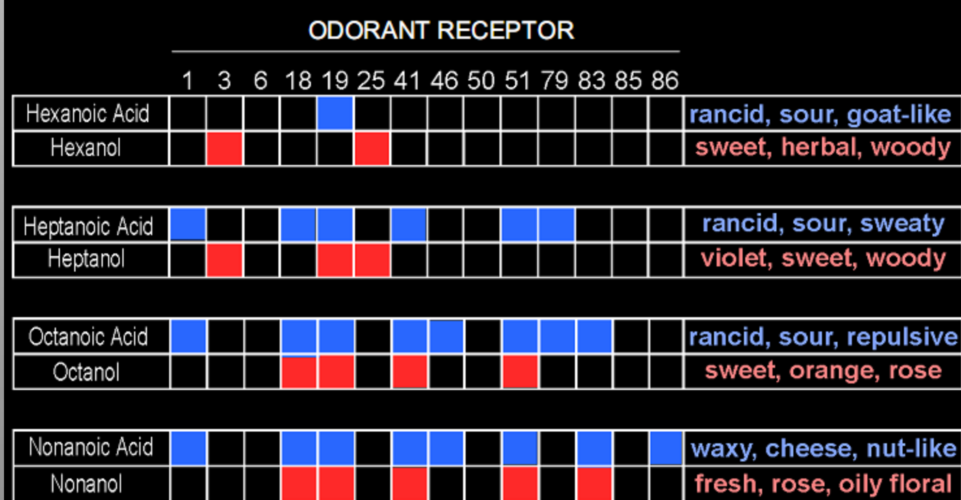
RECEPTOR CODES: THE EFFECT OF CONCENTRATION



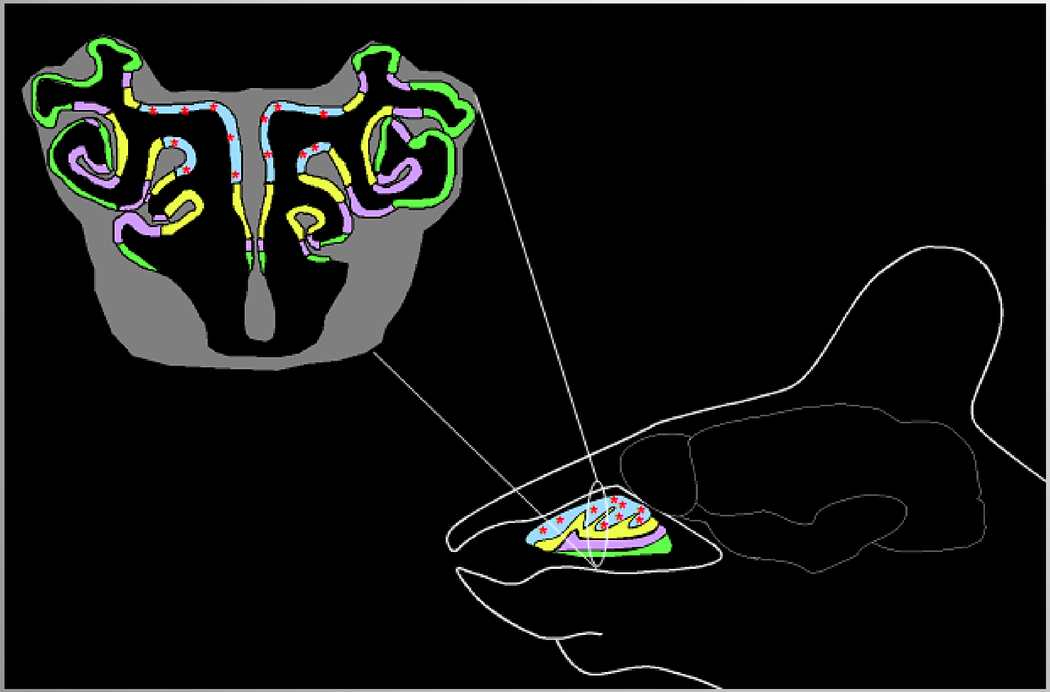
ODORANTS ARE DETECTED BY COMBINATIONS OF ORS



RECEPTOR CODES AND PERCEPTION



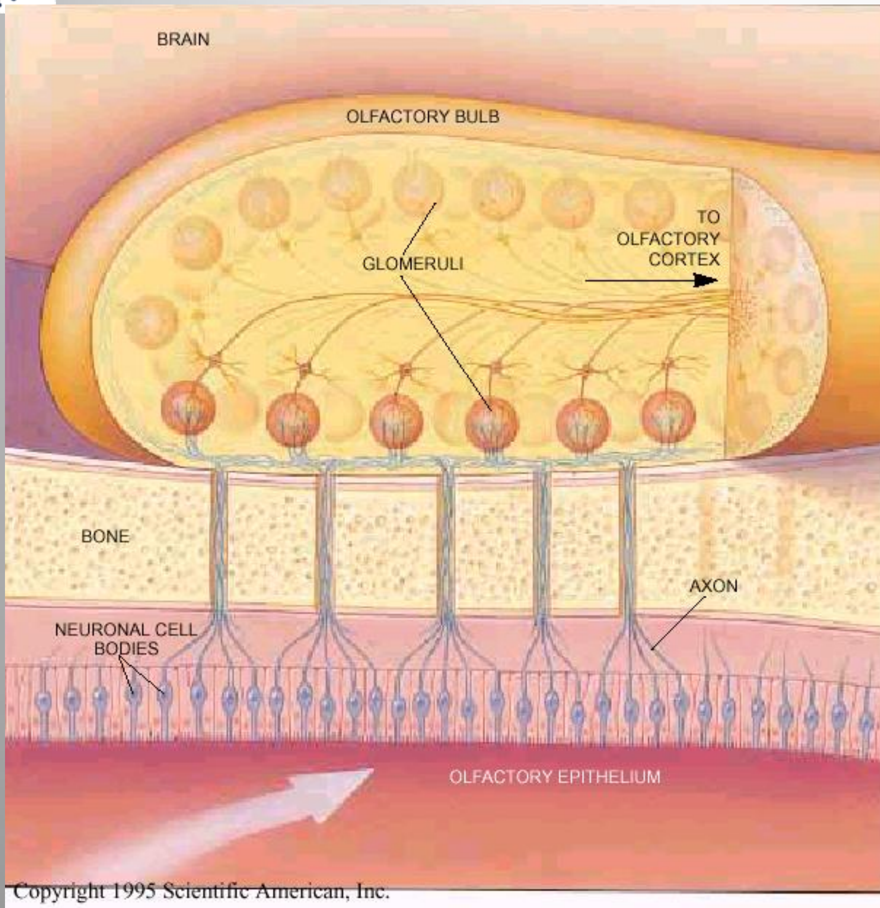
Olfactory Epithelium

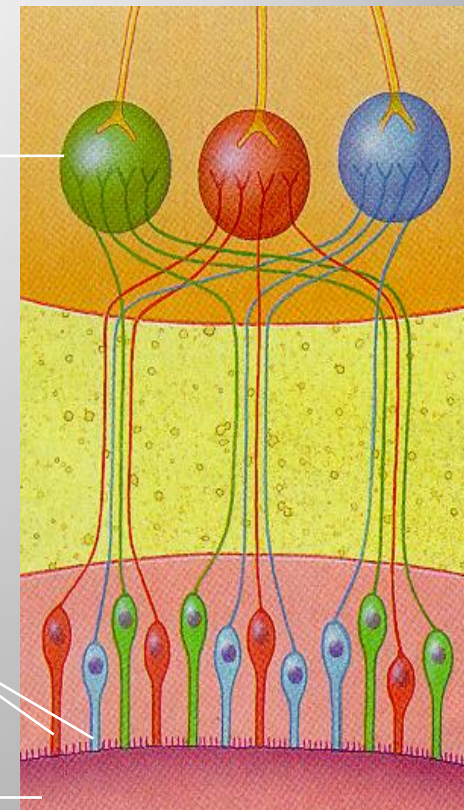


- There are 4 “zones” in the epithelium.
- Each zone contains a different set of ORNs.
- Within a zone the ORNs in that set are randomly distributed. (Minimize the effect of local variations in turbulent flow)

If you “unfold” the dog’s epithelium, it would measure 1 meter square!

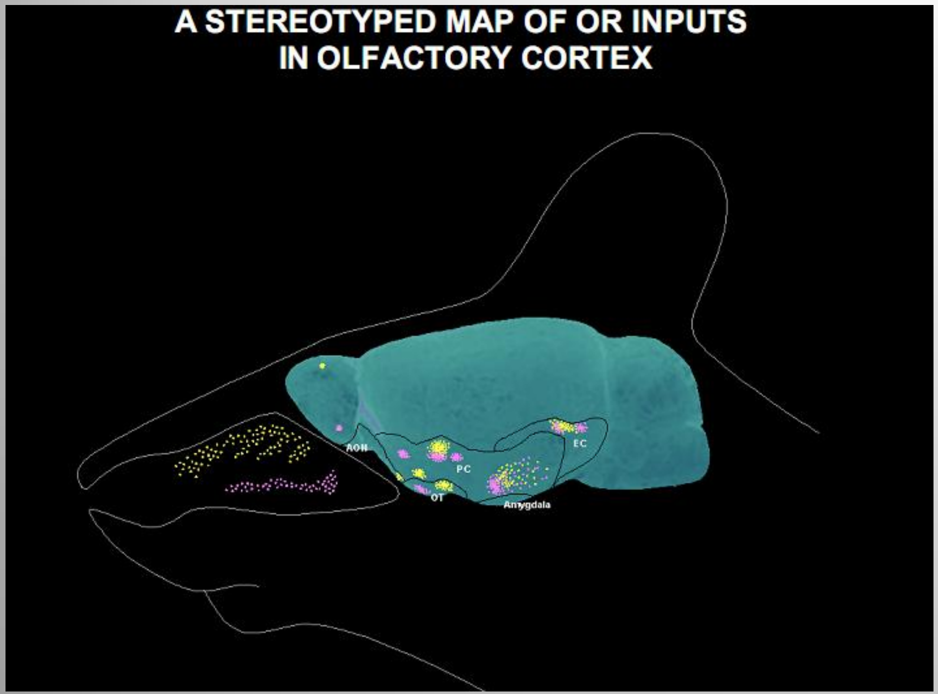
From ORNs to the Glomeruli in the Olfactory Bulb

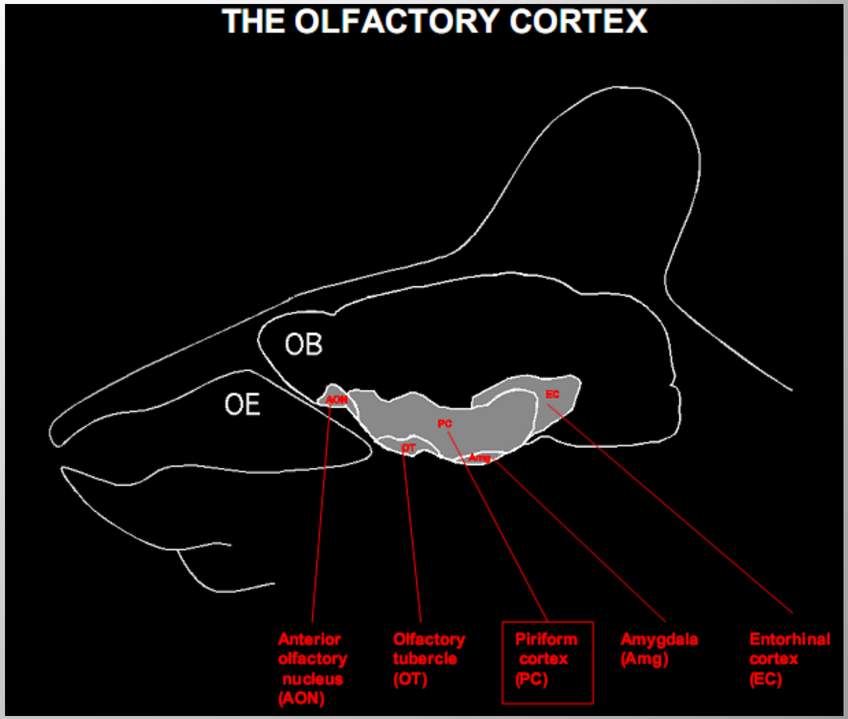




- **Each Glomerulus (~2000) receives signals from only *one* type of ORN.**
- **Approximately 2500 receptors impinging into each Glomerulus.**
- **This redundancy is needed because ORNs die off.**
- **Redundancy also improves signal-to-noise ratio by square root of N (a factor of~50).**

