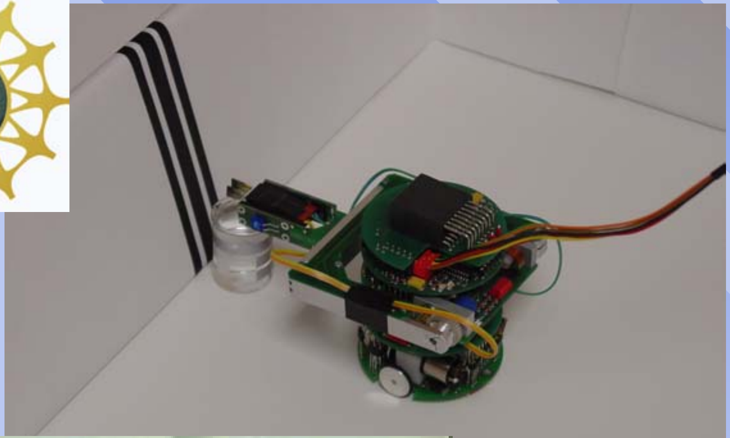
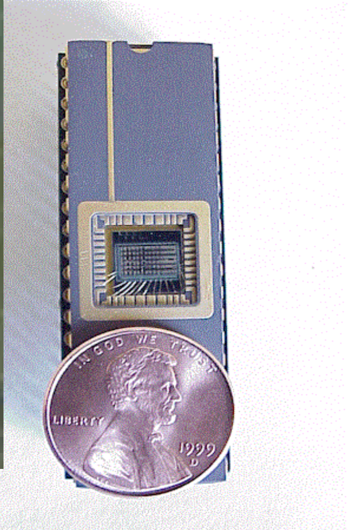
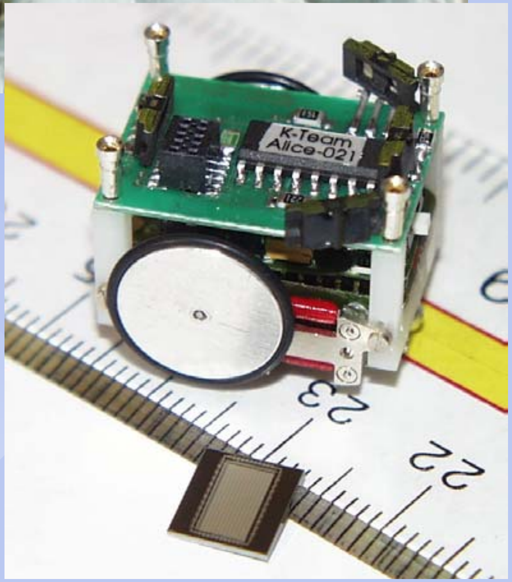
The Electronic Nose – From Neuromorphic Chips to Robot Swarms.

Rod Goodman

Cyrano Sciences Inc.
&
California Institute of Technology

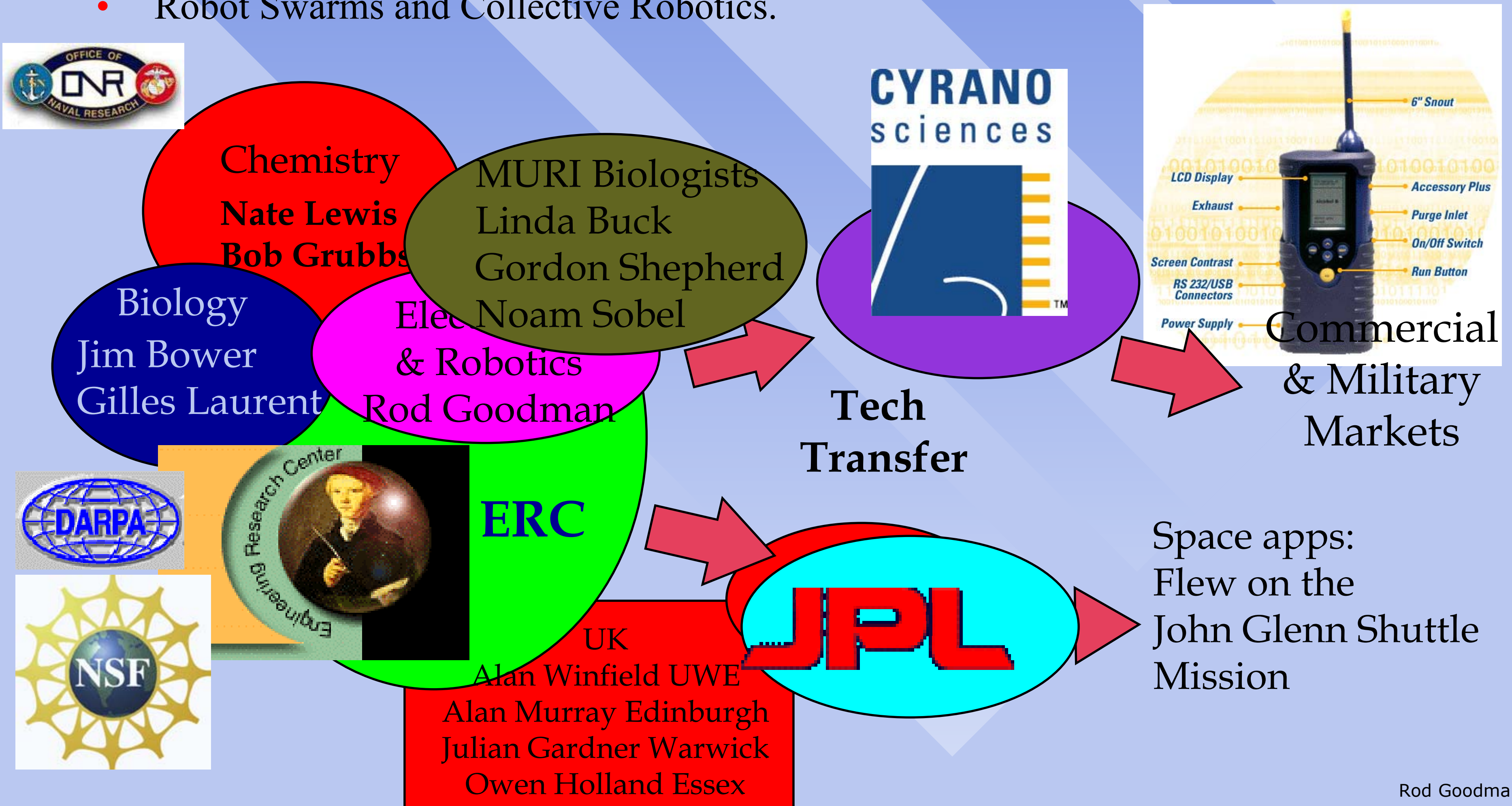






Research Themes

- Biological olfaction. * Polymer chemiresistor electronic nose technology.
- Integration of sensor arrays with neuromorphic CMOS processing. *"nose on a chip".
- Applications: Odor classification, Odor localization, Plume tracing, Odor mapping…
- Systems integration of nose chips onto robot platforms.
- Robot Swarms and Collective Robotics.



Chemistry
Nate Lewis
Bob Grubbs

MURI Biologists
Linda Buck
Gordon Shepherd
Noam Sobel

Biology
Jim Bower
Gilles Laurent

Elec
& Robotics
Rod Goodman

ERC

UK
Alan Winfield UWE
Alan Murray Edinburgh
Julian Gardner Warwick
Owen Holland Essex

CYRANO sciences

Tech Transfer

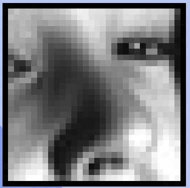
Commercial
& Military
Markets

JPL

Space apps:
Flew on the
John Glenn Shuttle
Mission

Chemical Sensing in Biology

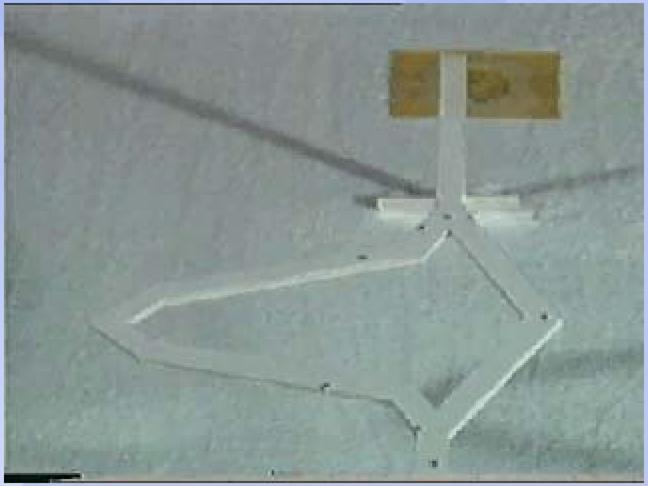
- Chemical sensing (chemoreception) is vital for survival in all animals.
- Used to find food, prey, mates.
- Used to recognize individuals of the same species, family members, predators.
- Used for communication.



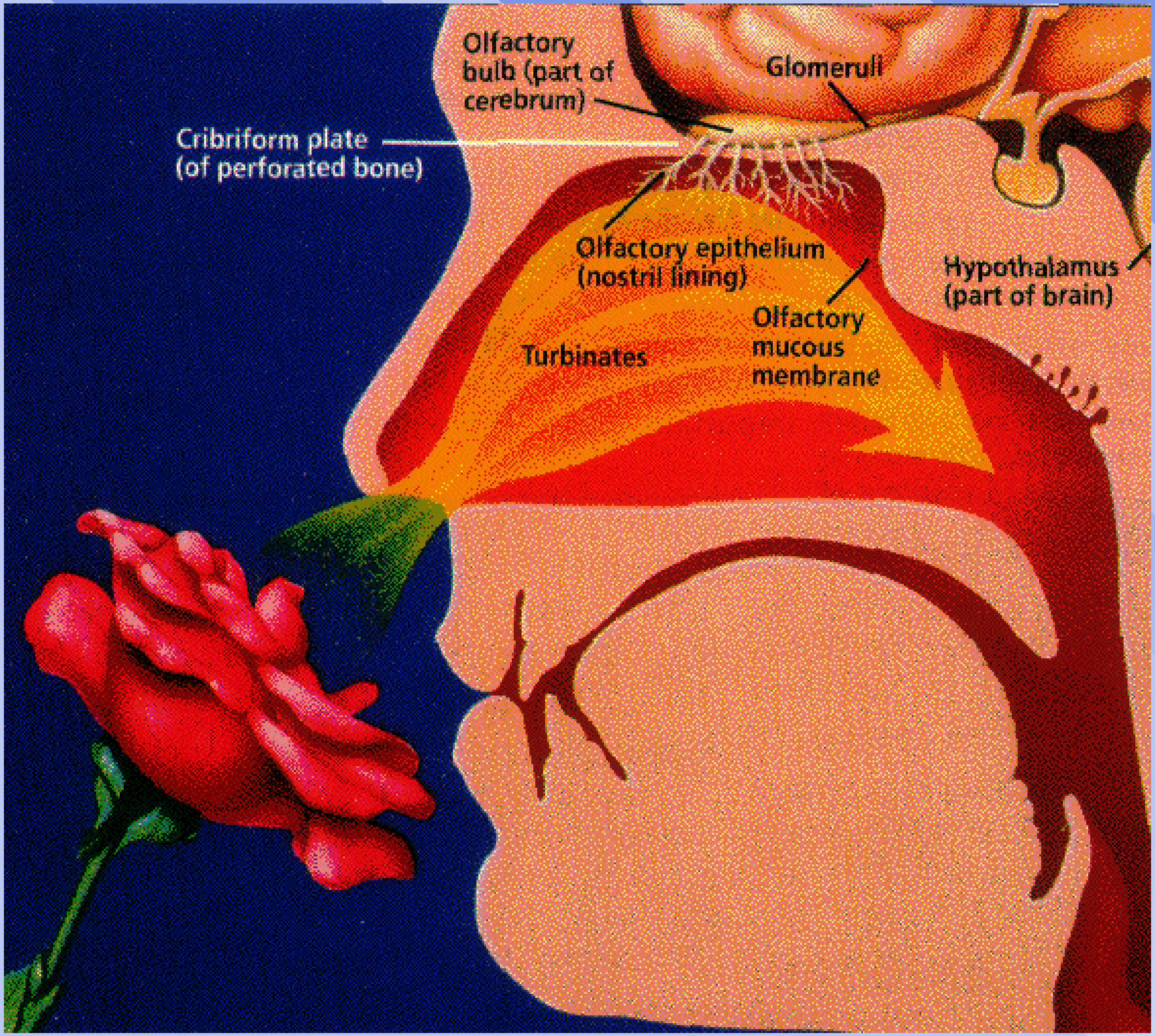
The snail gives a whole new meaning to the term "smelly feet." The snail can pick up odors with the front of its foot (the underside of a snail's body is known as the foot).

A lubber grasshopper

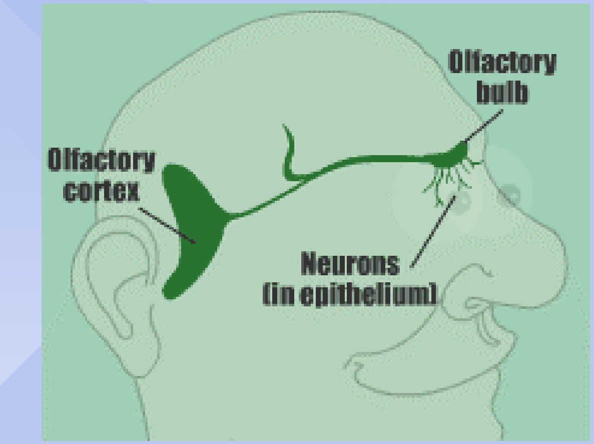
This species cannot fly.



Mammalian Olfaction



- 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.



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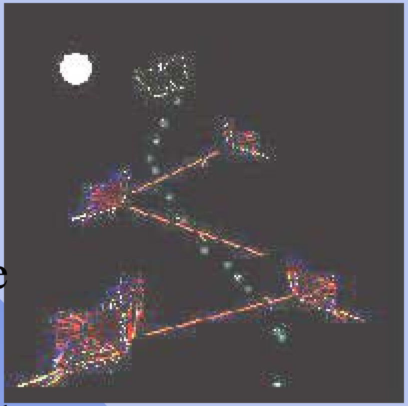
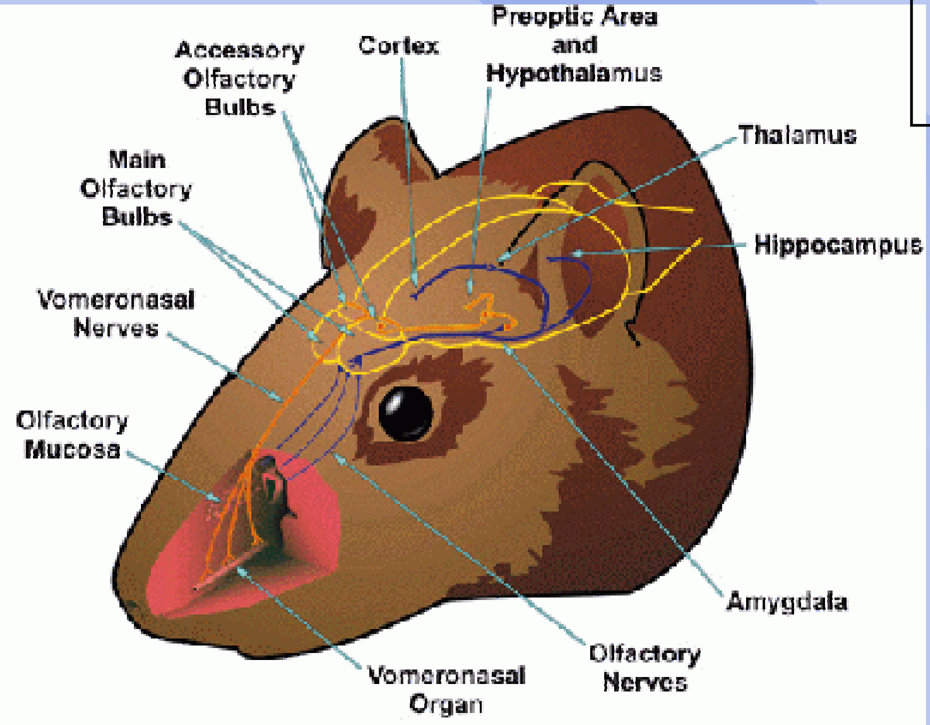
The “other” Smell Sense

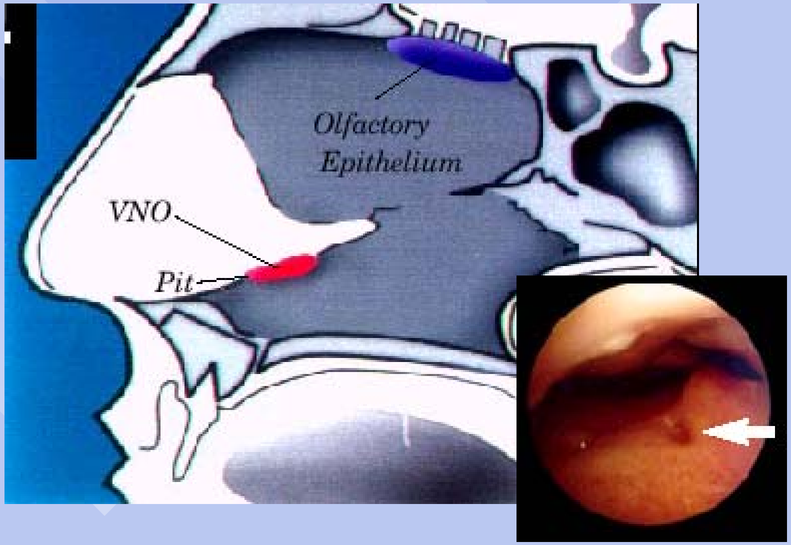


- Many insects use pheremones to signal to members of the opposite sex.
- The receptors for are very sensitive and specific. A moth can detect a single molecule of pheremone from a female a mile away.

- 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.





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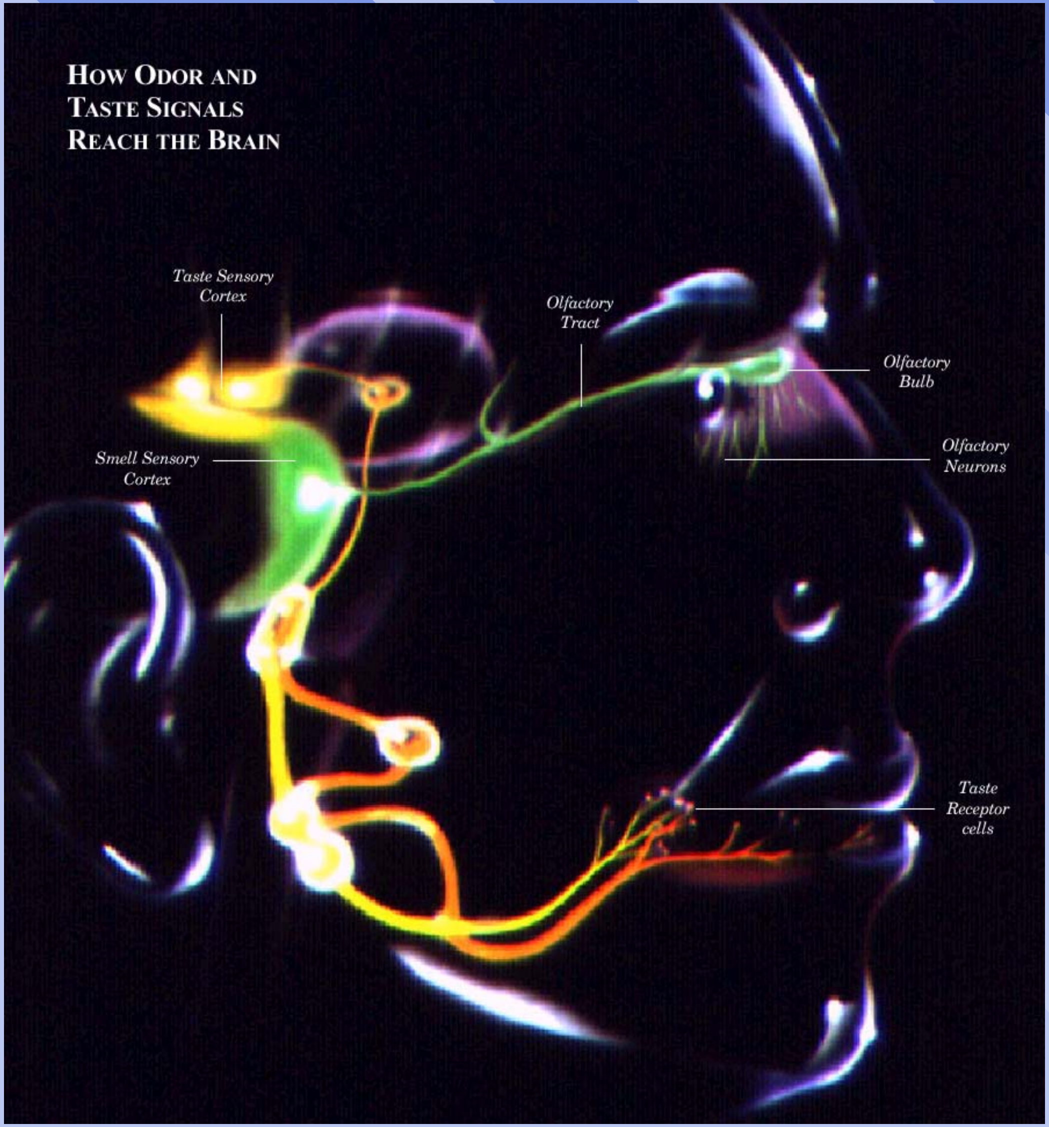
Smell, taste, and pain



- Most of taste is really smell.
- There are five tastes:Sweet, Sour, Salty, Bitter, Glutamate.
- But you can recognize about 10,000 different odors.
- The Nose is the gatekeeper for the mouth – if it smells bad don’t eat it!
- The taste pathways connect to the limbic system, a region of the brain concerned with motivation, emotion and certain kinds of memory.
- 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 system – e.g. menthol

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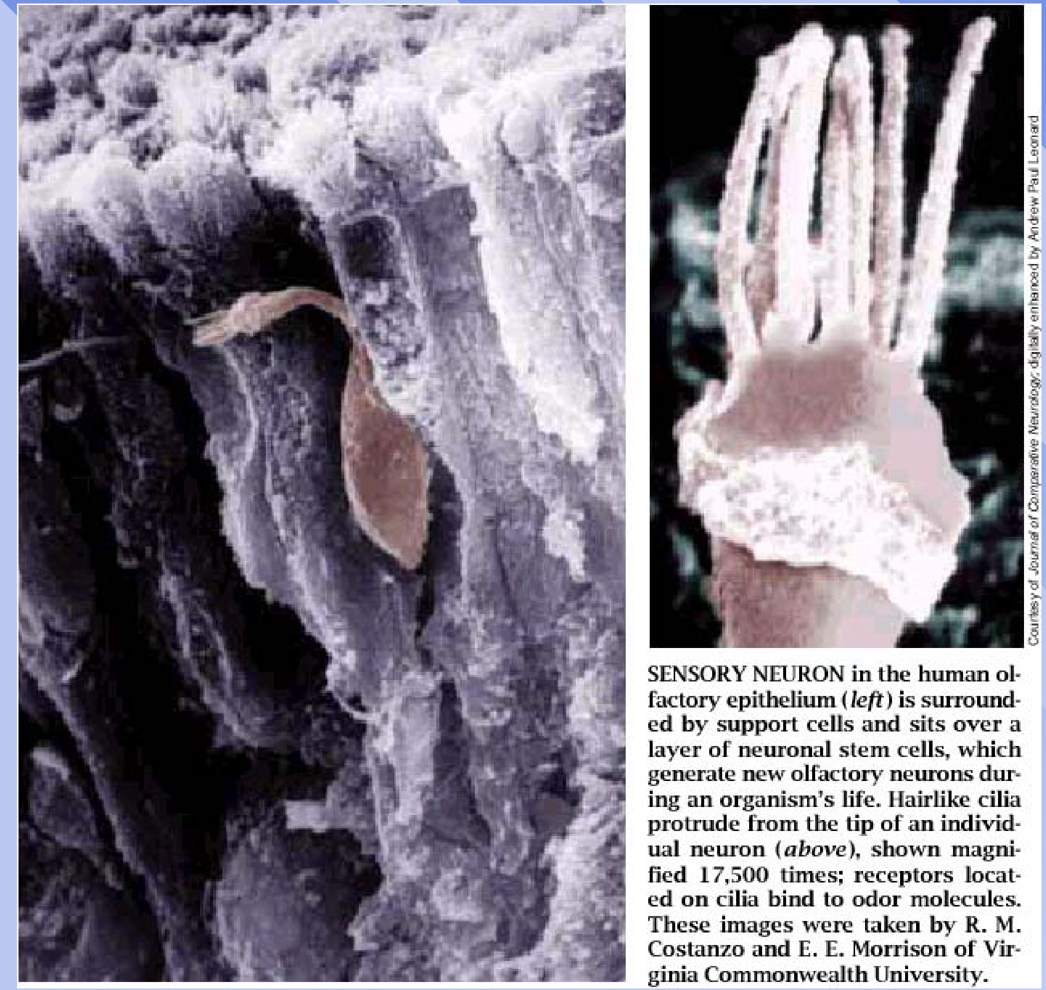
Olfactory Receptor Neurons

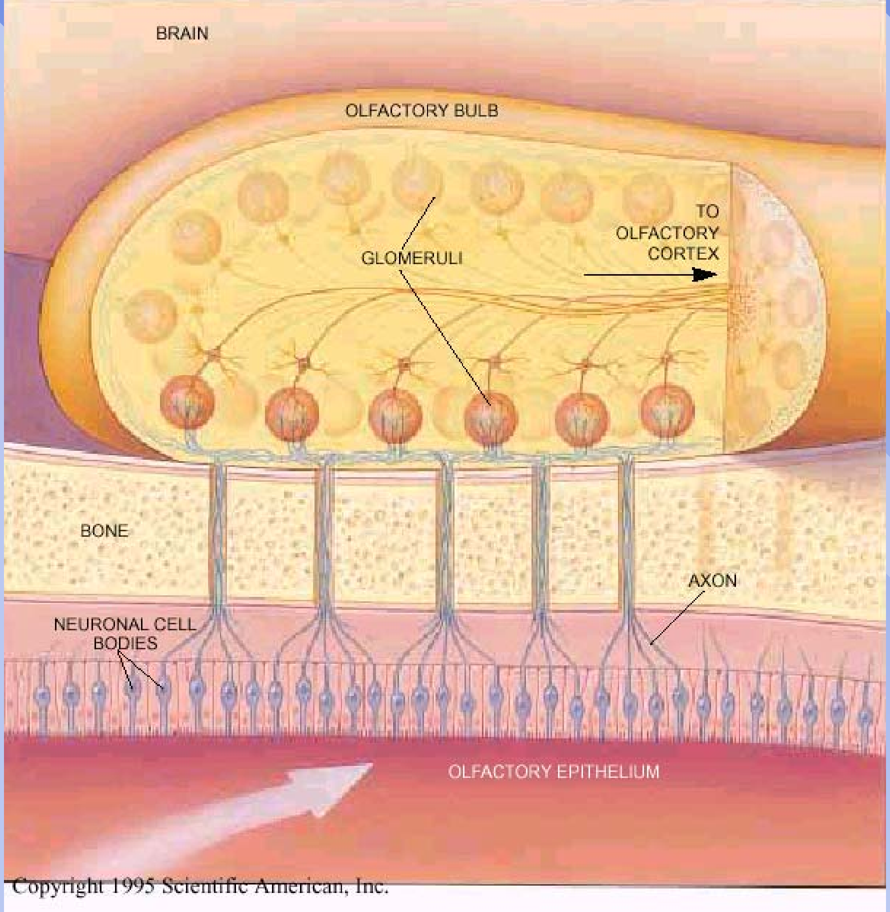


SENSORY NEURON in the human olfactory epithelium (*left*) is surrounded by support cells and sits over a layer of neuronal stem cells, which generate new olfactory neurons during an organism's life. Hairlike cilia protrude from the tip of an individual neuron (*above*), shown magnified 17,500 times; receptors located on cilia bind to odor molecules. These images were taken by R. M. Costanzo and E. E. Morrison of Virginia Commonwealth University.

Courtesy of *Journal of Comparative Neurology*; digitally enhanced by Andrew Paul Leonard

- Mammalian olfactory systems have large numbers of ORNs in the epithelium (~10M humans, ~100M dog).
- There are ~1000 ***different*** ORN genes. (We smell in ~1000 different “colors”).
- Sensors are ***broadly*** tuned:
  - Single receptor recognizes multiple odorants (ligands).
  - A single odorant is recognized by multiple receptors.
  - Up to 10% are firing for any given oderant.
- The only(?) neuron that regularly dies and is replaced by a new neuron about every 60 days.
- A full 1% of the rat genome is encoding for ORNs – smell is important!
- Each receptor expresses only ***one*** gene.