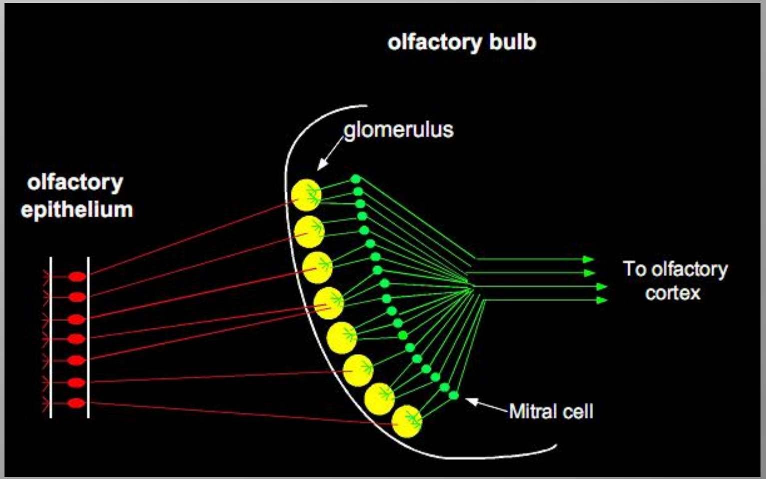
From The Olfactory Bulb to Olfactory Cortext



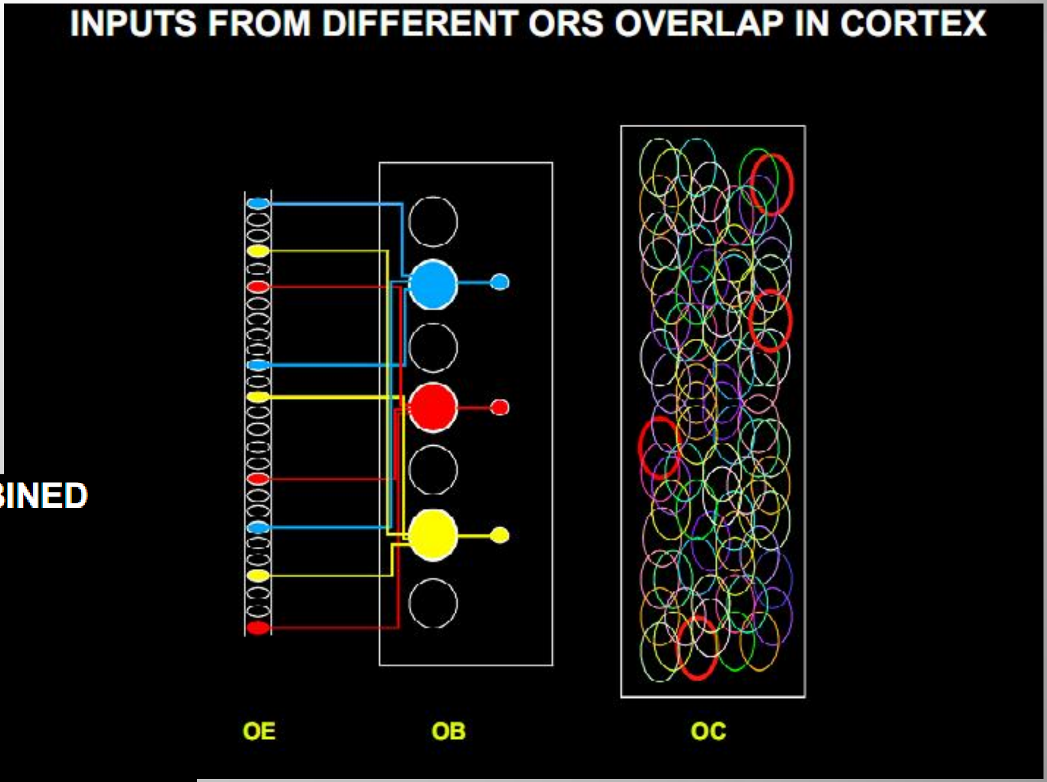


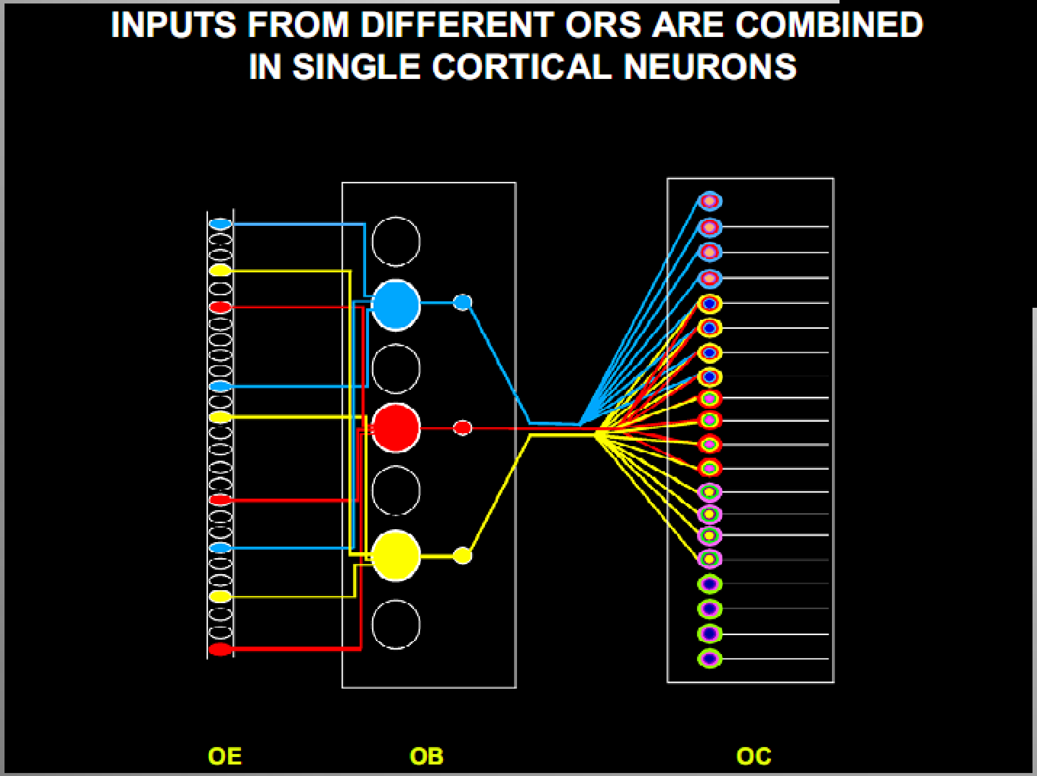
•**A single glomerulus mitral/tufted relay neuron projects axons to multiple cortical areas.**

•**Mitral cells project axons to the entire olfactory cortex, but tufted cells project only to the most anterior areas (AON, OT).**

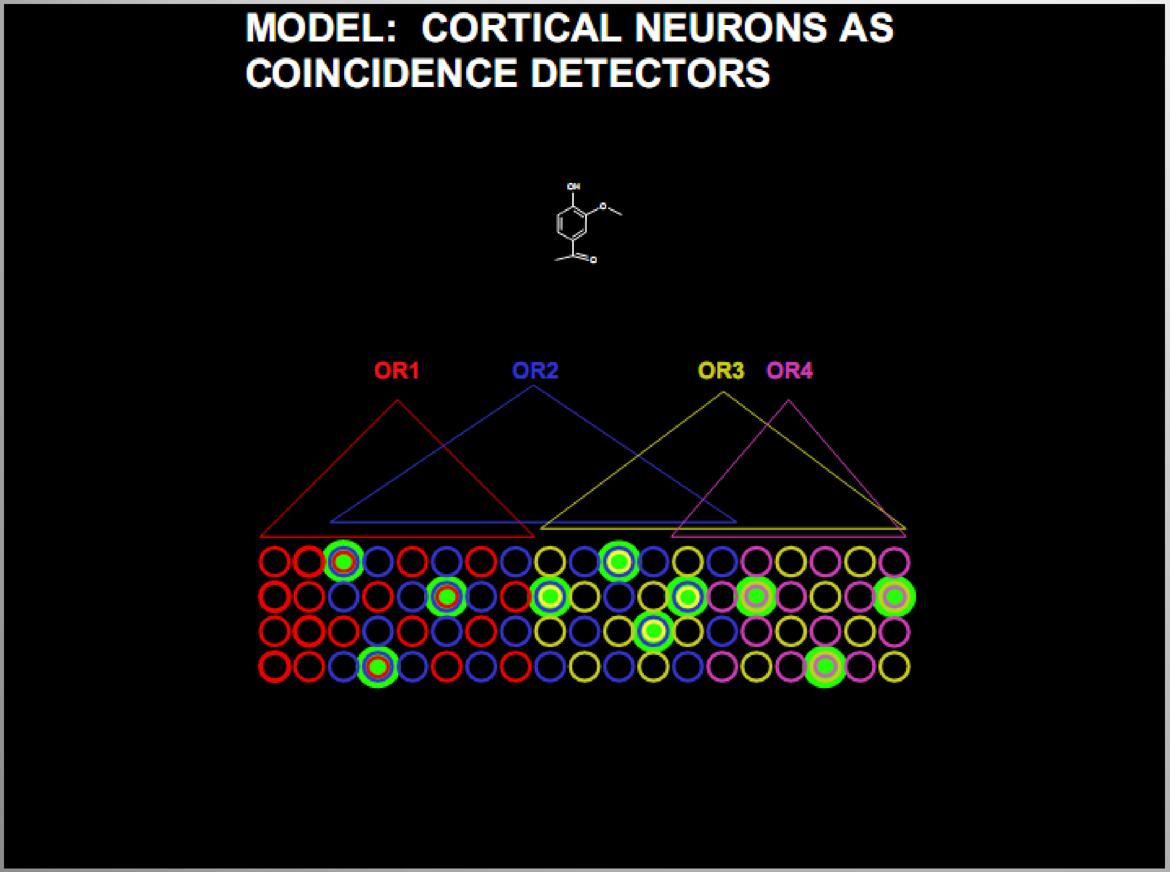


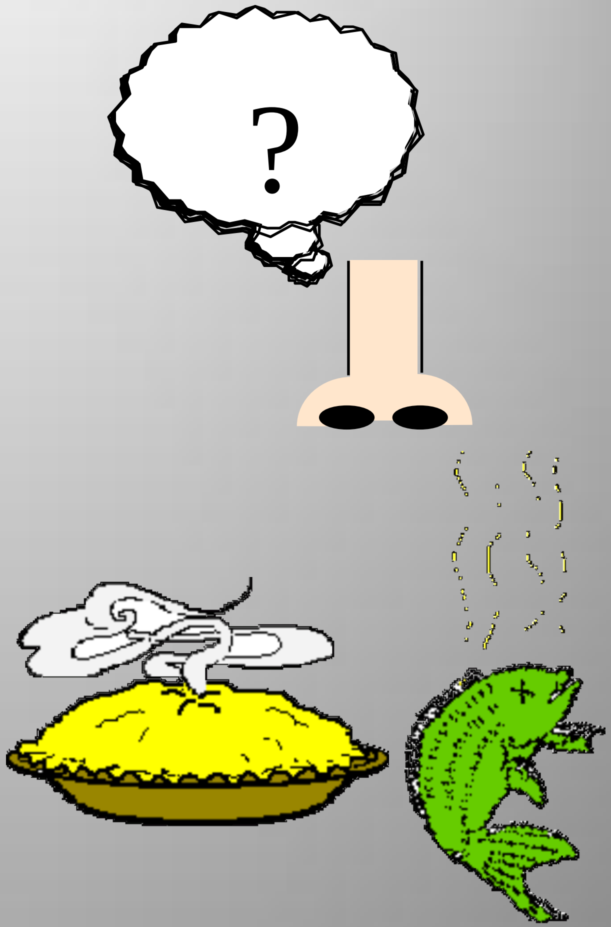
Olfactory Cortex





It's really the Code in the Cortex!