The journey from Olfactory Epithelium to the Olfactory Bulb



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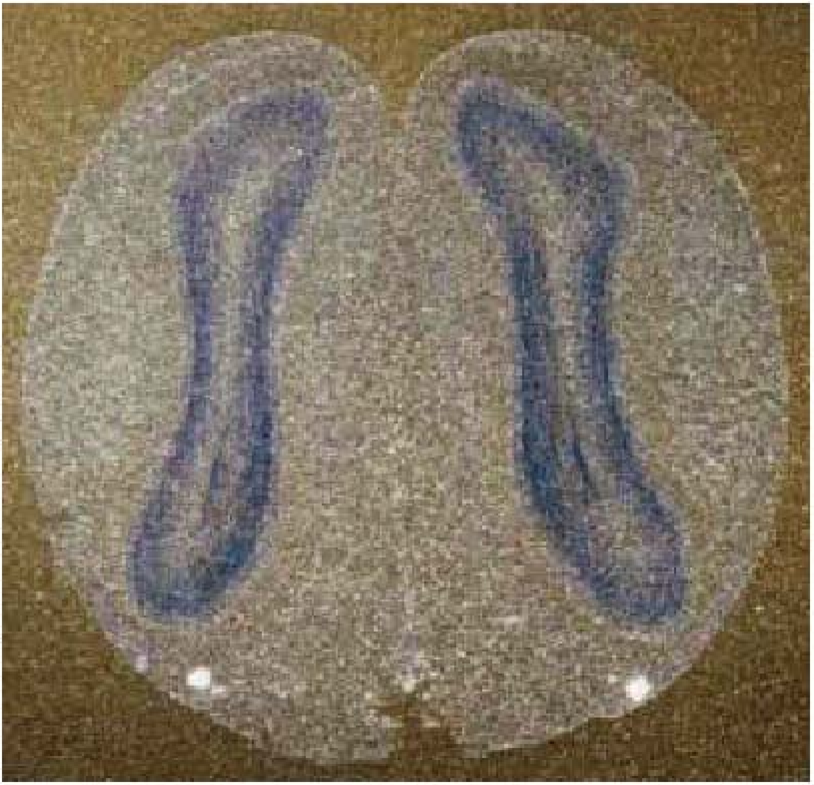
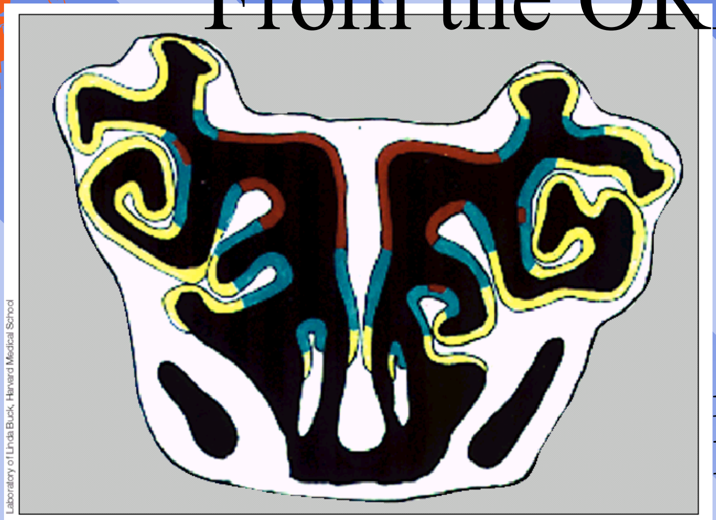


STEVE K. CHAO AND ROBERT VASSAR; courtesy of *Cell*

OLFACTORY BULB of a rat is seen in cross section in this micrograph. The two white spots indicate where axons that bear a specific receptor gene converge. Because each axon projects to a characteristic location in the olfactory bulb, the bulb provides a two-dimensional map of odor quality, which the olfactory cortex employs to decipher an odor.

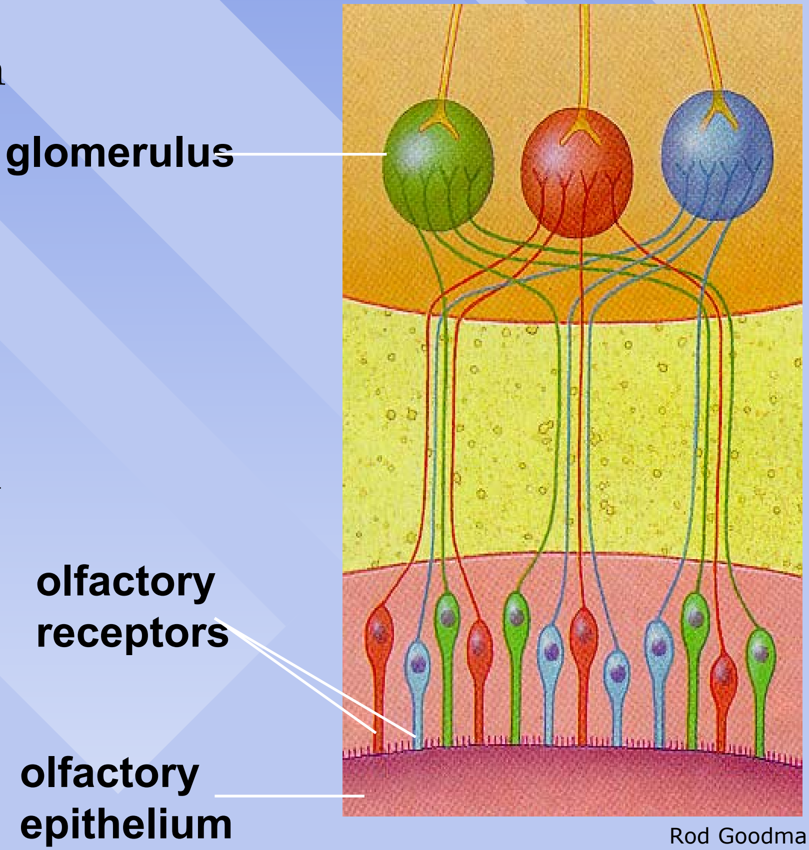
- There is some bi-lateral symmetry in the Olfactory bulb.
- Why? – not known - but you have a preferred nostril left or right which switches every hour.

From the ORN to the Glomeruli



- 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)

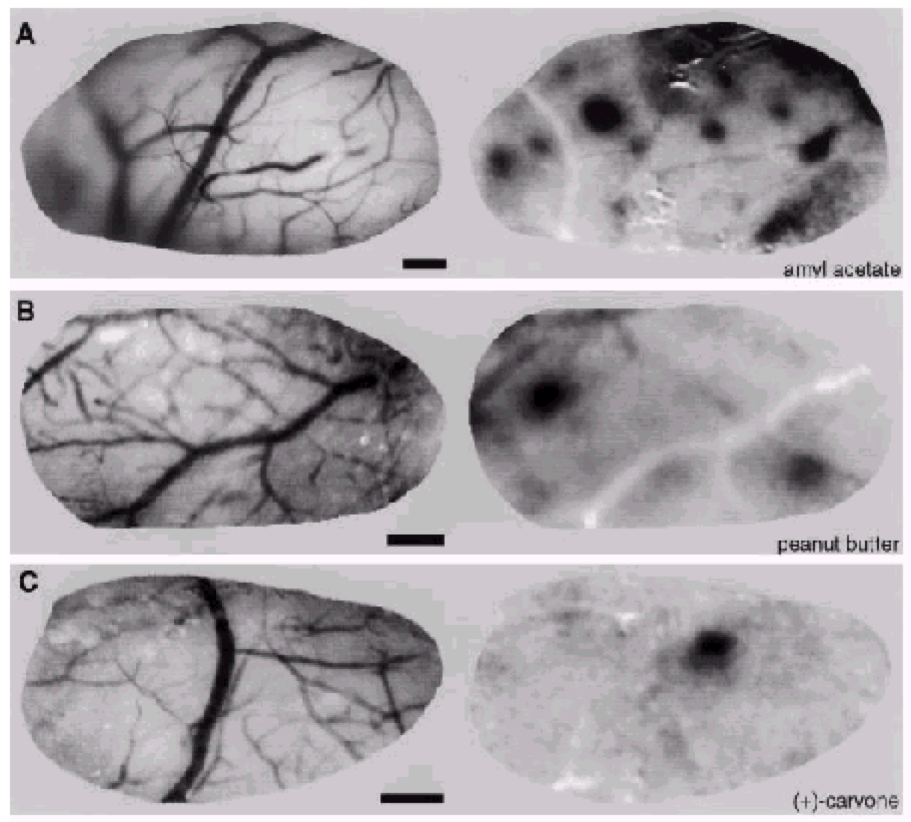
- Each Glomerulus (~2000) receives signals from only **one** type of ORN.
- The axons of a given ORN converge on 2 glomeruli, where they form synapses with bulb mitral and tufted relay neurons.
- The glomerulus also has projections from intrinsic periglomerular cells, Granule cells, and lateral M/TCs (not a simple relay!)
- Approximately 2500 receptors impinging into each Glomerulus. (This makes sense: ORNs die- you need redundancy, Improved signal to noise ratio by square root N.



Rod Goodman

A Code in the Nose

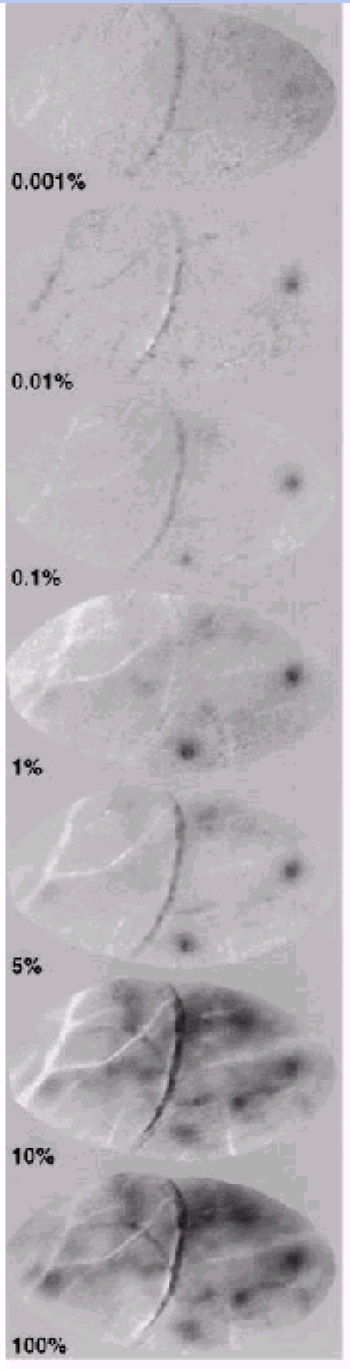
- The spatio-temporal pattern of glomeruli activation provides the pattern that is then interpreted by the brain as odor quality and intensity.
- The pattern is stereotyped across a species, and similar inter-species.



Rubin and Katz, Neuron, 1999

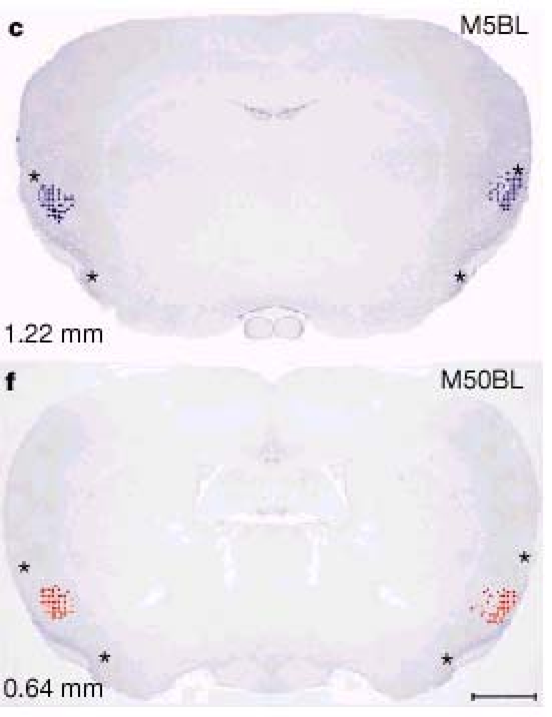
- Different odors activate different glomeruli

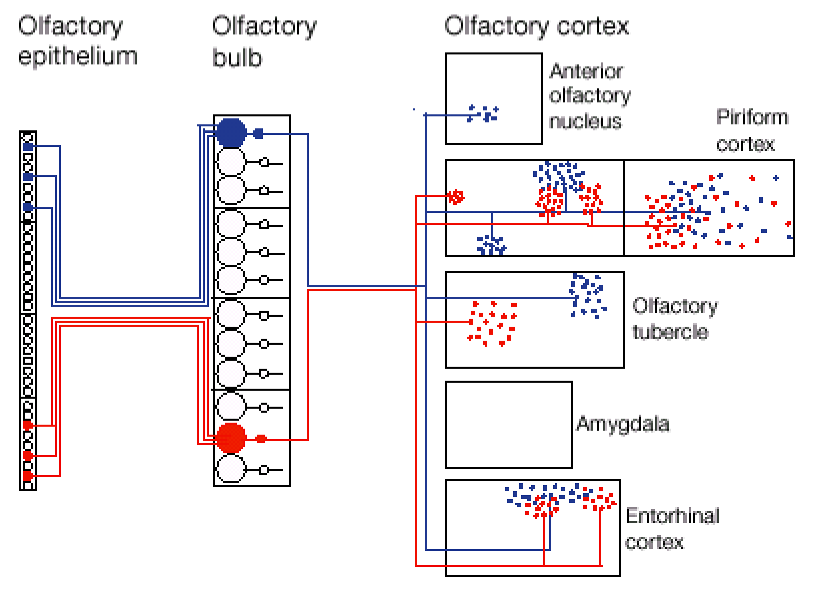
- As concentration increases more glomeruli are activated



A Code in the Cortex?

- The map in cortex is also stereotyped, with bilateral symmetry.
- A single glomerulus mitral/tufted relay neuron projects axons to multiple cortical areas. Some of which overlap.
- Mitral cells project axons to the entire olfactory cortex, but tufted cells project only to the most anterior areas (AON, OT).
- Single neurons in cortex may receive combinatorial inputs from multiple ORs.
- This may allow for parallel and perhaps differential processing.





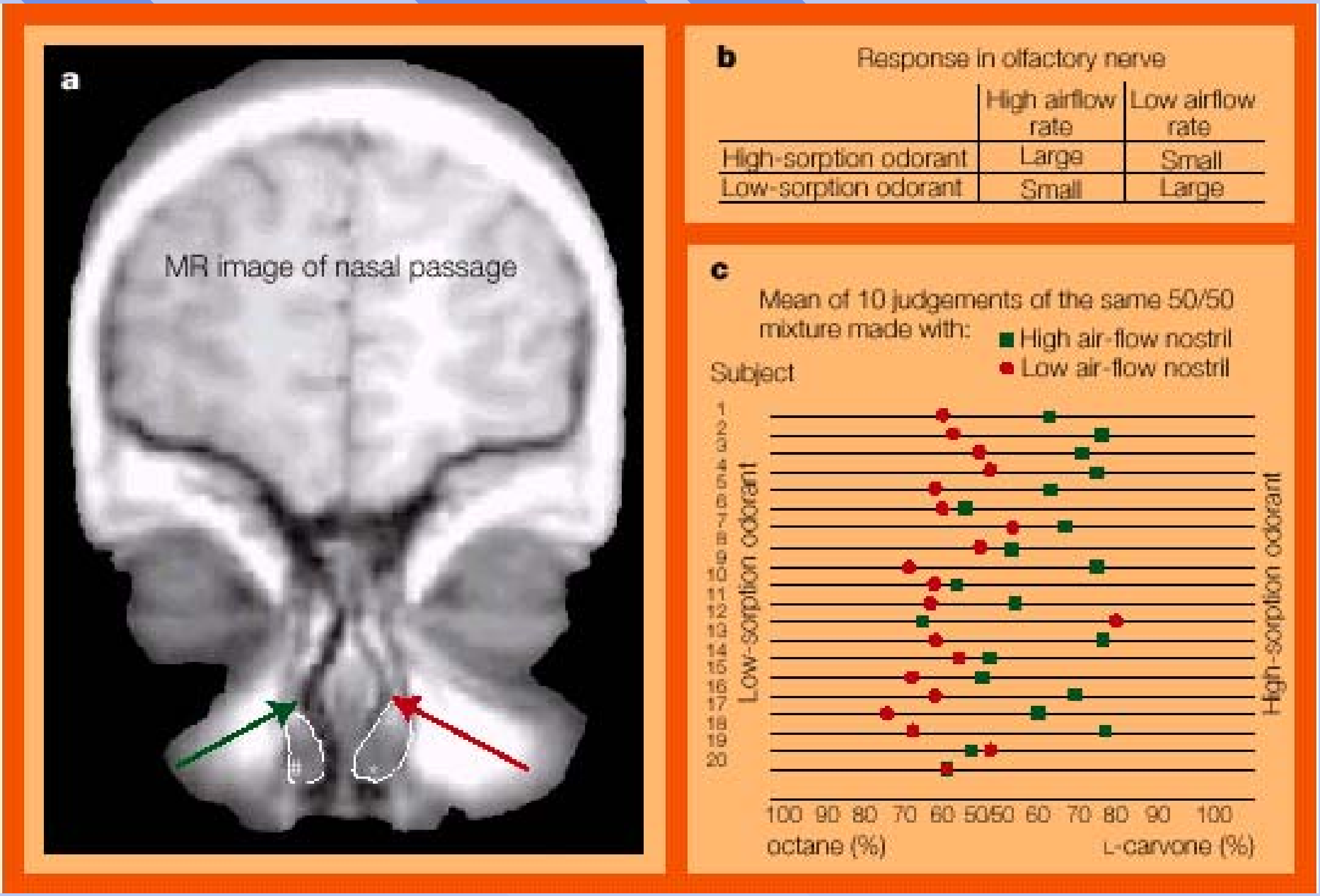
Linda Buck, Nature Nov 2001

Rod Goodman

Subtleties in a Sniff

Noam Sobel,
Nature 1999

- Evidence of "pre-concentration" in olfactory mucosa.
- Different maps from low and high flow nostril.
- Depends on the sorption characteristics of the odorant.



Response in olfactory nerve

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

High-sorption (low Vapor Presuure) odorants at low flow are sorbed to the epithelium before moving far hence response is concentrated to a small area and is low, conversely at higher flow they are spread out more in area and response is high.

Vice-versa for Low-sorption (high Vapor Pressure) odorants.

The Role of Oscillations

- Gilles Laurent (Caltech) (Annu. Rev. Neurosci. 2001) has shown that oscillations are a key part of the coding performed in the olfactory bulb (I.e. in the locust antennal lobe).
- He has observed initial intensity coding (for coarse categorization) gives way to synchronized activations (for fine discrimination) as the intensity habituates.
- He postulates that the OB performs a fundamental re-coding of the ORN signals to exploit the use of time, which is possible because olfaction is a slow sensory modality.
- Thus olfactory memories are stored as dynamic activation trajectories in (possibly associative memory) as opposed to “static” Hopfield type “attractors”.

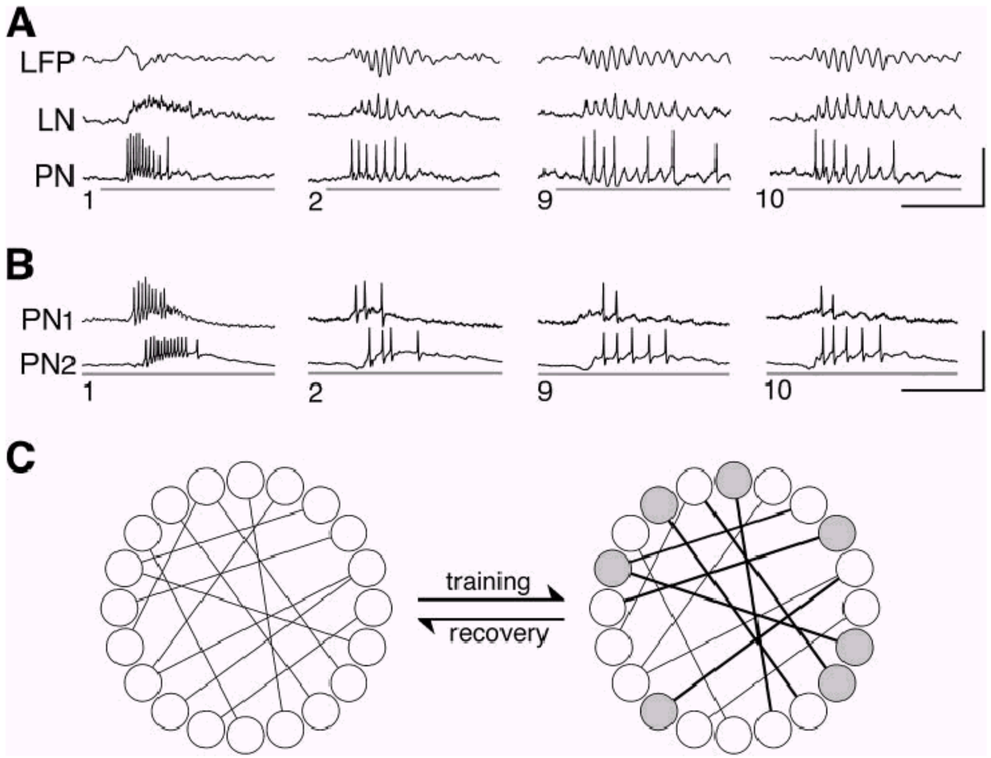


Figure 2 Nonstationarity of network dynamics. Repeated exposure to an odor causes a decrease in response intensity but an increase in oscillatory coherence and spike time precision. (*A*) Simultaneous local field potential (LFP) and intracellular recordings from a local (LN) and projection (PN) neurons during early (1–2) and later (9–10) trials. Horizontal bar indicates odor delivery. Calibration: horizontal, 300 ms; vertical (mV), .8 (LFP), 10 (LN), and 40 (PN). (*B*) From a separate experiment, odor-elicited responses in two simultaneously recorded PNs illustrate increasing spike time precision over successive stimulus trials. Calibration: horizontal, 200 ms; vertical: top trace, 70 mV; bottom trace, 40 mV. (*C*) Putative mechanisms for use-dependent changes in network dynamics; when the naïve AL receives repeated stimulations, only the activated neurons and/or their interconnections undergo (as yet uncharacterized) modifications (training) that endure for several minutes in the absence of further odor stimulation and spontaneously returns to the naïve state (recovery) once stimulation ends (see Stopfer & Laurent 1999).

The Dimensionality of odor Space?

- In many e-nose applications about 5 principle components are sufficient.
- Work of Chris Chee and Jim Bower at Caltech suggests there may be three "perceptual" opponency axes:
  - Fruity-Sulfur
  - Floral-Putrid
  - Green-Fatty

- They suggest that olfaction may be evolved to be a detector of "metabolic" procesess (e.g. food decay, metabolic characteristics of a predator, etc))

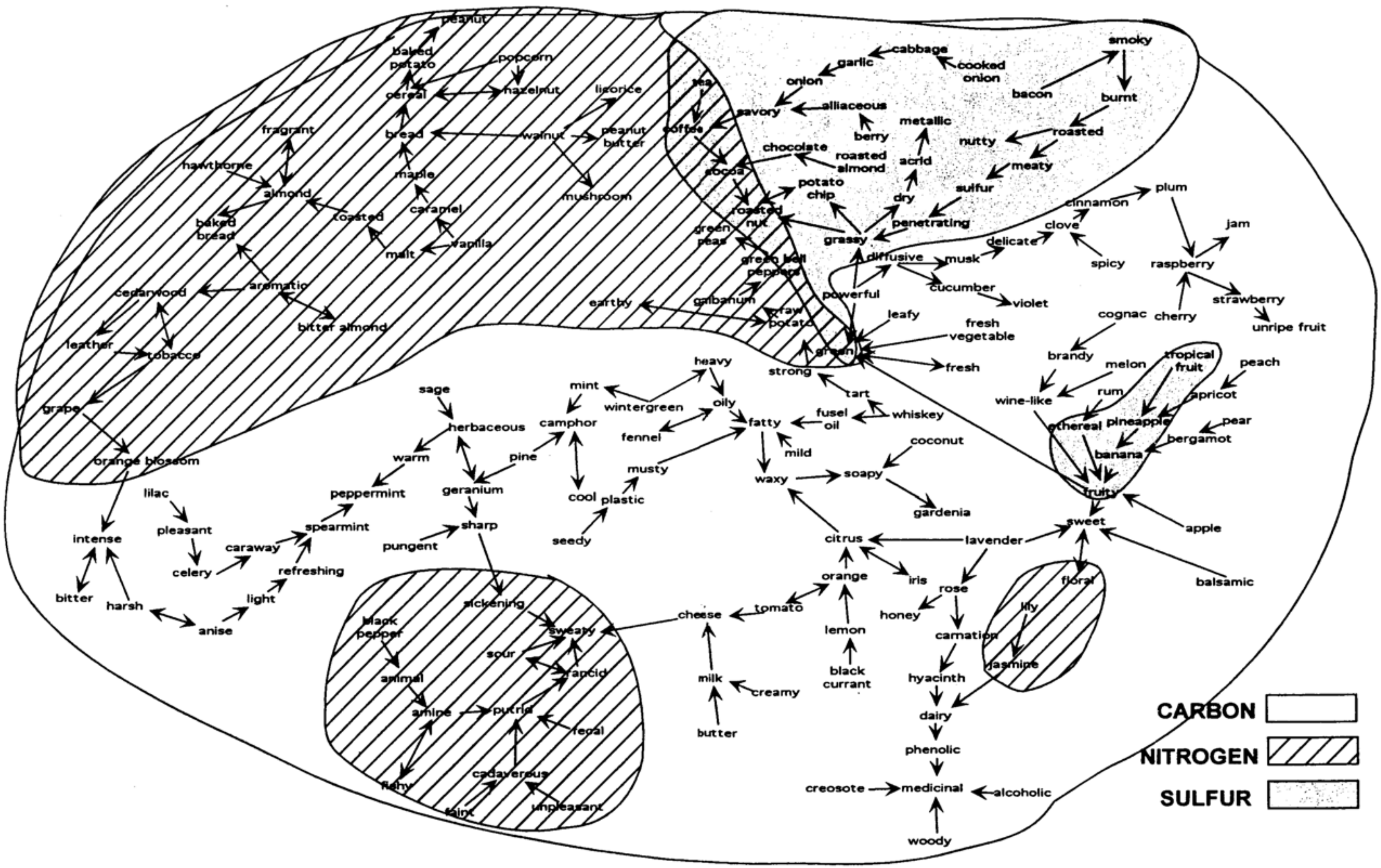
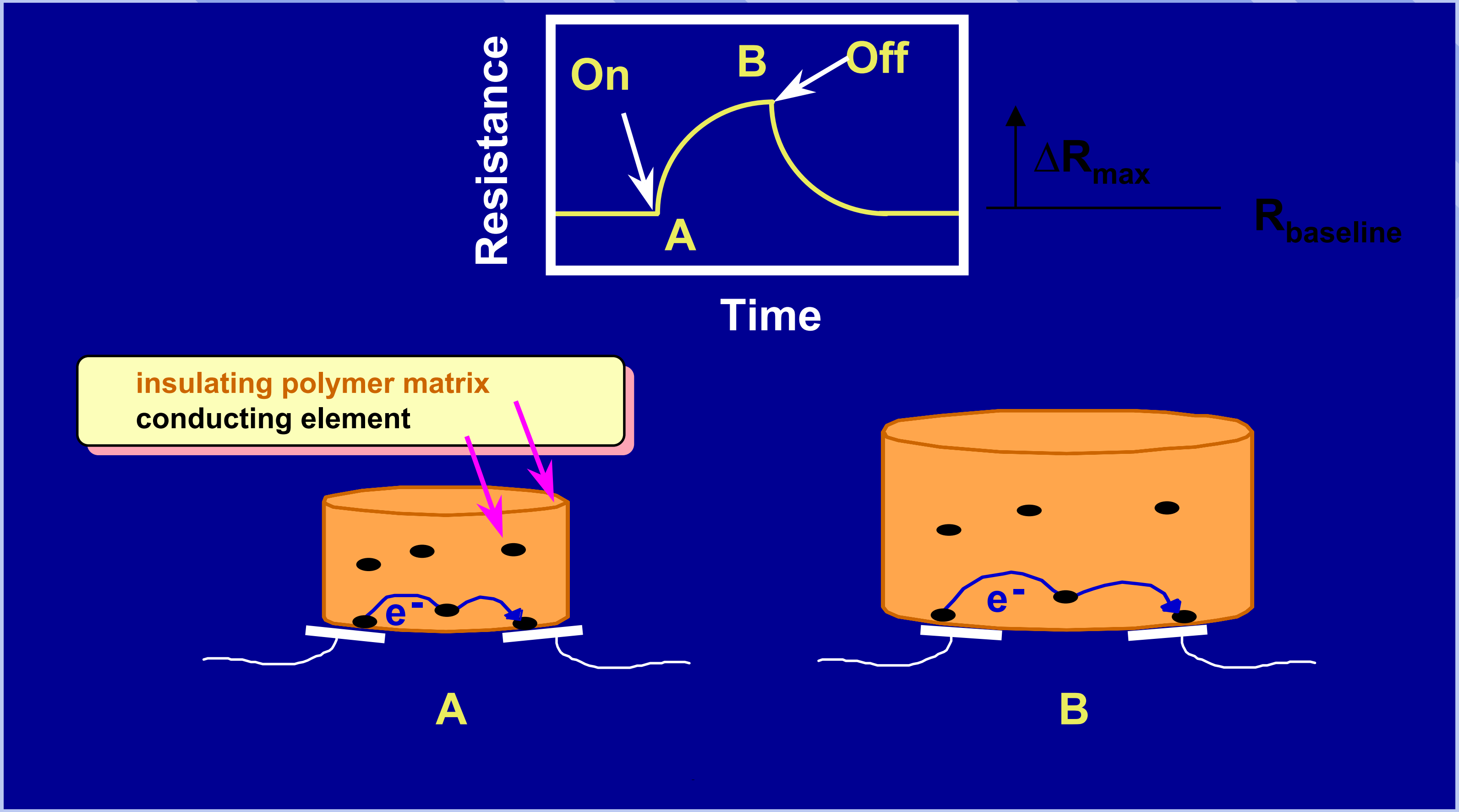


Figure 5. Carbon, Nitrogen, and Sulfur map to contiguous regions on the Aldrich map.