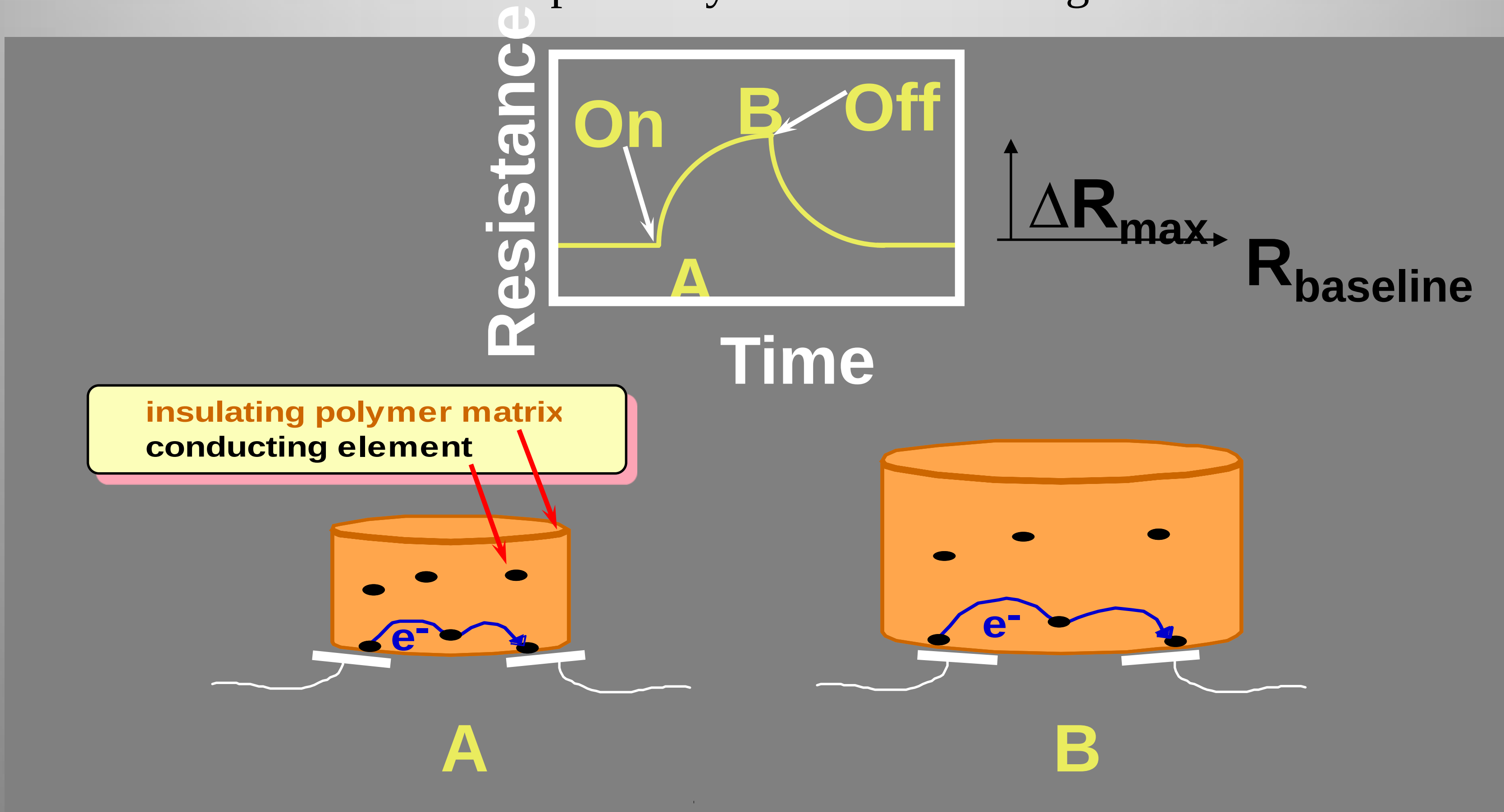


The pattern of cortical neurons firing tells you whether it's a yummy apple pie or a stinky fish.

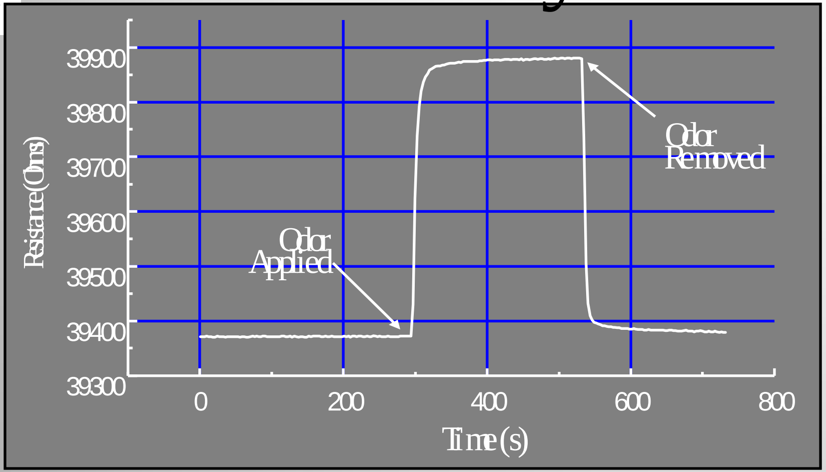
Artificial Olfaction:
The Electronic Nose

Polymer Odour Sensors
Developed by Lewis and Grubbs at Caltech

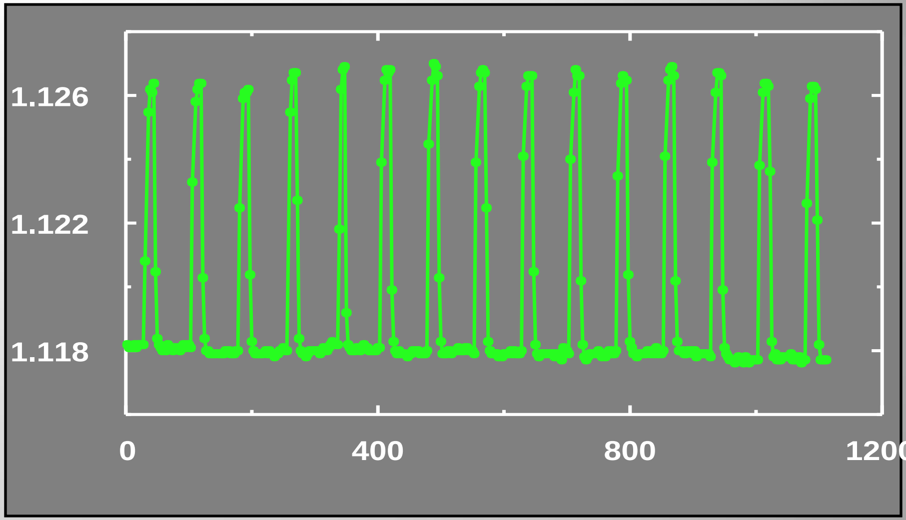
- Insulating polymer doped with conducting particles.
- Sensor polymer material swells upon exposure to odor.
- Results in a long path for current, hence higher resistance.
- Conduction mechanism primarily electron tunneling.



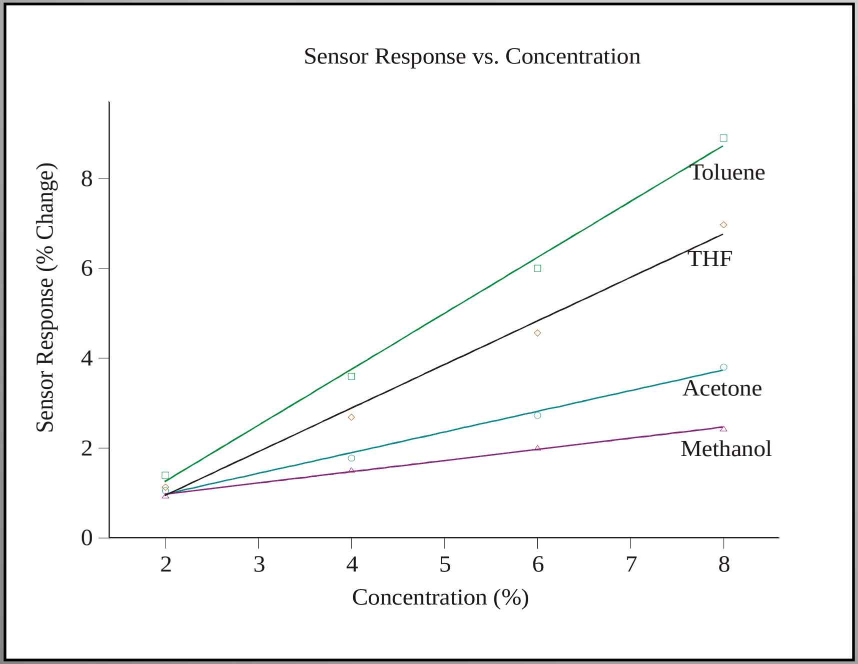
Polymer Sensors are:



•**Fast** (<100ms) – essential for robotic applications



•**Repeatable**-essential for real world applications



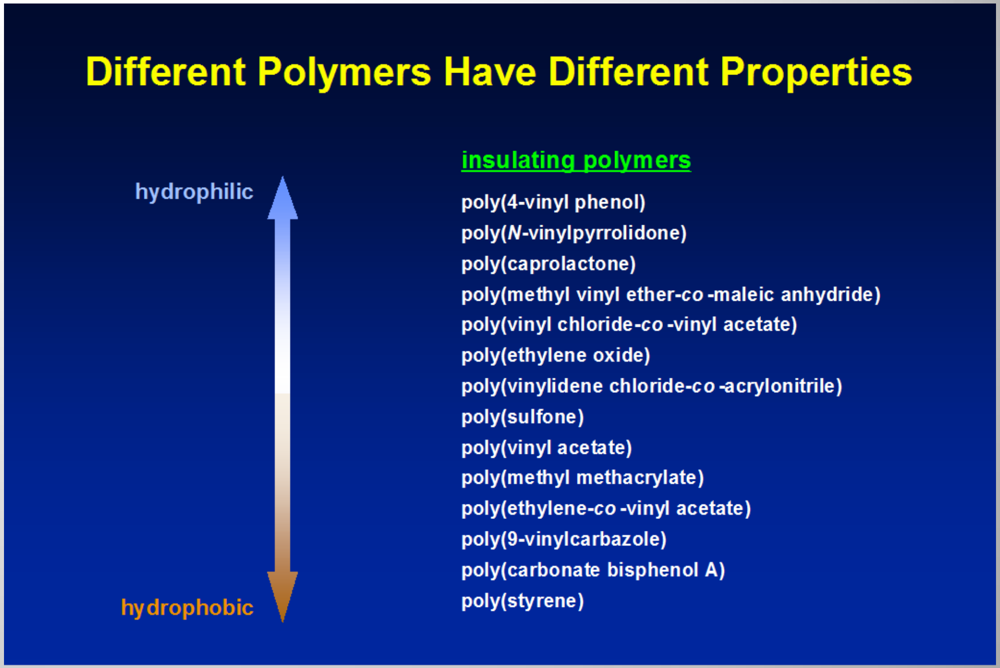
•**Linear with concentration** – essential for simple concentration invariant pattern recognition (unlike the mammalian olfactory system)

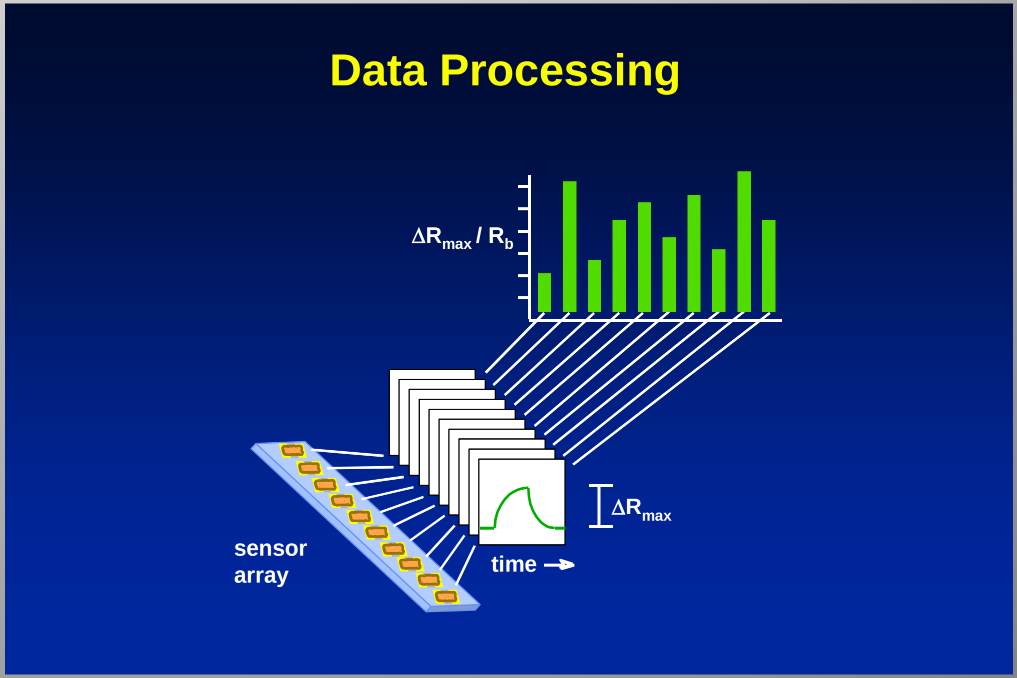
•**Broadly tuned** – one sensor responds to many different odours to varying degrees (like the mammalian olfactory system)

Array Based Sensing

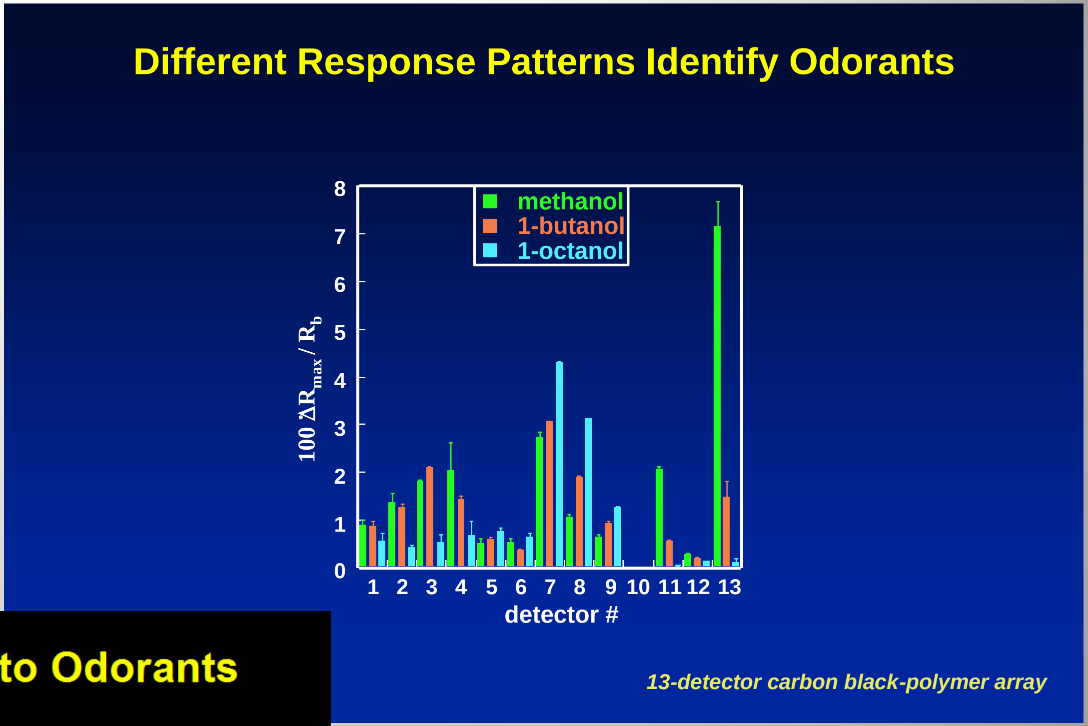
Technologies:

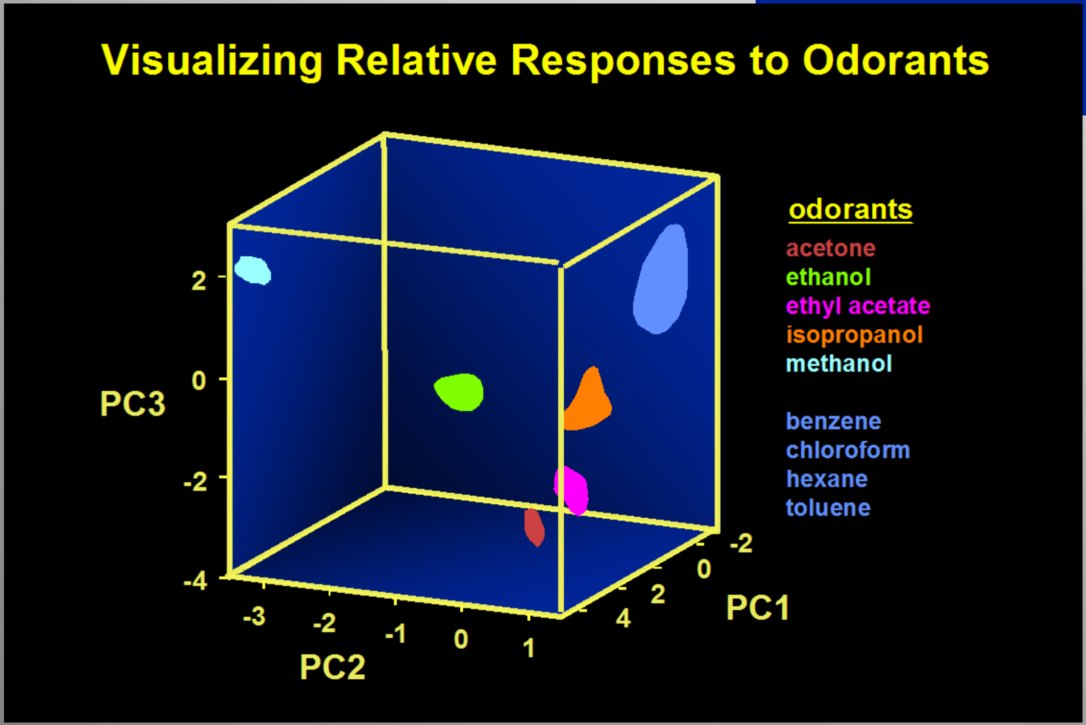
- **Arrays of carbon black-polymer composite detectors *(Lewis et al)***
- **Arrays of conducting polymer detectors *(Persaud, Gardner et al)***
- **Arrays of QCM detectors *(Grate et al)***
- **Arrays of polymer-fluorescent dye detectors *(Walt et al)***
- **Arrays of SnO_2 detectors *(Gardner et al)***
- ***Arrays of Chemfets (Gardner et al)***





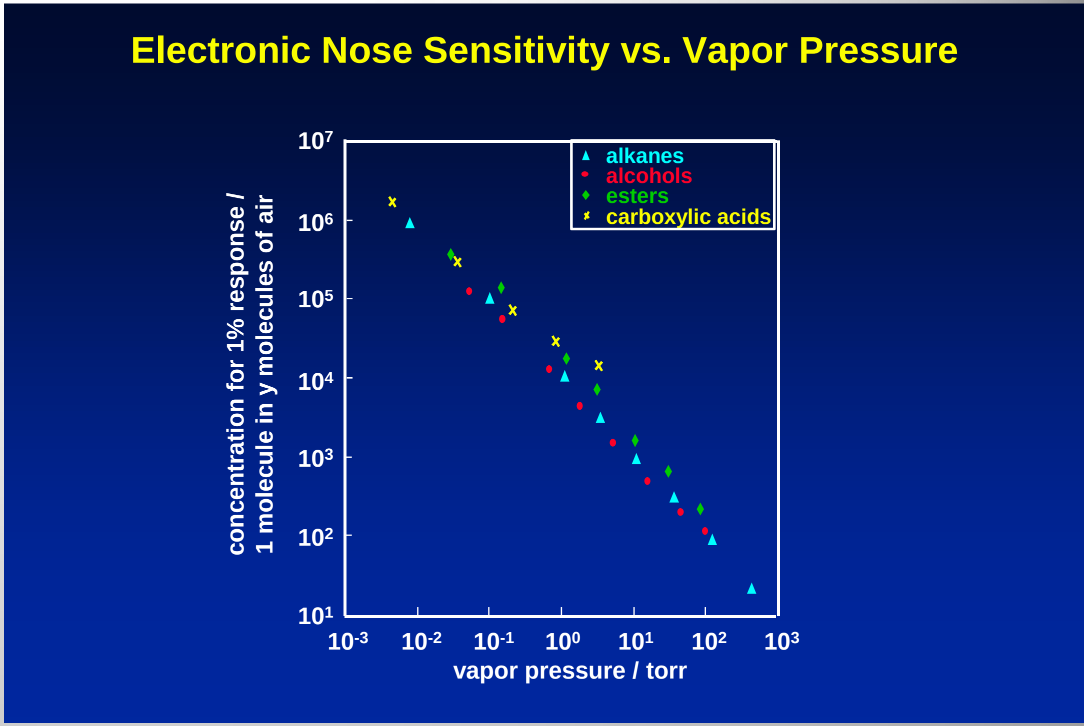
$\Delta R_{max} / R_b$ for each sensor normalized across the array results in a concentration independent pattern that characterizes the odour.

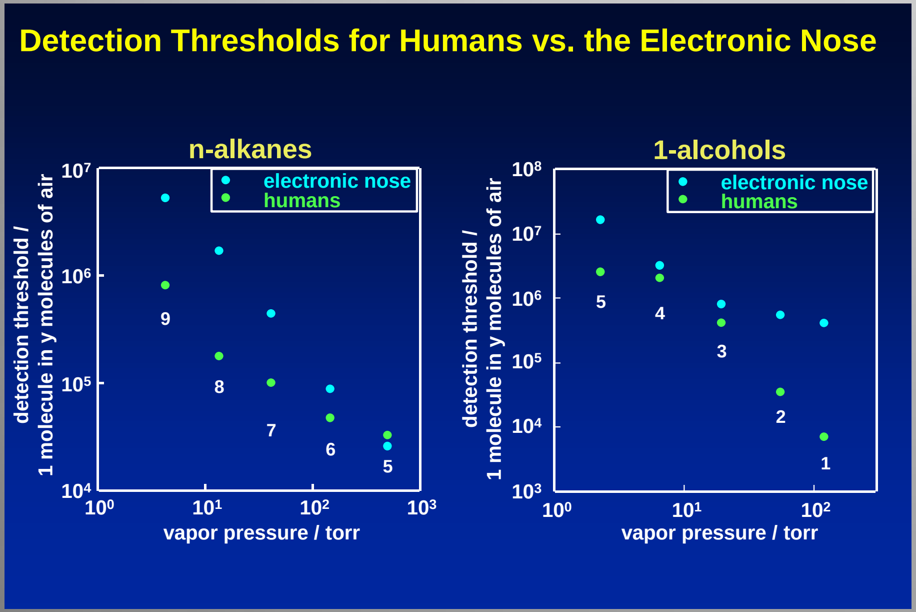




•E-nose sensitivity to an odorant is inversely proportional to odorant vapor pressure.

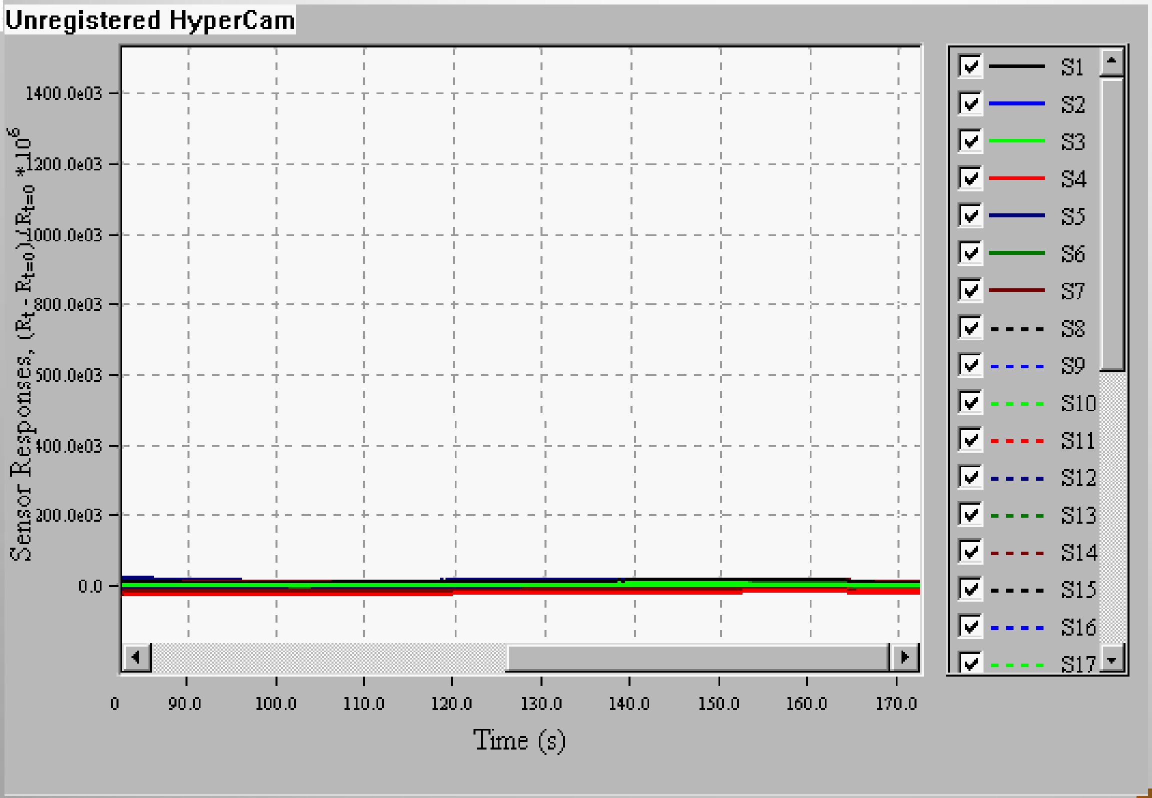
•Conversely, when different odorants are presented to a sensor at a concentration equal to the same % of saturated vapor pressure for that odorant, the $\Delta R_{max} / R_b$ response is the same.





This trend also observed in mammalian olfaction-with some notable exceptions (e.g. amines – cadaverine, putricine etc really stink to us and are detectable at very low concentrations!