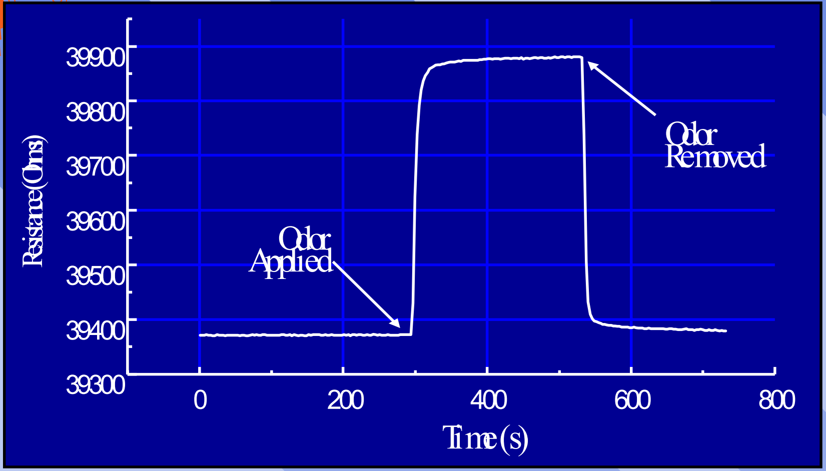
Chris Chee

Polymer Enose Technology – developed by Lewis lab (Chemistry) at Caltech

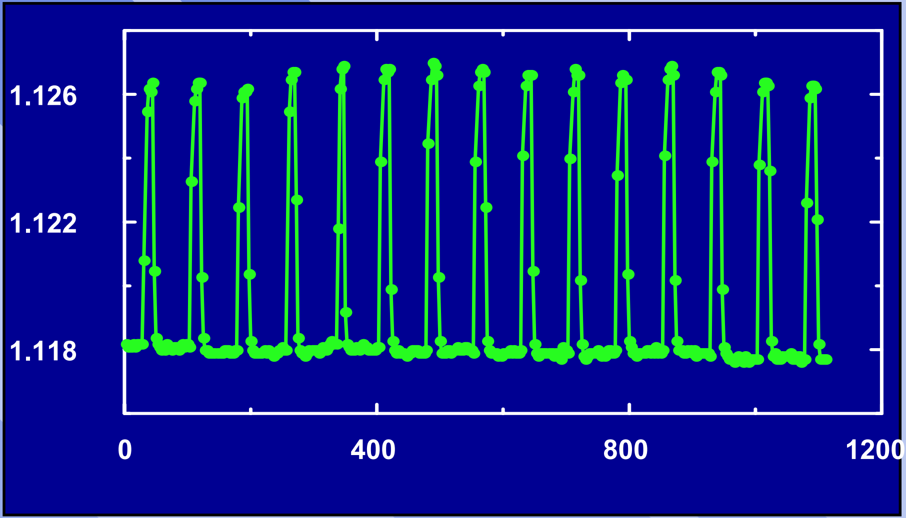
- Polymer doped with conducting particles.
- Sensor polymer material swells upon exposure to odor.
- Results in a long path for current, hence higher resistance.
- Conduction mechanism primarily electron tunneling.



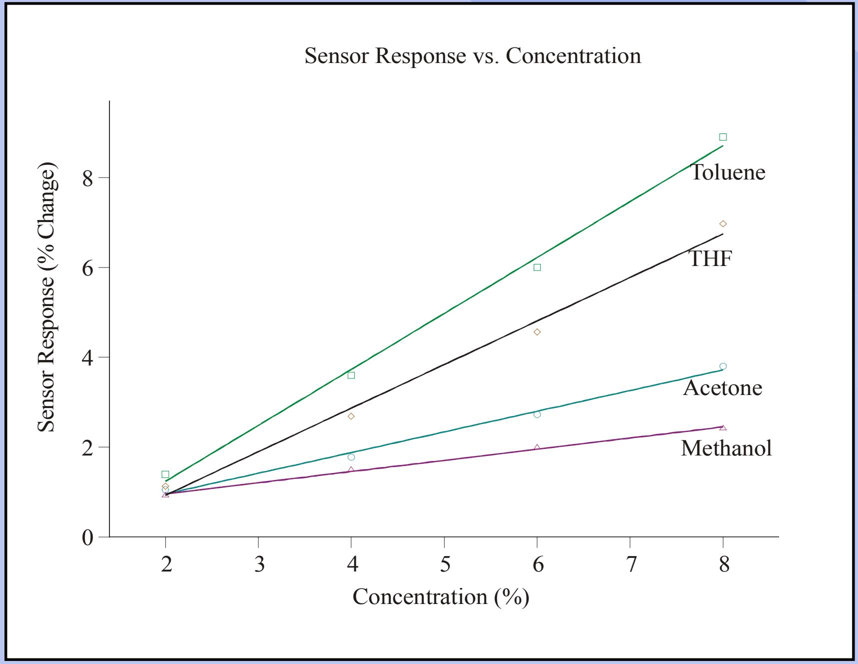
Sensors are:



Fast (<100ms) – essential for robotic applications



Repeatable-essential for real world applications

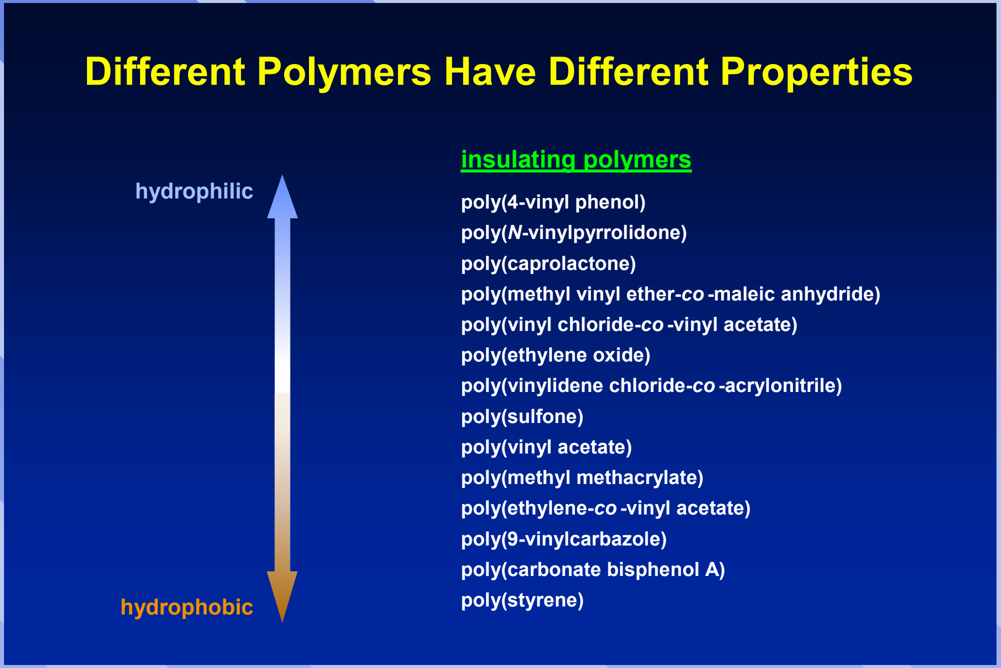

Sensor Response vs. Concentration

- **Linear with concentration** – essential for simple concentration invariant pattern recognition (unlike the mammalian olfactory system)
- **Broadly tuned** – one sensor responds to many different odors to varying degrees (like the mammalian olfactory system)

Array based sensing

Technologies:

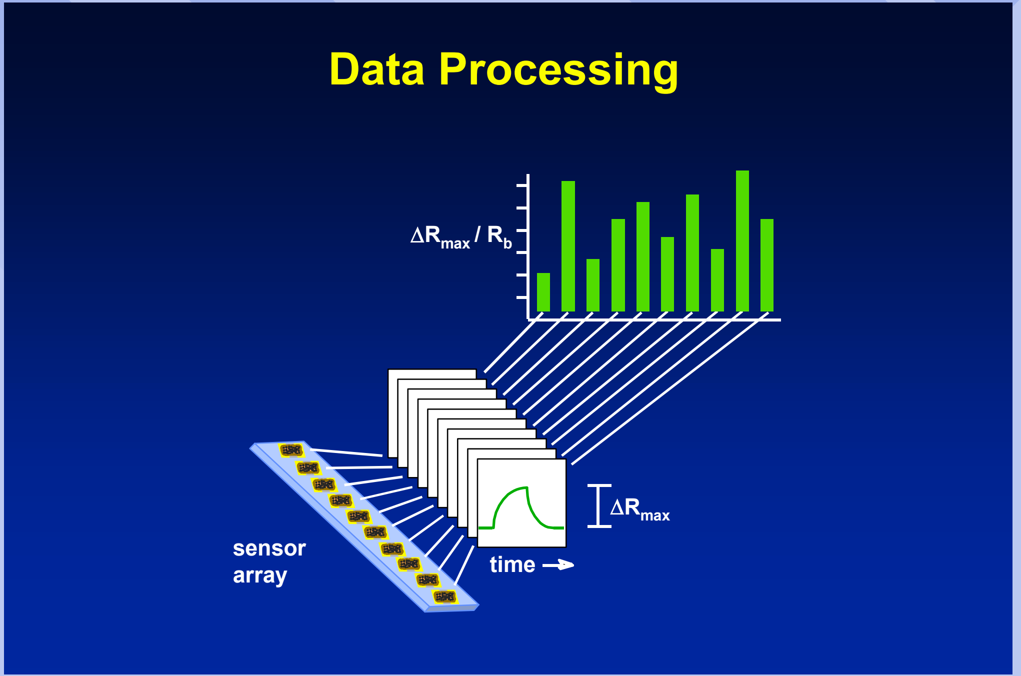
- **Arrays of carbon black-polymer composite detectors *(Lewis et al)***
- **Arrays of conducting polymer detectors *(Persaud, Gardner et al)***
- **Arrays of QCM detectors *(Grate et al)***
- **Arrays of polymer-fluorescent dye detectors *(Walt et al)***
- **Arrays of SnO_2 detectors *(Gardner et al)***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



Different Polymers Have Different Properties

insulating polymers

poly(4-vinyl phenol)
poly(*N*-vinylpyrrolidone)
poly(caprolactone)
poly(methyl vinyl ether-*co*-maleic anhydride)
poly(vinyl chloride-*co*-vinyl acetate)
poly(ethylene oxide)
poly(vinylidene chloride-*co*-acrylonitrile)
poly(sulfone)
poly(vinyl acetate)
poly(methyl methacrylate)
poly(ethylene-*co*-vinyl acetate)
poly(9-vinylcarbazole)
poly(carbonate bisphenol A)
poly(styrene)



Data Processing

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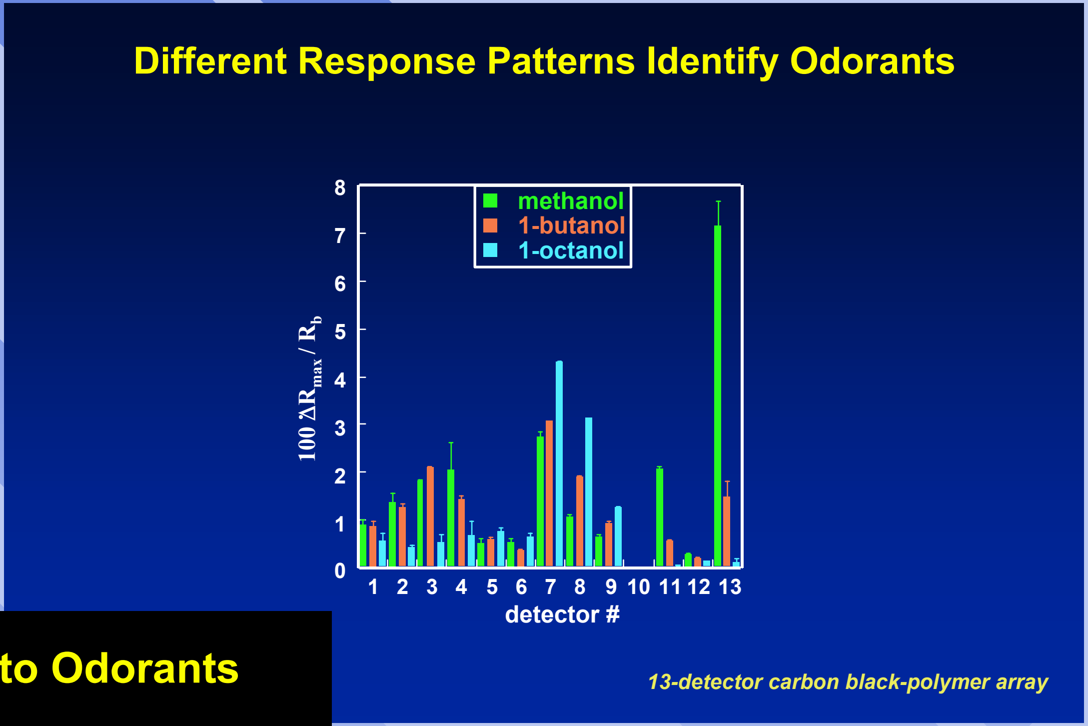
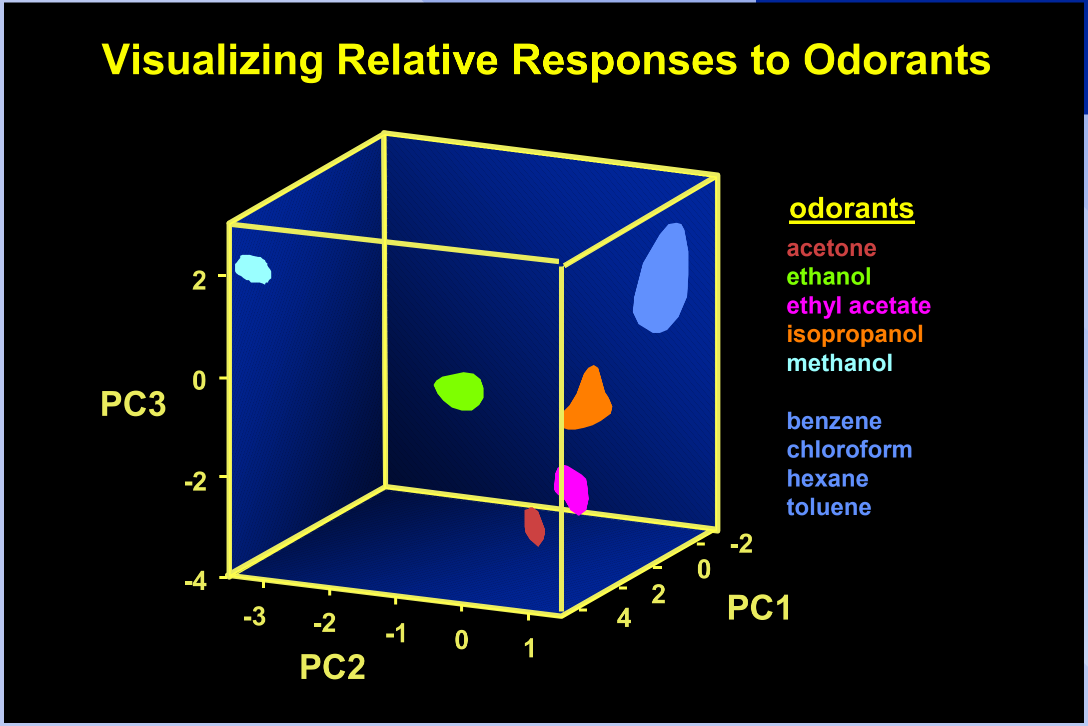
$\Delta R_{max} / R_b$ for each sensor normalized across the array results in a concentration independent pattern that characterizes the odor.



Different Response Patterns Identify Odorants

13-detector carbon black-polymer array



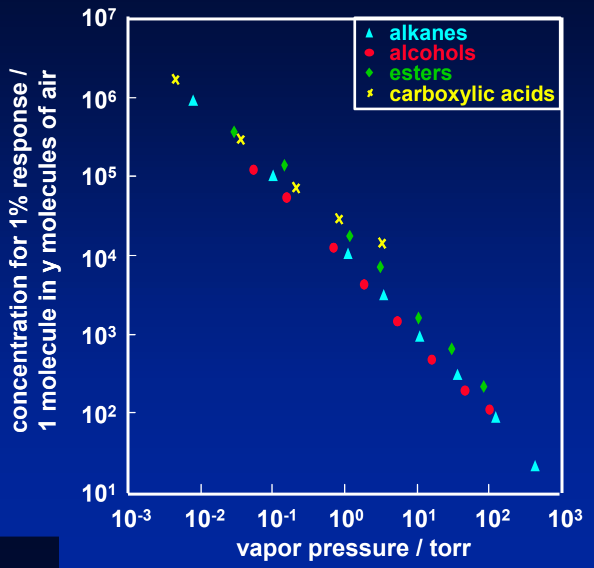
Visualizing Relative Responses to Odorants

Rod Goodman

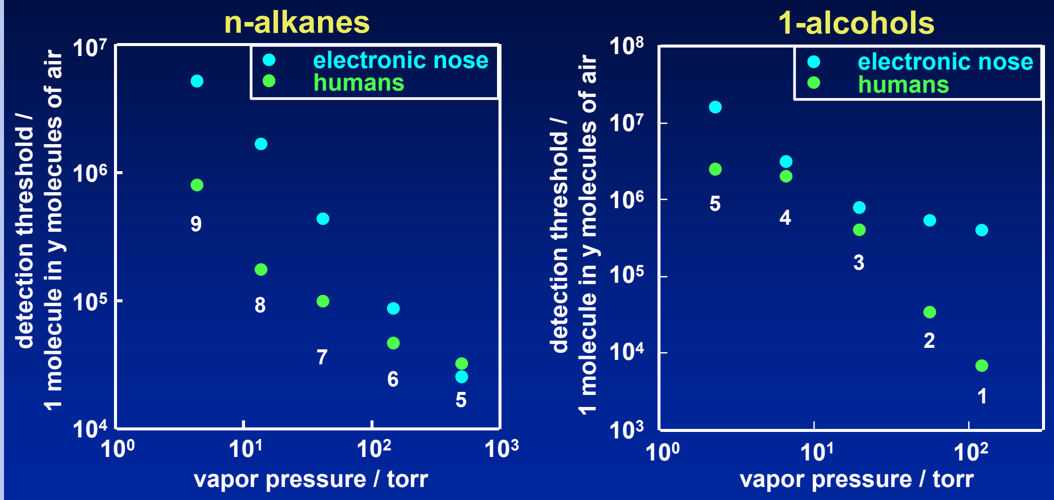
- Enose sensitivity to an odorant is inversely proportional to odorant vapor pressure.

- 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.

Electronic Nose Sensitivity vs. Vapor Pressure



Detection Thresholds for Humans vs. the Electronic Nose

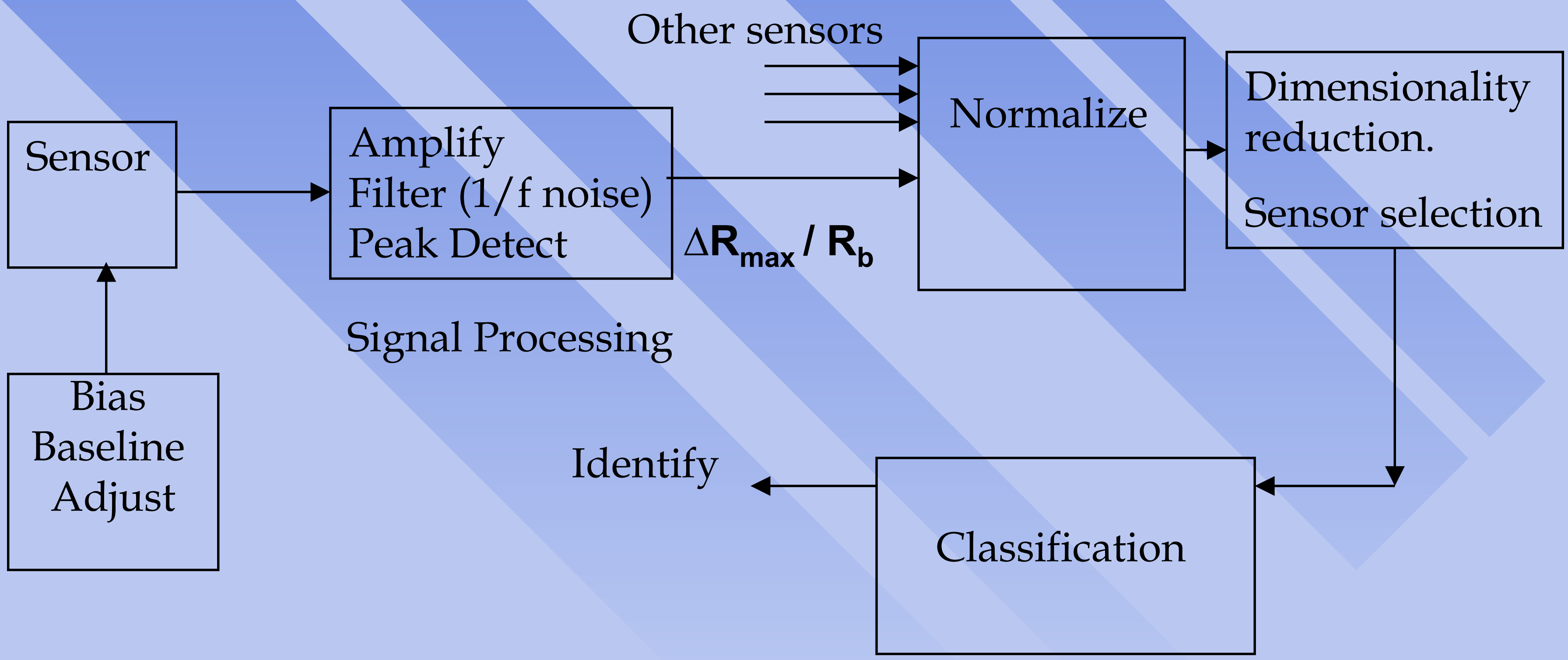

n-alkanes

1-alcohols

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!

Rod Goodman

System Architecture of an Enose



Other sensors

Sensor

Amplify
Filter (1/f noise)
Peak Detect

Signal Processing

$\Delta R_{max} / R_b$

Normalize

Dimensionality reduction.

Sensor selection

Bias
Baseline
Adjust

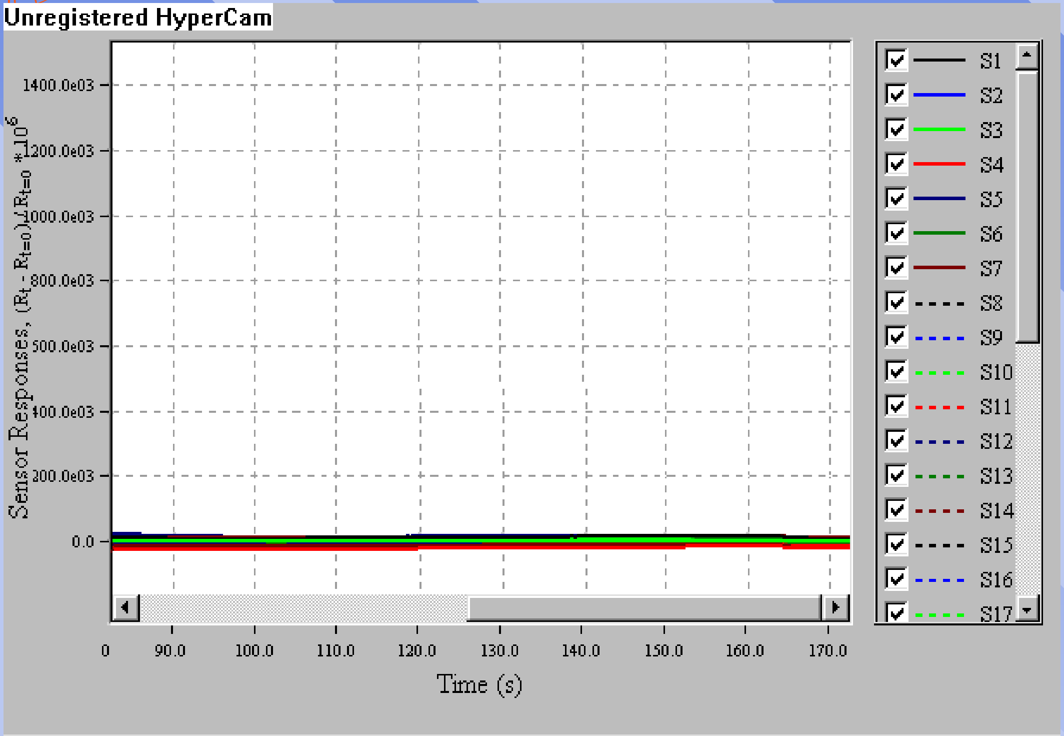
Identify

Classification

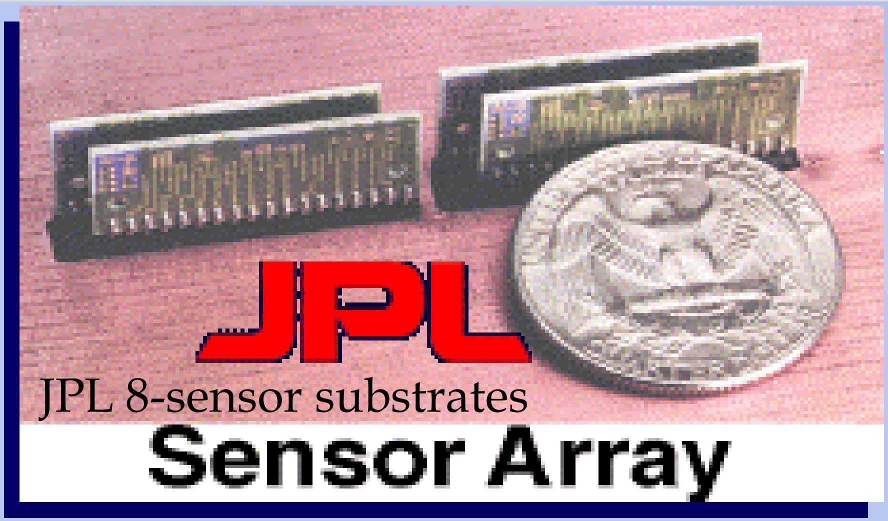
- Baseline adjust tunes out “background” odors.
- Dimensionality reduction removes sensors that are not providing discrimination information.
- Different classification algorithms used depending on complexity of problem.
- KNN, Canonical Linear Discriminant, Generalized LMS, Neural Network.