Cyranose 320 Hand-Held E-nose



Sensors (32) → Signal Processor → Pattern Classifier → ID

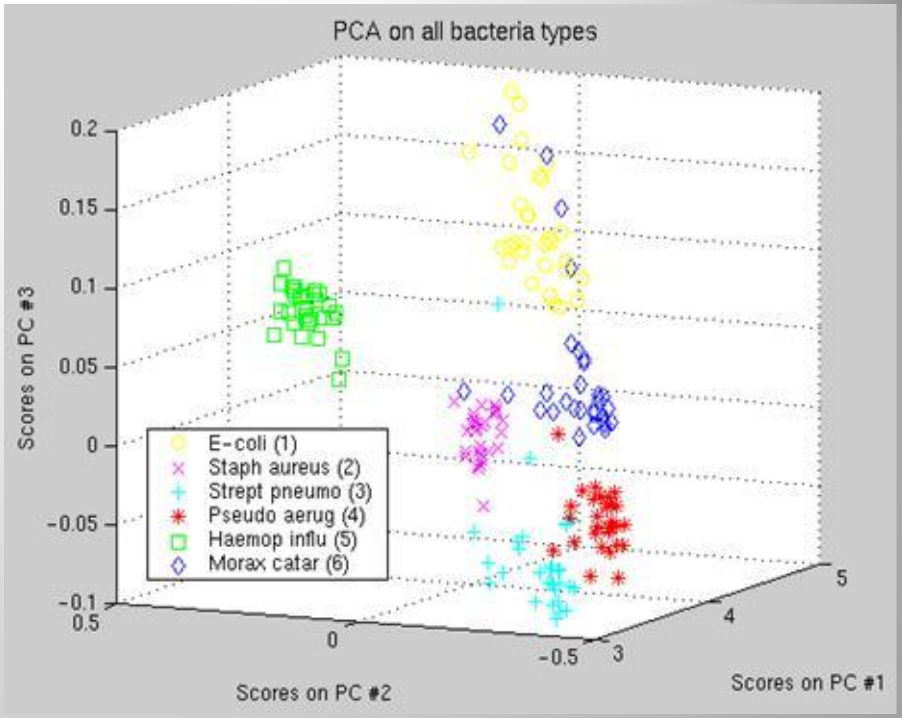
Signal Processor ⇧
- Amplify
- Baseline Adjust
- Normalize

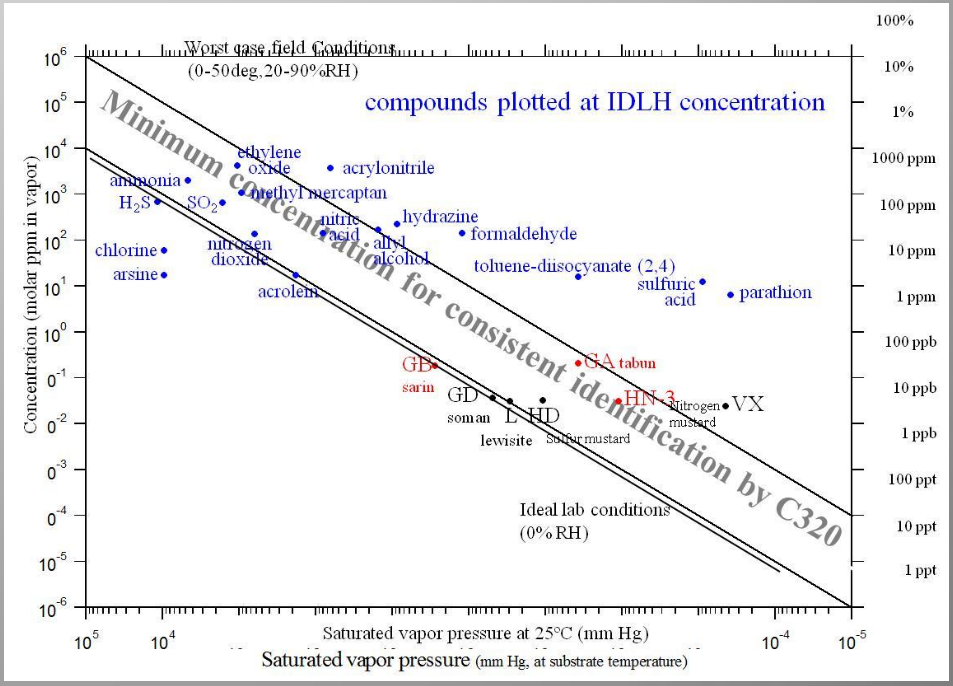
Pattern Classifier ⇧ Trained Database of Odour Patterns

Demo

Applications

- The C320 is being used to smell:
  - fish quality in an Alaska packing factory.
  - cooking oil quality in MacDonalds (trial).
  - “new car smell” in Cadillac.
  - for contaminants in 5 gallon water containers (Australia).
  - Diabetes analysis for emergency paramedics (Boston).
  - Strep and Staff Throat (trial)
  - Toxic Industrial Chemicals (TICS) by OSHA (Occupational Health and Safety) in California.
  - Very very bad Chemical Warfare Agents (CWA) by the US military.
  - more

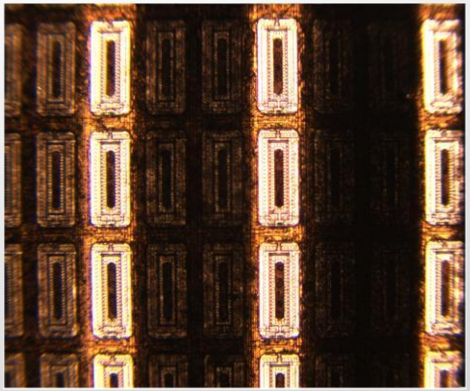




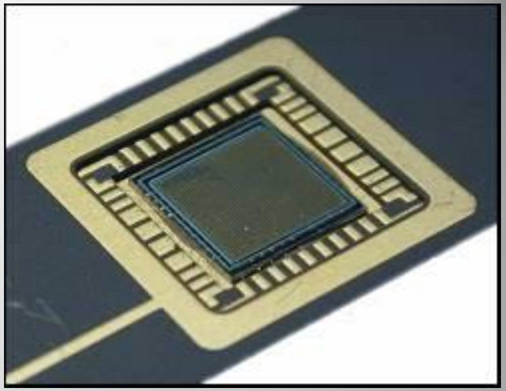
Cyranose 320 Stars in CSI!
(Crime Scene International)

Integration –sensor chips

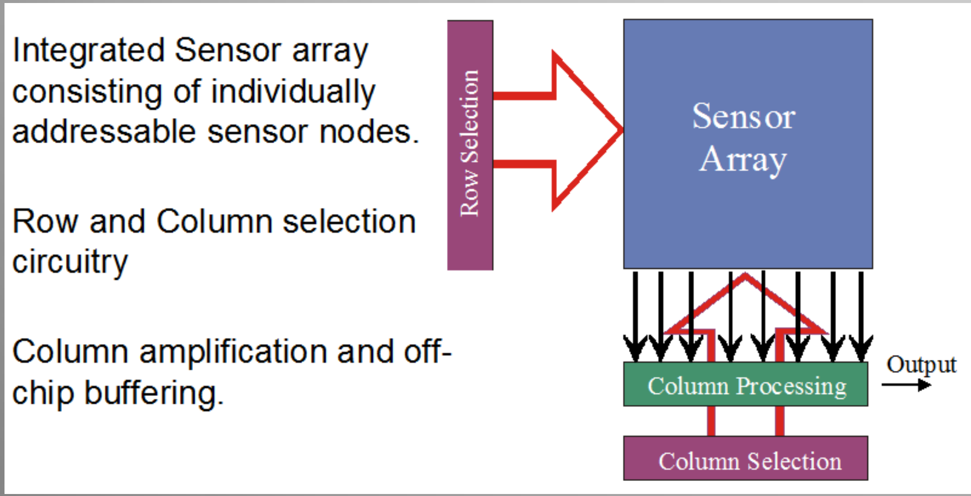
- Integration of sensors enables a large number of chemical sensors to be fabricated in a small area.
- Redundancy gives square root N Signal-to-Noise improvement.
- Gain and signal processing can be fabricated in close proximity to the individual sensor.
- Three layers: polymer – gold contacts –VLSI circuits.



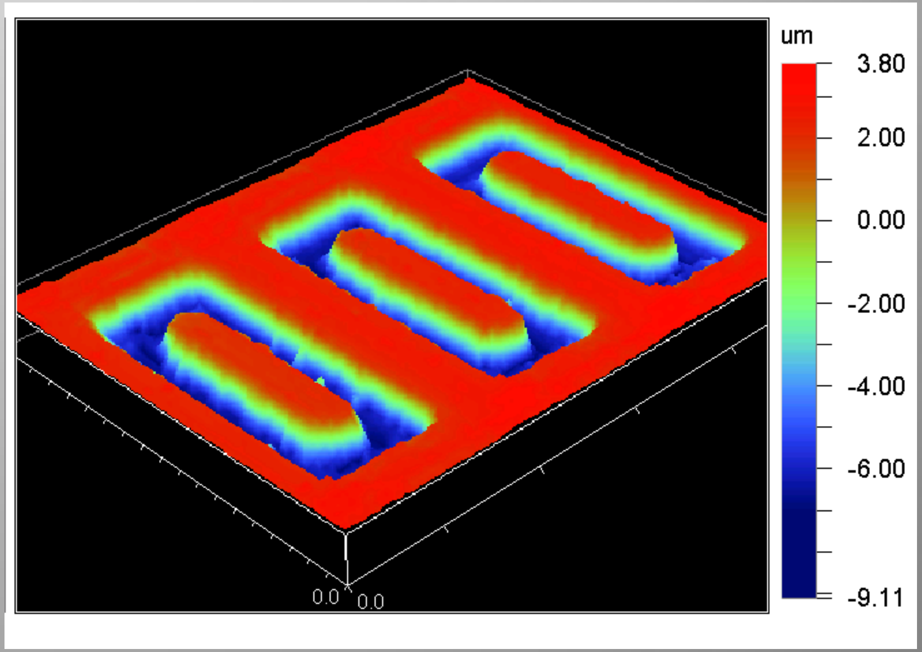
Polymer Deposition
By Robotic Airbrush



1,800 sensor chip

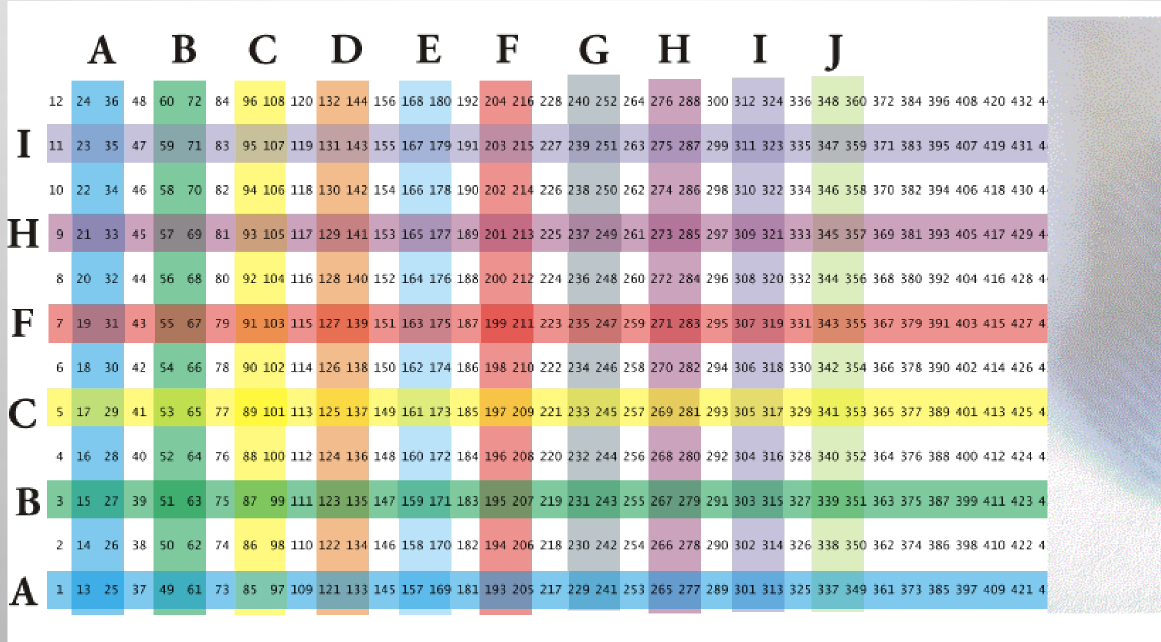


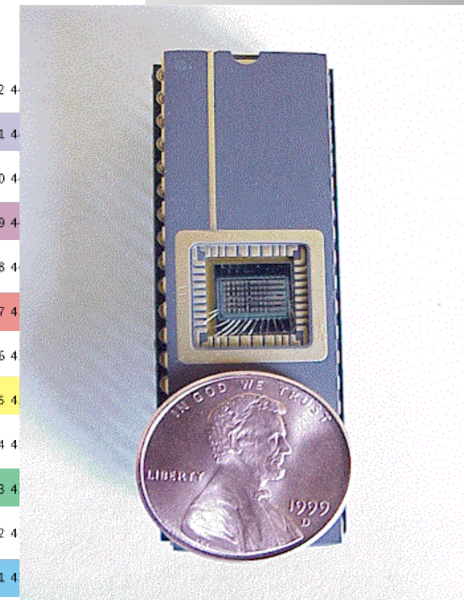
Row – Column Architecture like RAM



Electroless gold post-processing deposits gold on aluminum forming wells.