Rod Goodman

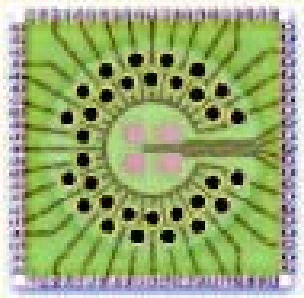
Discrete Sensor Noses



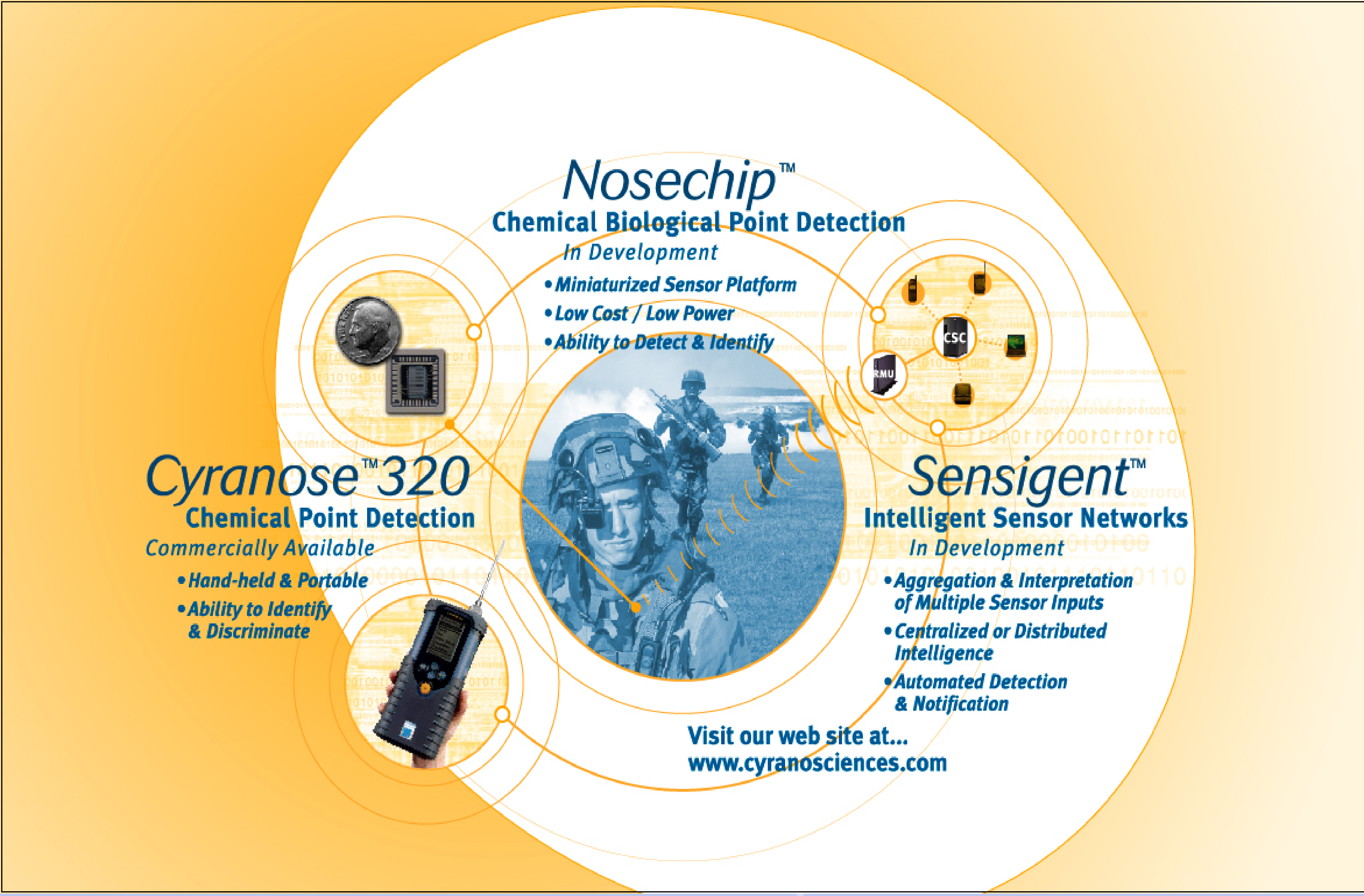
Cyrano C320
32 sensor enose



JPL 8-sensor substrates



CYRANO
sciences



Nosechip™

Chemical Biological Point Detection

In Development

- ***Miniaturized Sensor Platform***
- ***Low Cost / Low Power***
- ***Ability to Detect & Identify***

Cyranose™ 320

Chemical Point Detection

Commercially Available

- ***Hand-held & Portable***
- ***Ability to Identify & Discriminate***

Sensigent™

Intelligent Sensor Networks

In Development

- ***Aggregation & Interpretation of Multiple Sensor Inputs***
- ***Centralized or Distributed Intelligence***
- ***Automated Detection & Notification***

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www.cyranosciences.com

Next Generation Products

- Miniaturized
- Badge/gasmask
- Wireless
- Distributed Networked sensors

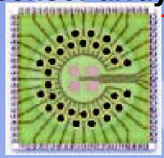
***Homeland Security & Military*:**
- **Border/Cargo screening**
- **Mass Transit inspection**
- **First responders (FD, PD, EMS)**
- **Facility & weapons inspection**

Alarm

wireless sensors

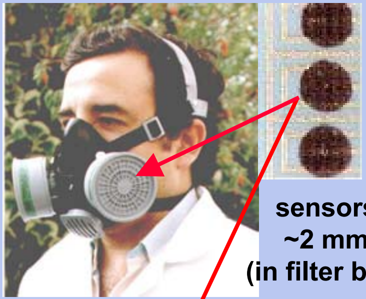
Migration path

chemresistor sensor array



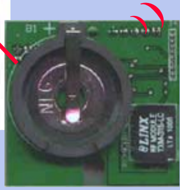
Cyrano COTS detector

Unit cost < $10,000
Weight < 2 lbs (with battery)



sensors ~2 mm (in filter bed)

End of Service Life Indicator (ESLI) for chemical filters for Military, Homeland Security & Industry:
- **Forward-deployed personnel**
- **Facility & weapons inspection**
- **Embassy/Civilian personnel**
- **First responders (FD, PD, EMS)**
- **Hazardous chemical handling**



Alarm !
breakthrough
filter bar code
date & time

Cyrano
ESLI annunciator
or wireless TX/RX
(durable inside mask)

Distributed chemical sensors for perimeter detection of CWA or hazardous chemical release prior to entry by law enforcement personnel:

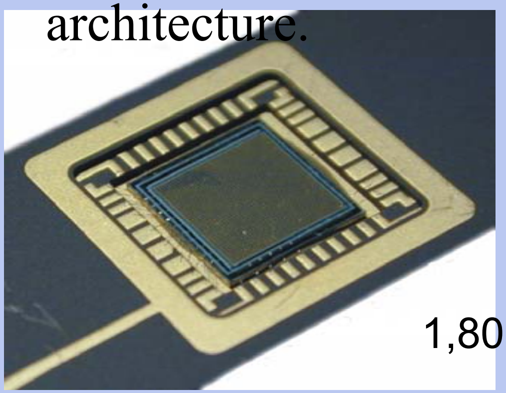
- **Early-warning detection for PD, FD, national guard**
- **Low power detectors (battery life > 1 yr)**
- **Low cost detectors for high density deployment**

Alarm !
chemical
release
detected

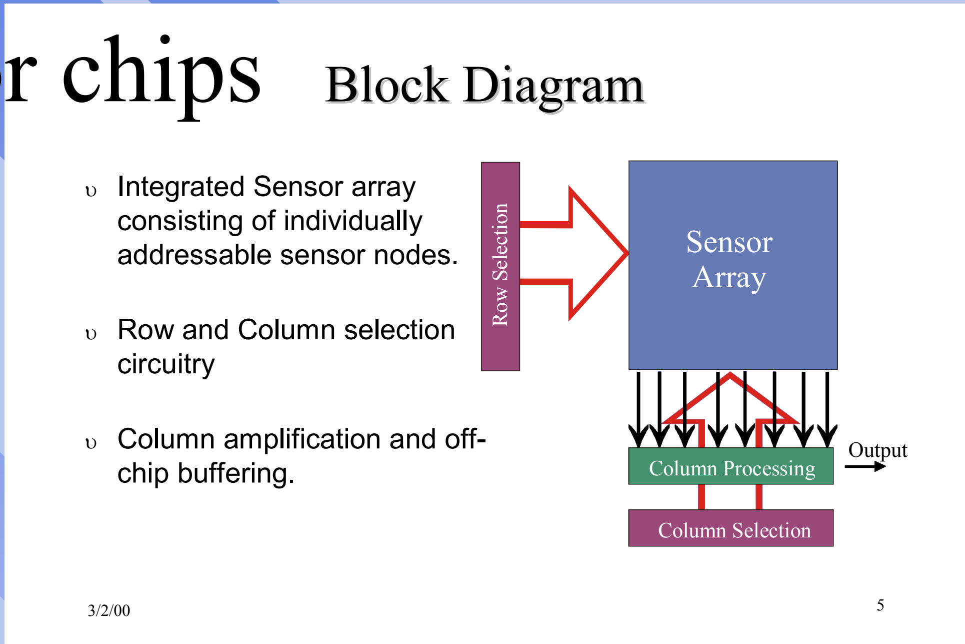
Homeland Security for:
- **Domestic terrorism incidents**
- **Raids on clandestine drug labs**

Integration –sensor chips

- Integration of sensors enables a large number of chemical sensors to be fabricated in a small area.
- Allows for redundancy (1/sqrtN) SNR improvement.
- Gain and signal processing can be fabricated in close proximity to the individual sensor.
- Three layers: polymer – gold contacts –VLSI circuits.
- Higher order processing such as classification, compatible with the architecture.



1,800 sensor chip



Block Diagram

- Integrated Sensor array consisting of individually addressable sensor nodes.
- Row and Column selection circuitry
- Column amplification and off-chip buffering.

Row Selection

Sensor Array

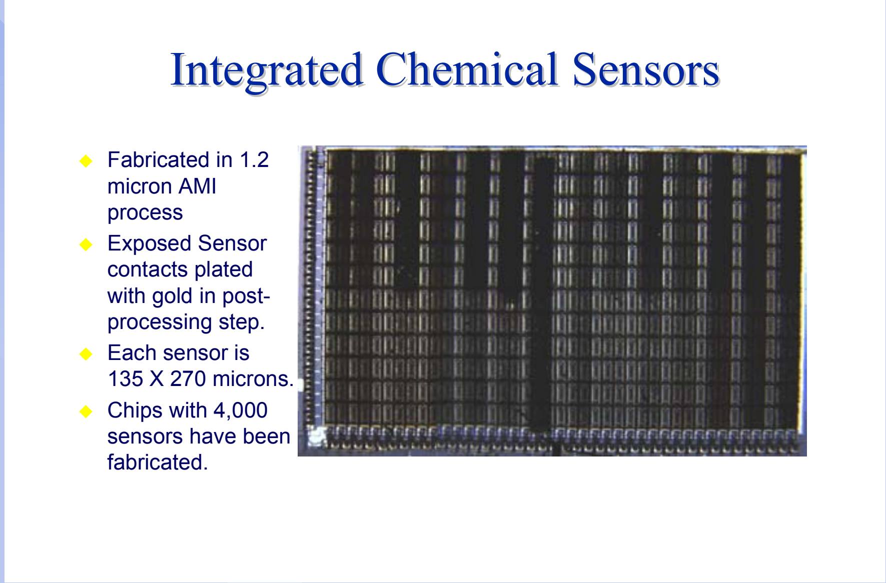
Column Processing

Output

Column Selection

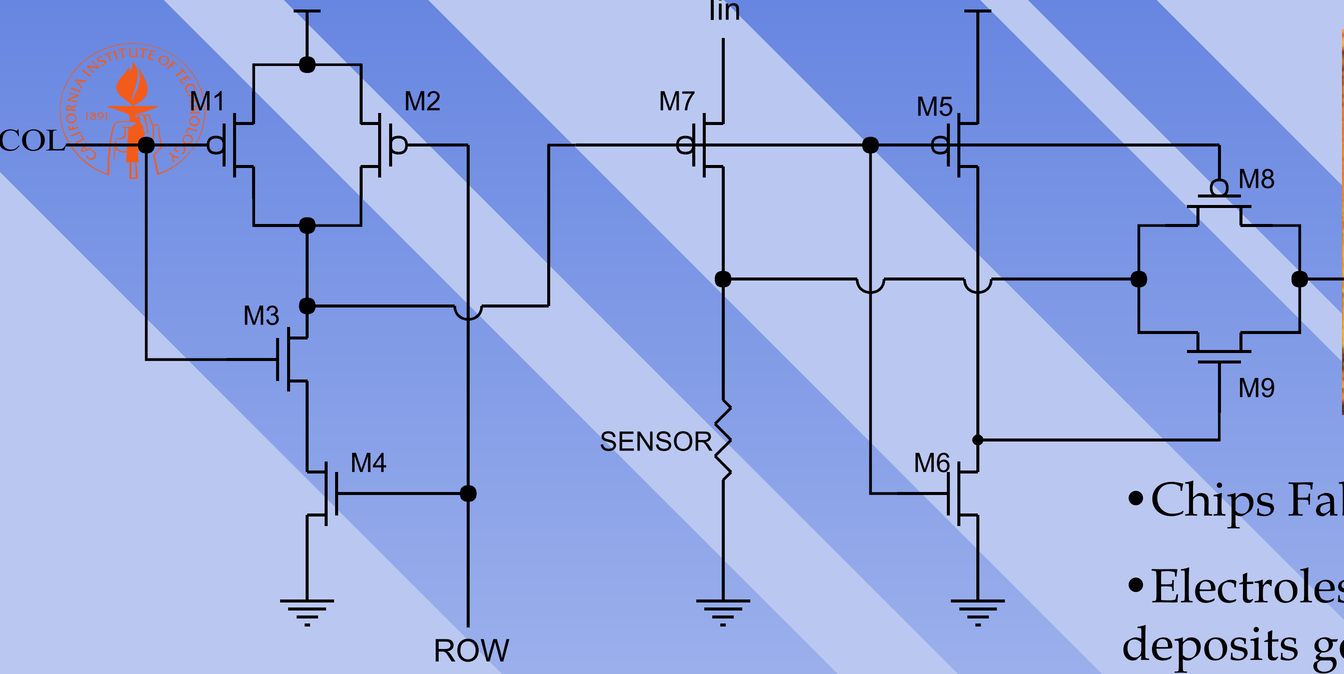
3/2/00

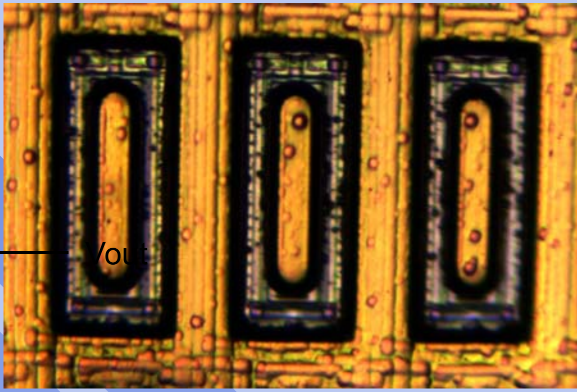
5



Integrated Chemical Sensors

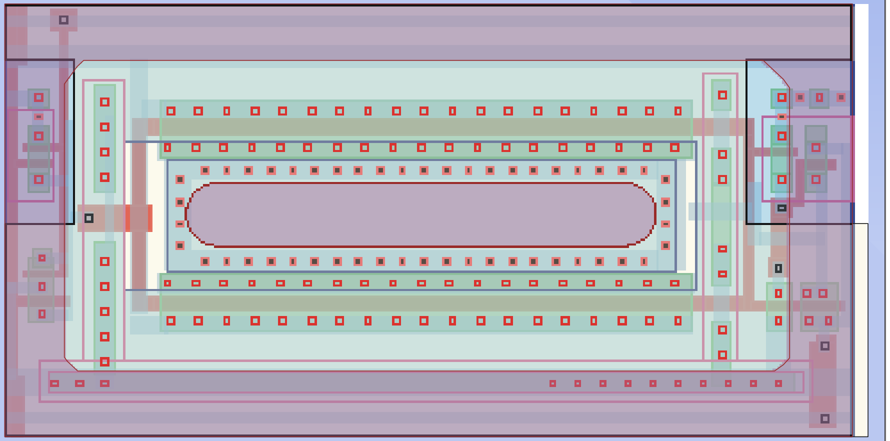
- Fabricated in 1.2 micron AMI process
- Exposed Sensor contacts plated with gold in post-processing step.
- Each sensor is 135 X 270 microns.
- Chips with 4,000 sensors have been fabricated.