Combinatorial Pixel Array





A poly(ethylene oxide)

B PEVA 25

C poly(5-Butadiene)

D poly(vinyl-carbazole)

E poly(vinyl acetate)

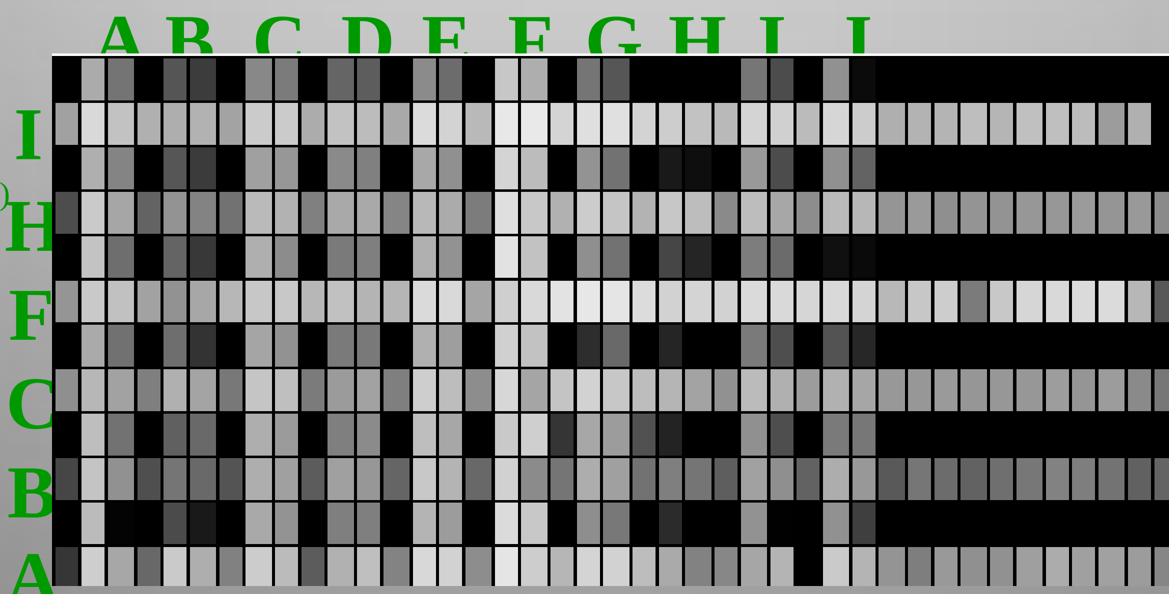
F poly(capralactone)

G poly(sulfone)

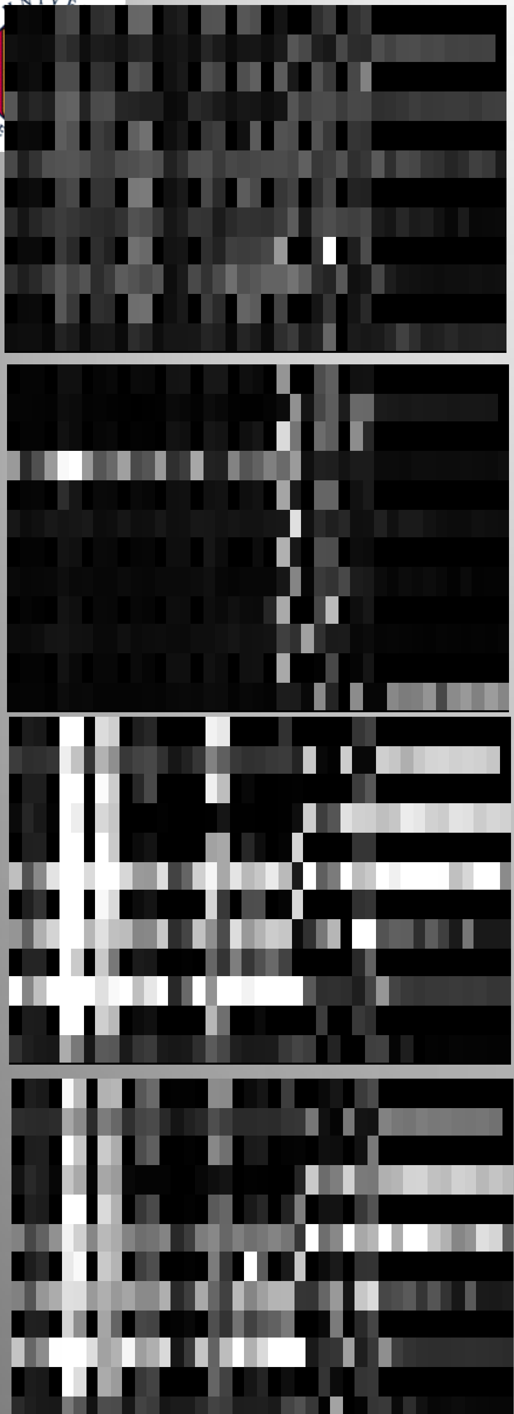
H poly(vinyl pyyrolidone)

I poly(4-vinyl phenol)

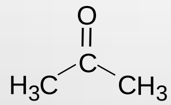
J poly(methyloctadecyl-siloxane)



ΔR/Rb Responses Mapped onto Chip

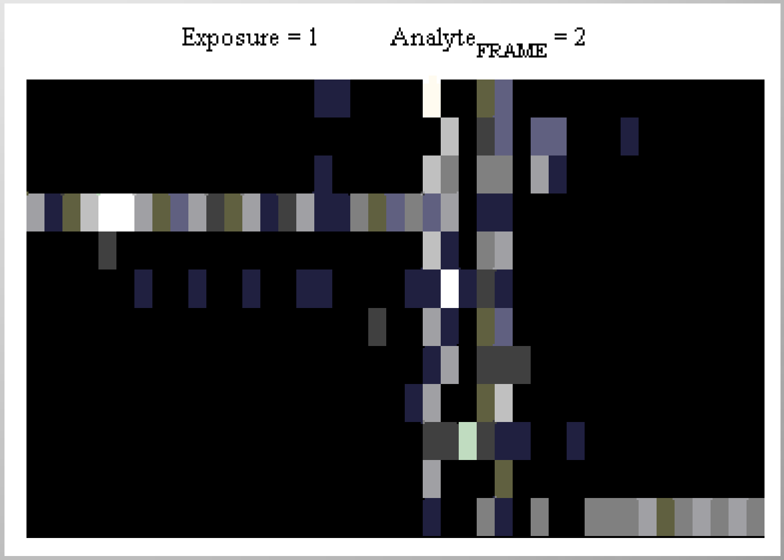


1 Acetone

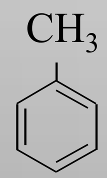


2 Methanol

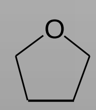
CH_3OH



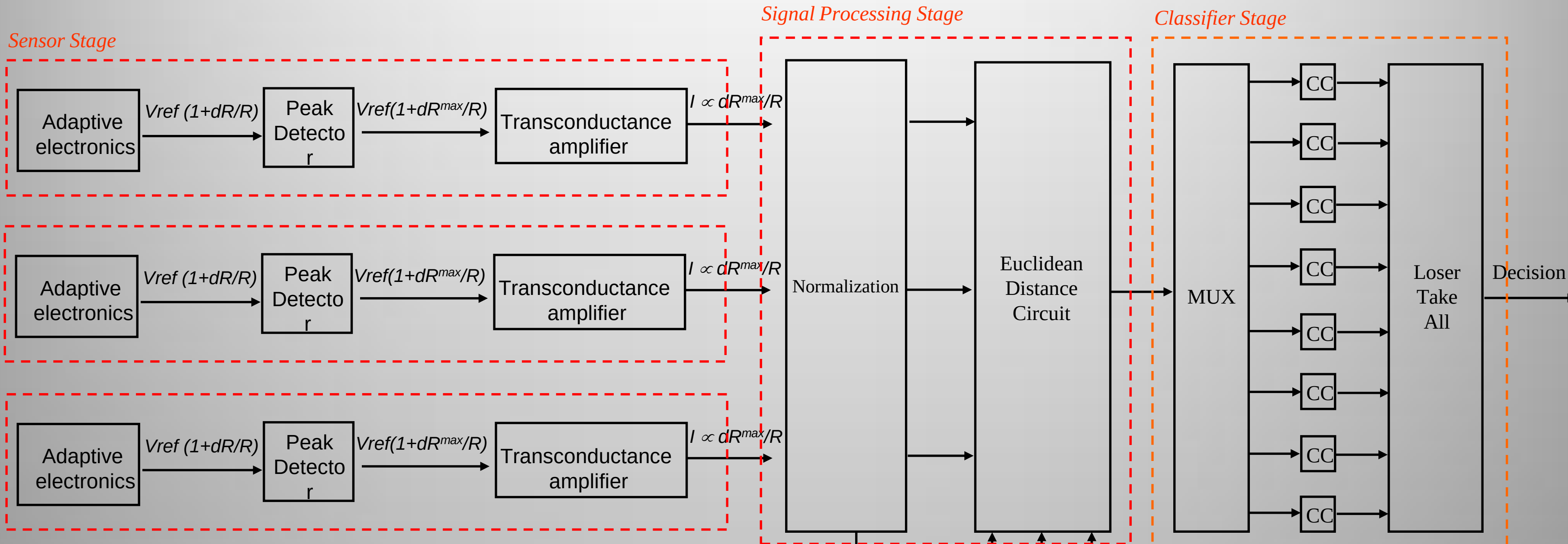
3 Toluene

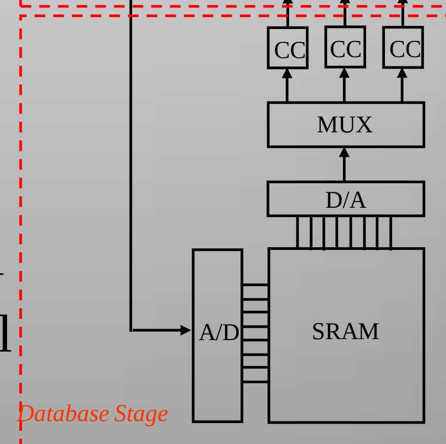


4 Tetrahydrofuran

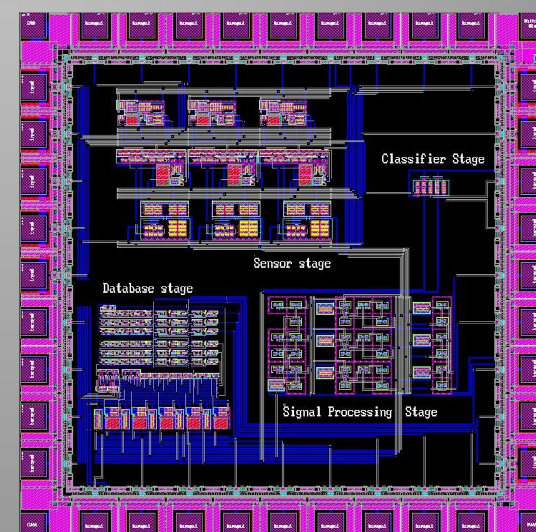


Hybrid Analog/Digital Integration of a complete nose-on-a-chip processor – interfaces to sensor array chips





- Sensor stage: baseline adapt, $\Delta R/R_b$.
- Signal processing stage: normalize , compute Euclidean distance.
- Database stage: pattern training and recall
- Classifier stage: Euclidean distance neural network.
- Correctly classifies methanol, 2-propanol, hexane, ethyl acetate, acetone, benzene.



MOSIS AMI 1.2um process

60 IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS—I: REGULAR PAPERS, VOL. 54, NO. 1, JANUARY 2007

Analog VLSI Circuit Implementation of an Adaptive Neuromorphic Olfaction Chip

Thomas Jacob Koickal, Alister Hamilton, Su Lim Tan, *Member, IEEE*, James A. Covington, Julian W. Gardner, *Senior Member, IEEE*, and Tim C. Pearce

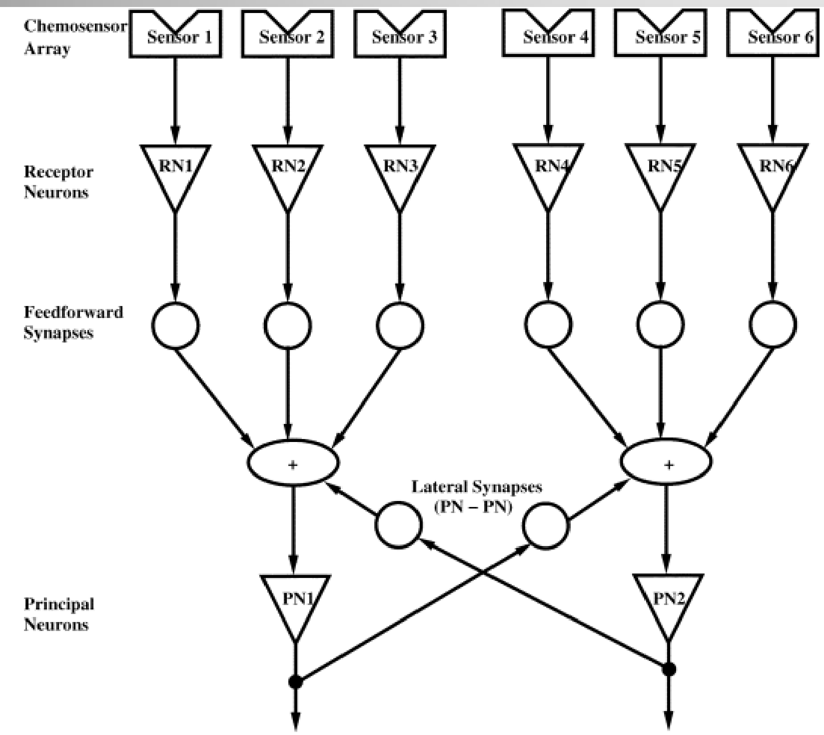
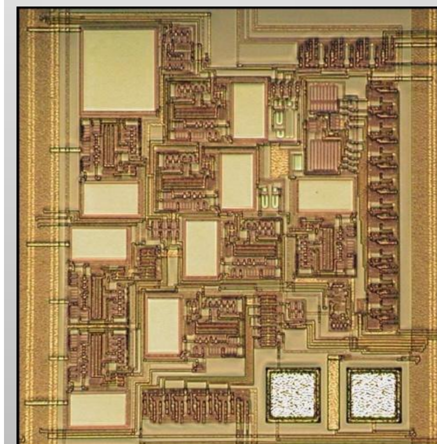
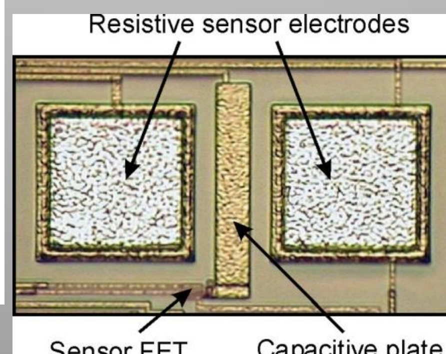
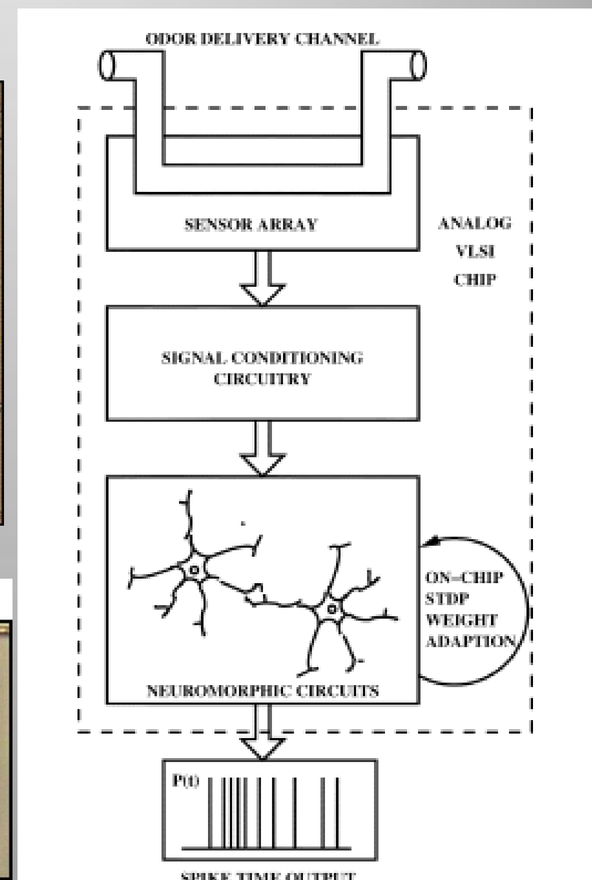


Fig. 2. Slice of the neuromorphic olfactory model. RN1 to RN3 are fed from sensors of the same type, similarly for RN4 to RN6. Here, RNs correspond to biological ORNs, PNs to M/T cells, and lateral synapses to granule cells. Weight adaption at all synapses using STDP.





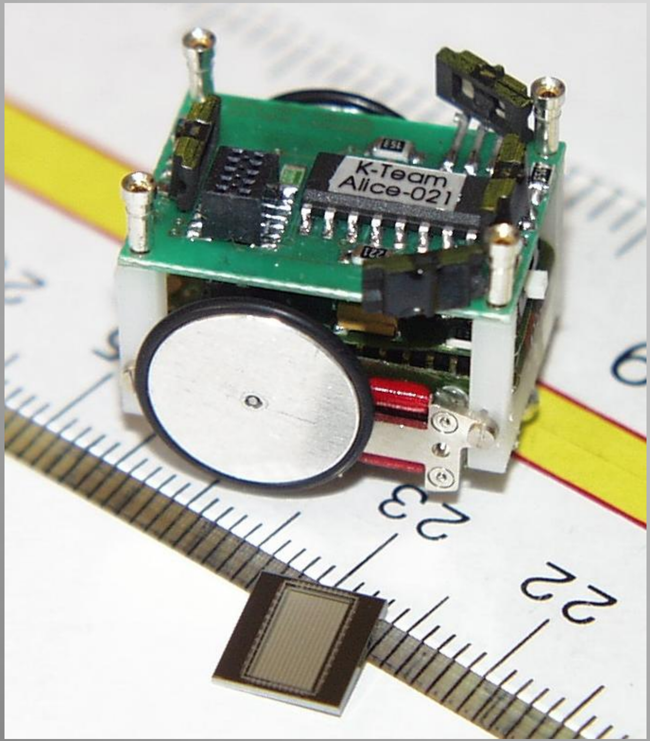


Robot Noses

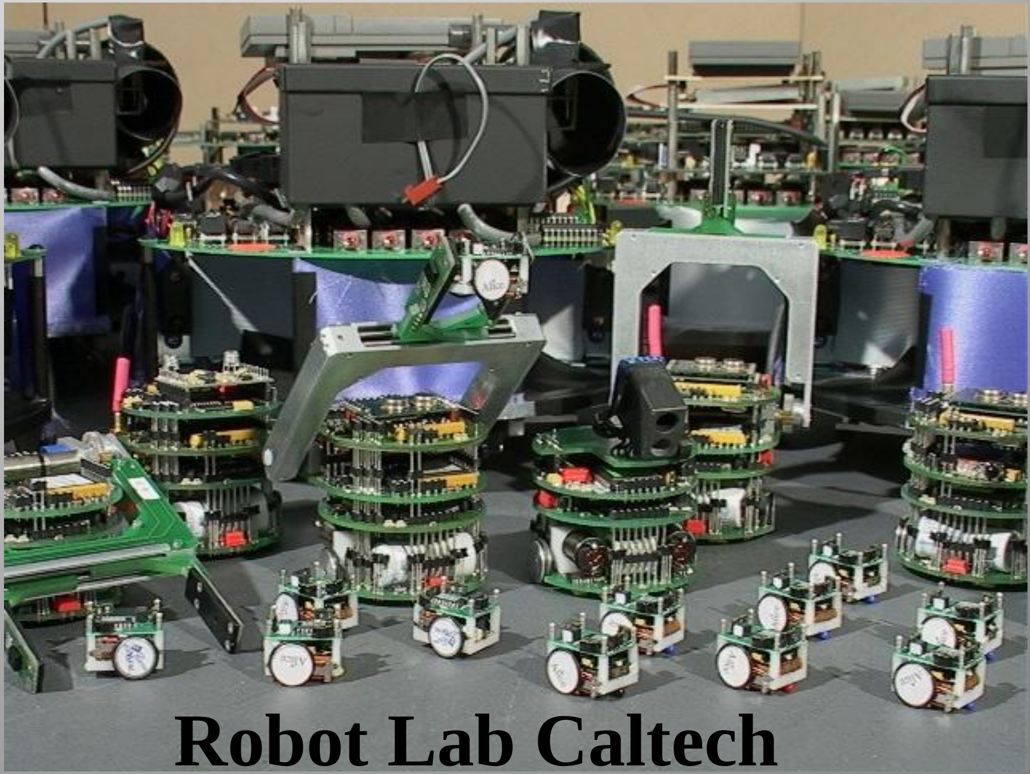
Mobile Robot Noses

- Odor classification/discrimination
- Odor localization
- Plume tracing
- Plume and odor mapping

Alice microrobots



Alice with 18x18 nose chip



Robot Lab Caltech

Biological Inspiration

- Animals are capable of impressive performance in classifying, localizing, tracking, and tracing odor trails and plumes.
- Moths can use single-molecule hits of pheromone to locate the female.
- Dogs can track scent trails of a particular person and identify buried land mines.
- Rats build complex mental maps of the odor environment to avoid exposing themselves to danger.
- Simple insects use wind sensors and chemical sensors.
- Mammals use wind, chemical, and vision processing, as well as higher cognitive mapping and behavioral strategies.
- How can we get robots to do this?

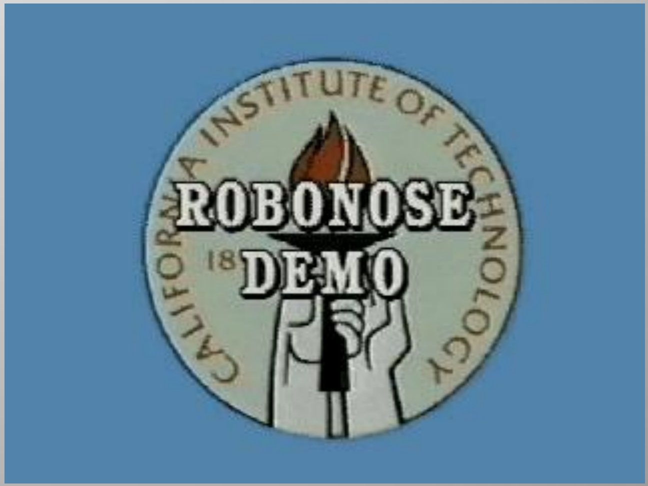
Training landmine sniffer dogs in Bosnia

Dog tracks pheasant in the dark

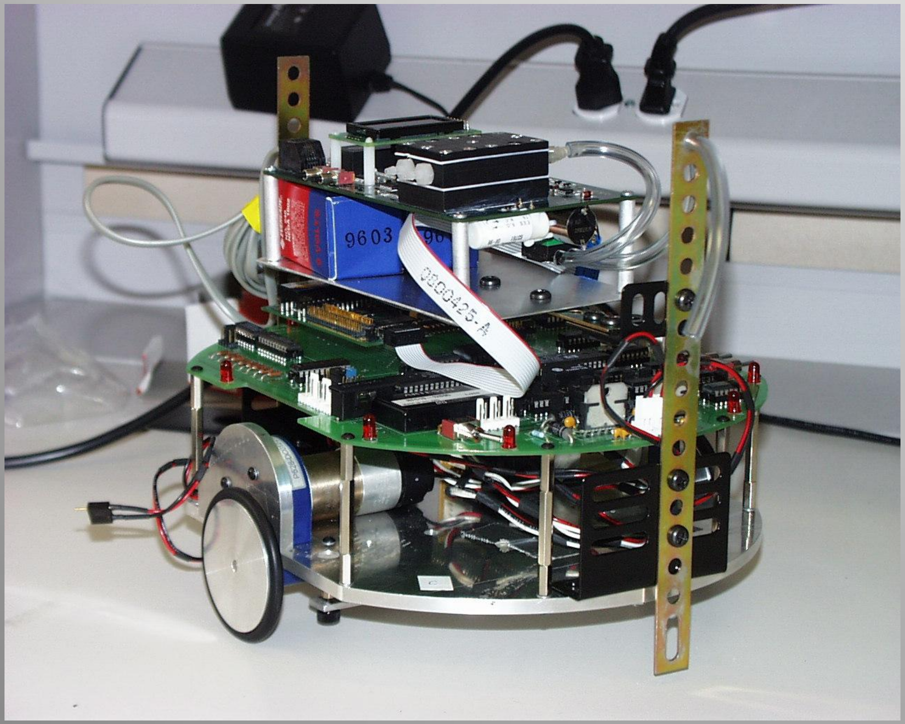
Osmotropotaxis

Termite following pheromone trail

Robot

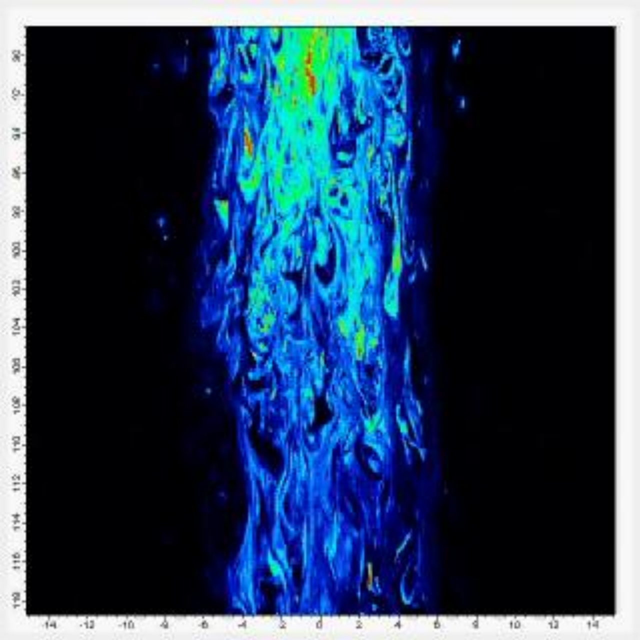


Odor Discrimination



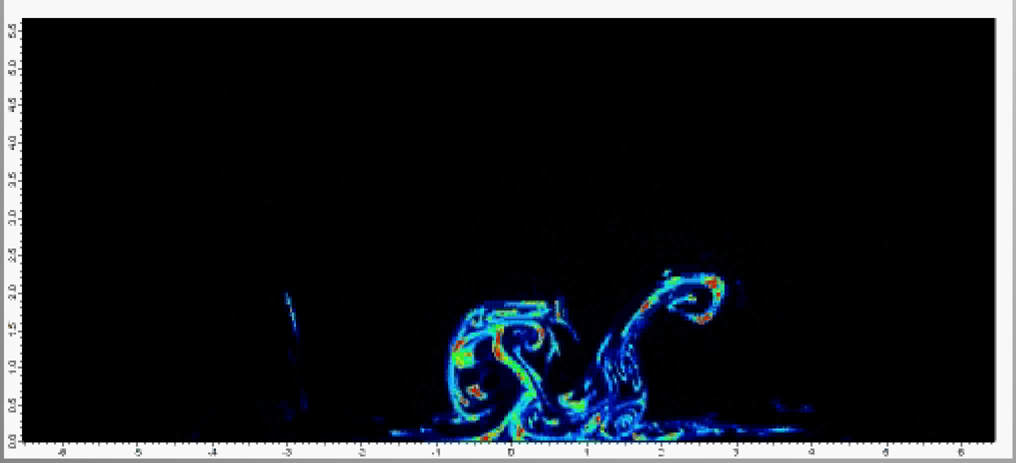
Moorebot with
Cyrano 32 sensor E-nose

Tracking an Odour Plume to its Source



View from Above

- Plume has complex dynamic "packet" structure.
- Not a simple gradient-following task.
- Instantaneous concentration far downstream can be as high as near the source.
- Yes, one can stop at a location, time average to get an estimate of local concentration, then move up-gradient.
- That takes a lot of time – the animal with a better algorithm will get the food or the mate first!

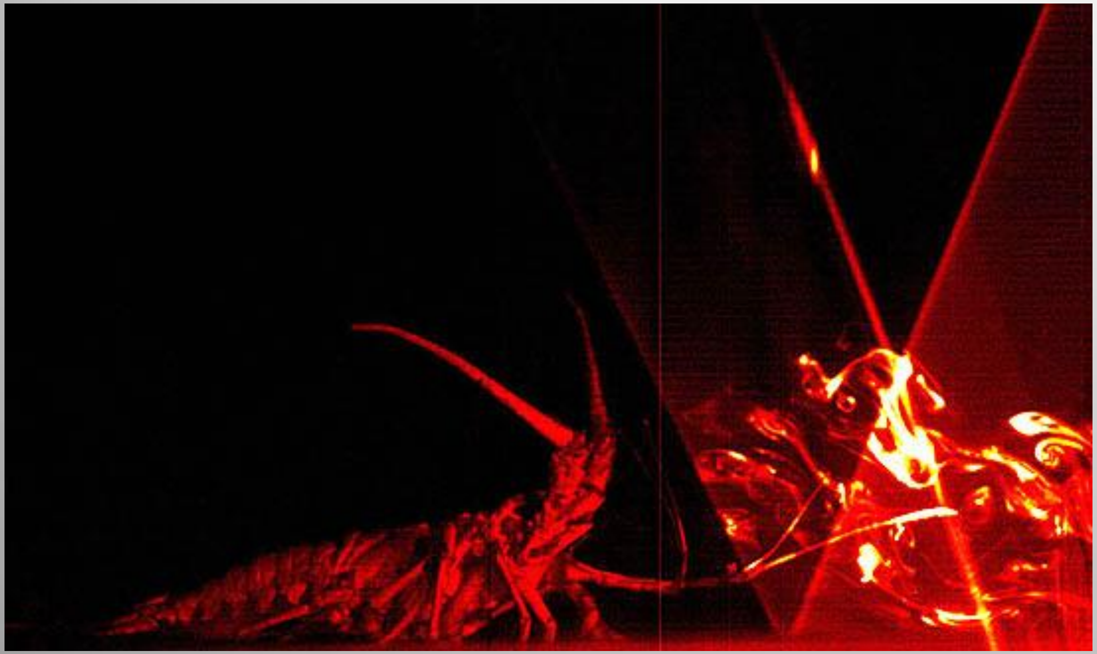


Cross Section View

Behaviorally:

1. Acquire the plume
2. Track the plume to source
3. Declare the source found (Often another modality – vision, touch)

The Lobster "knows" some Physics with its antennae "flicking" behavior



- The fast down stroke breaks the boundary layer on the sensors, so that they can purge , and then odor molecules can dive in.
- The slow upstroke then acts as a "paddle" that keeps water away from the sensors so that the smell can be decoded.
- "Flow" sensors give the upstream direction.

Plume Osmotropotaxis- Wagbot

- Uses a simple tropotaxis to detect the left or right edge of the plume and turns “inwards”.
- Uses the “physics” of the problem:
    - Waggly antennae breaks the boundary layer, purges sensor.
    - Sufficient difference in sensor facing upstream vs downstream to decode up from down with simple time delays.

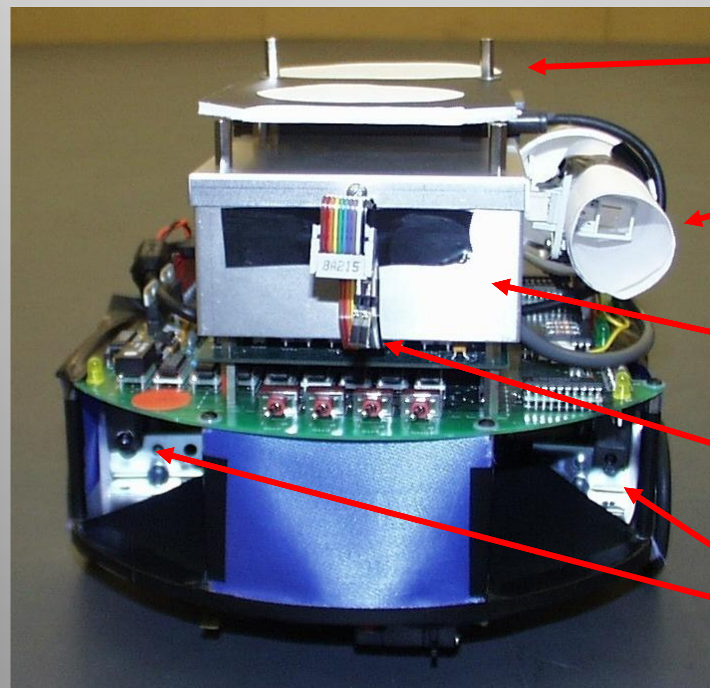
Robot Plume Source Localization

- Given odour plume, find the source of the odor plume as efficiently as possible.
- Chemical Agent Tracking.
- Task Decomposition:
  - Plume finding
  - Plume traversal
  - Source declaration

MooreBot with Integrated Wind and Odor Sensors

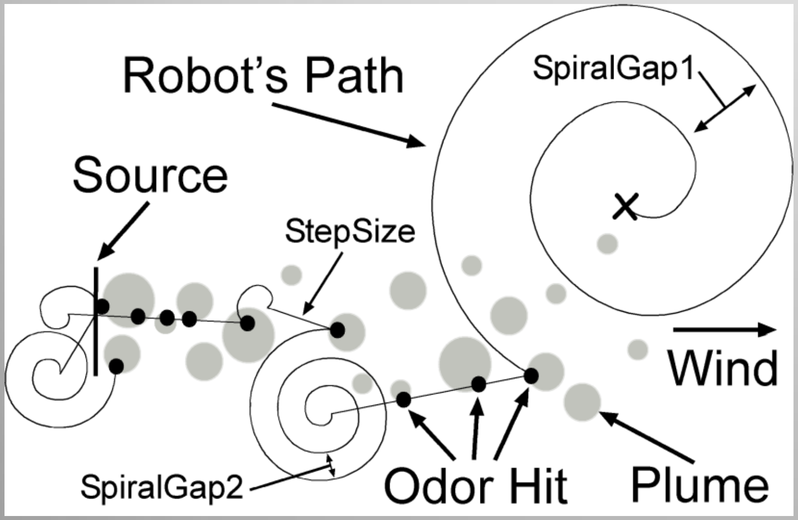

IEEE
SENSORS JOURNAL
A PUBLICATION OF THE IEEE SENSORS COUNCIL WWW.IEEE.ORG/SENSORS
JUNE 2002 VOLUME 2 NUMBER 3 ISJEAZ (ISSN 1530-437X)
SPECIAL ISSUE ON ARTIFICIAL OLFACTION

IEEE



Collective Plume Tracing

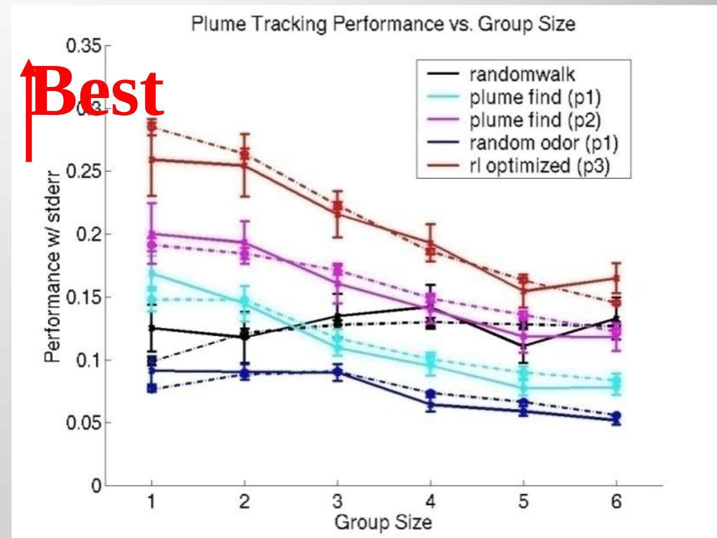
- Single Robot Behavior
  - Spiral-Surge Algorithm
  - Loosely based on moth “casting”
    - If no hit – spiral out
    - If hit – surge upwind

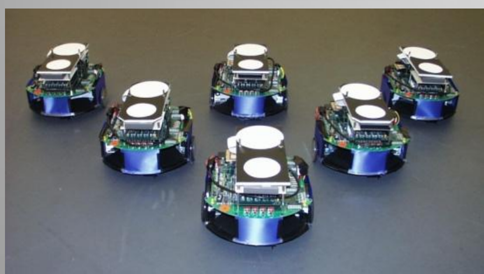


- Multi-Robot Collaboration
- Robots signal via IR beacons
  - “I have hits – come to me”.
  - “No hits here – go away”.

Collective Performance

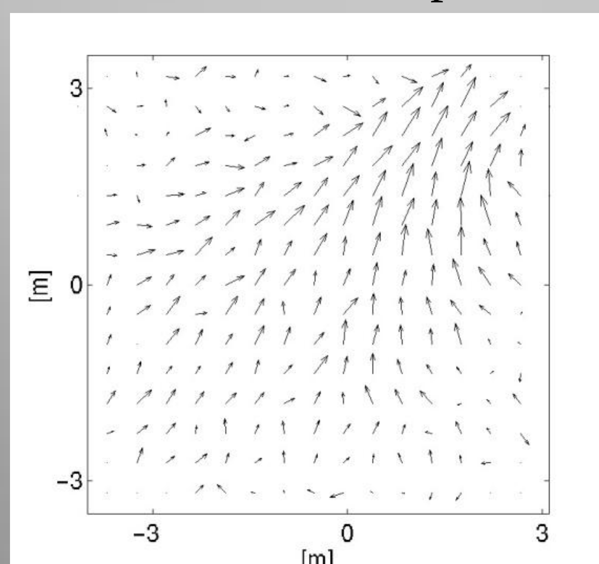
- Define performance metric = Group Energy *AND* Time First Robot.
- Optimize 7 parameters (spiralgap size, surge length, cast time, etc).
- Learned solution (p3) significantly better than hand-coded ones (p1,p2)



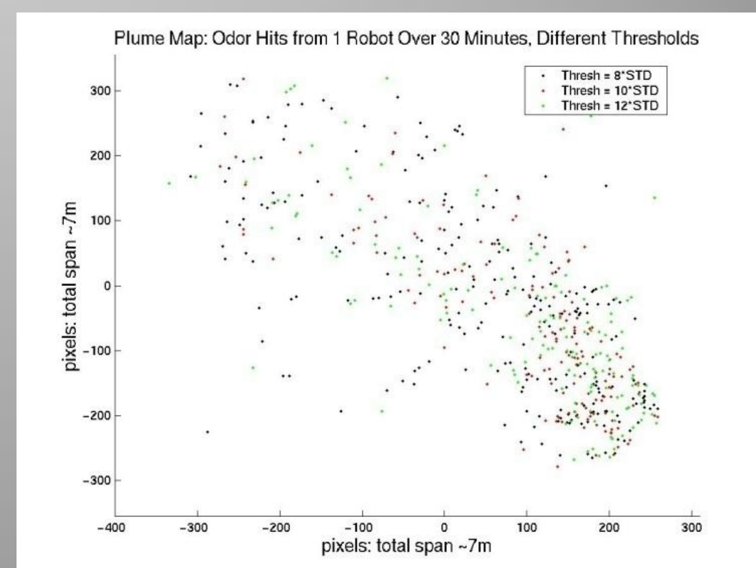


6 Robots

Wind Speed and Direction Map



Plume Hits Map



Flying Noses
being tested on Blimps and Helicopters

UWE BRISTOL
University of the West of England

The Flying Flock
Alan Winfield, Owen Holland,
Bristol Robotics Lab (UWE)

UK Defence Procurement Minister Lord Drayson congratulating Swarm Systems CEO Stephen Crampton (left) and Prof. Owen Holland (right) on winning MOD funding for the UK MOD Grand Challenge

The Mystery Substance!

- Who can’t smell it?
- Who thought it was nice/neutral? – descriptors?
- Who thought it was disgusting? – descriptors?

The Mystery Substance!

- Androstenone
- Pheremone from the sweat of a male pig!
- Beware of Internet scams selling this as the “Human Pheremone!”