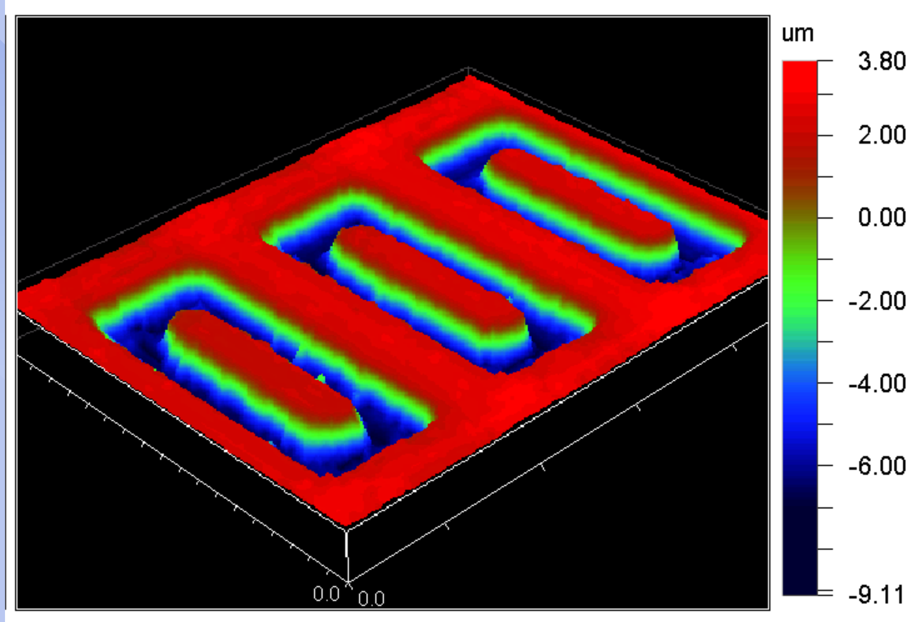


- Chips Fabricated via MOSIS
- Electroless gold post-processing deposits gold on aluminum forming wells

Sensor Osmel



Cell Layout

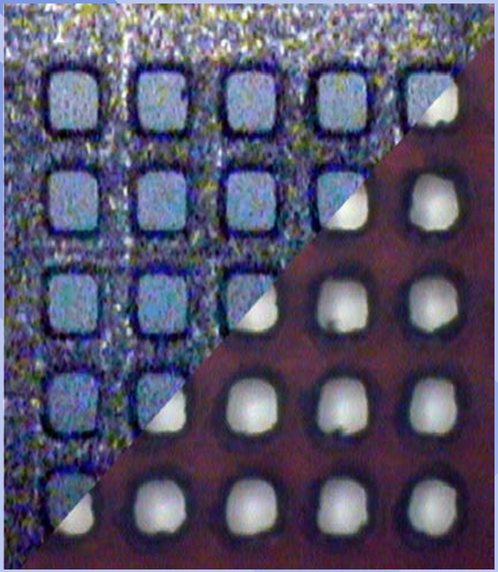


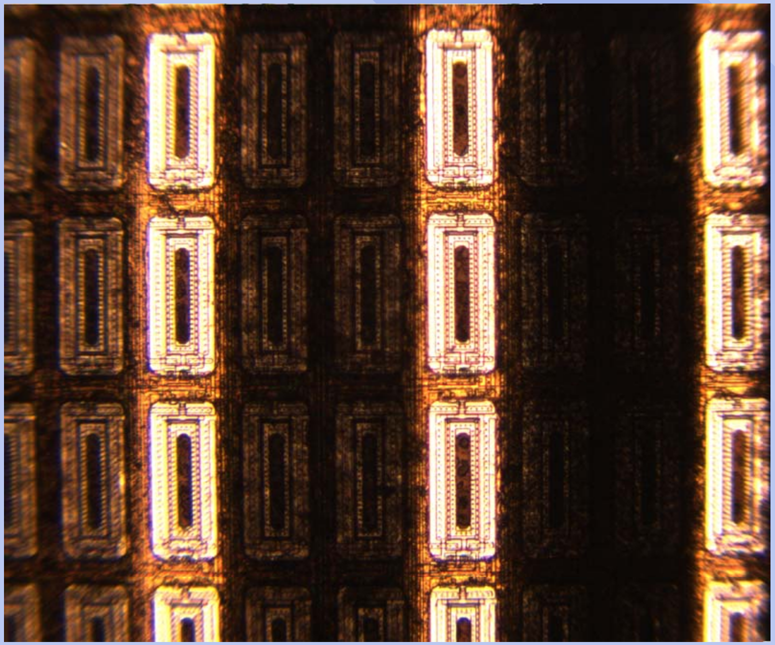
Profilometry shows wells created by gold

Rod Goodman

Deposition of Sensor Material

- Polymer/Carbon Black deposition by Air Brush and/or Mask.
- Many patterns: strips, cells, crossed strips, blobs
- Mask created by electroforming of Nickel or Laser cutting of Polymide. (270 micron wide apertures shown.)

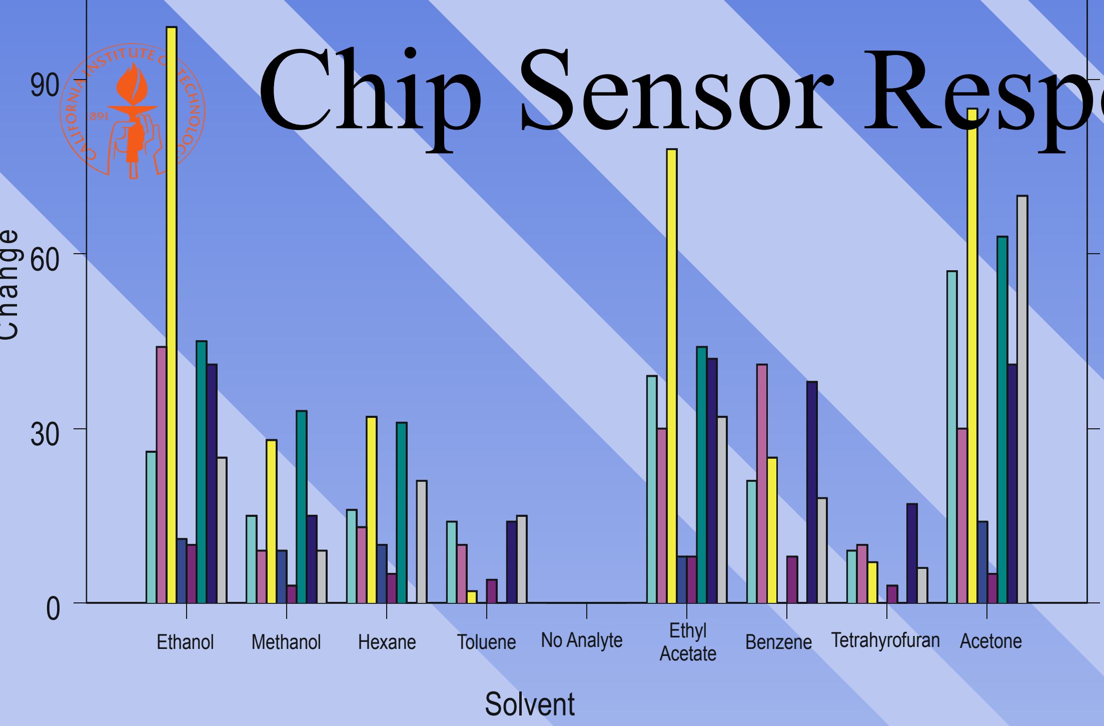


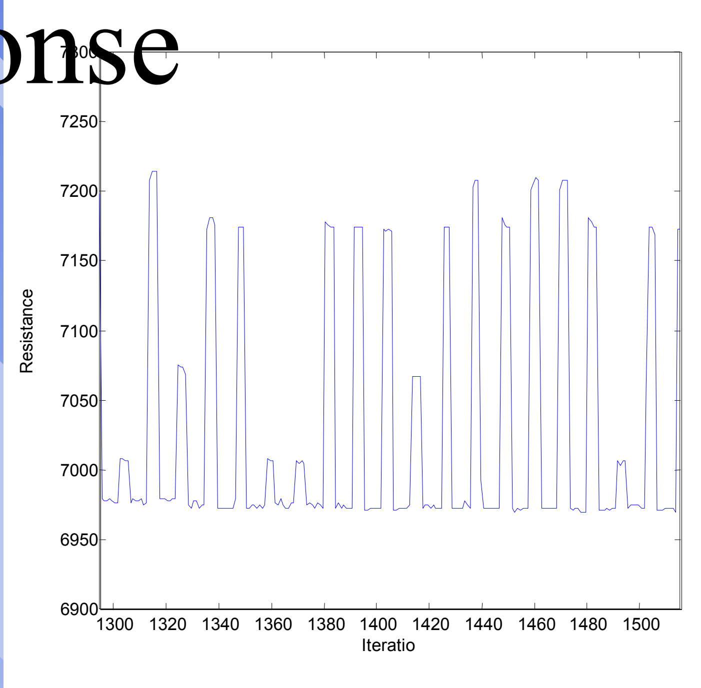


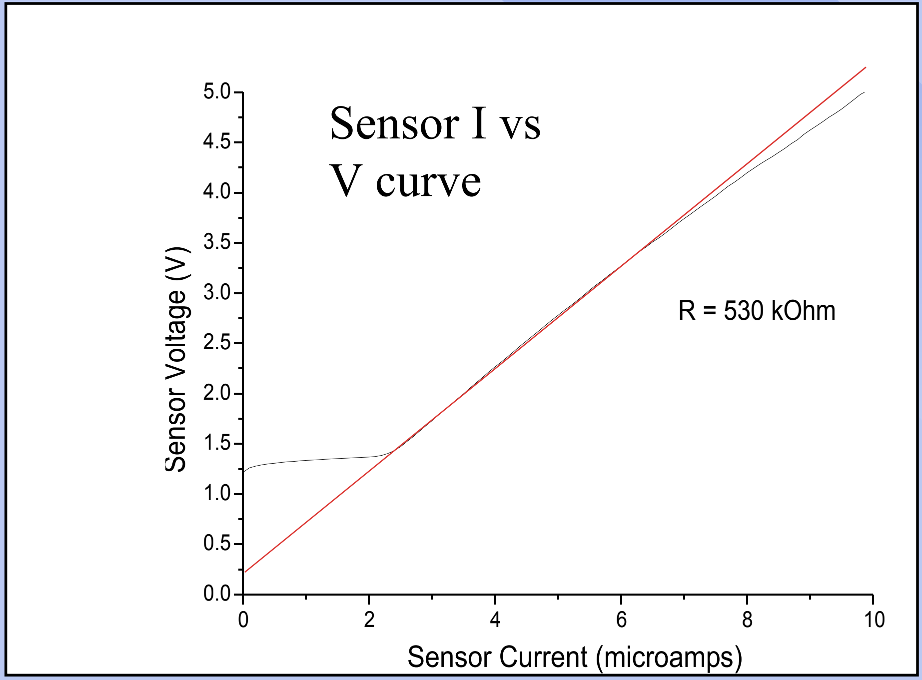
Striped air-brushed chip

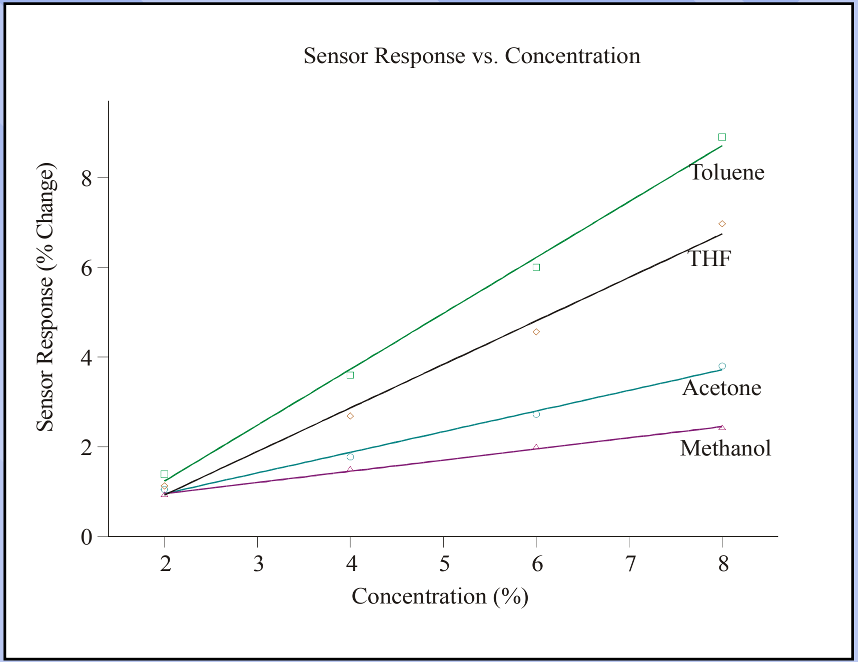
- Polyamide mask 50um thick
- Computer controlled laser cut
- Can get 50um resolution
- Sprayed in strips of 2 sensors wide
- One-sensor gap between
- 8 Polymers used
- 41x12 array = 492 sensors
- Chip 0.5cmx0.25cm 2um CMOS

Chip Sensor Response

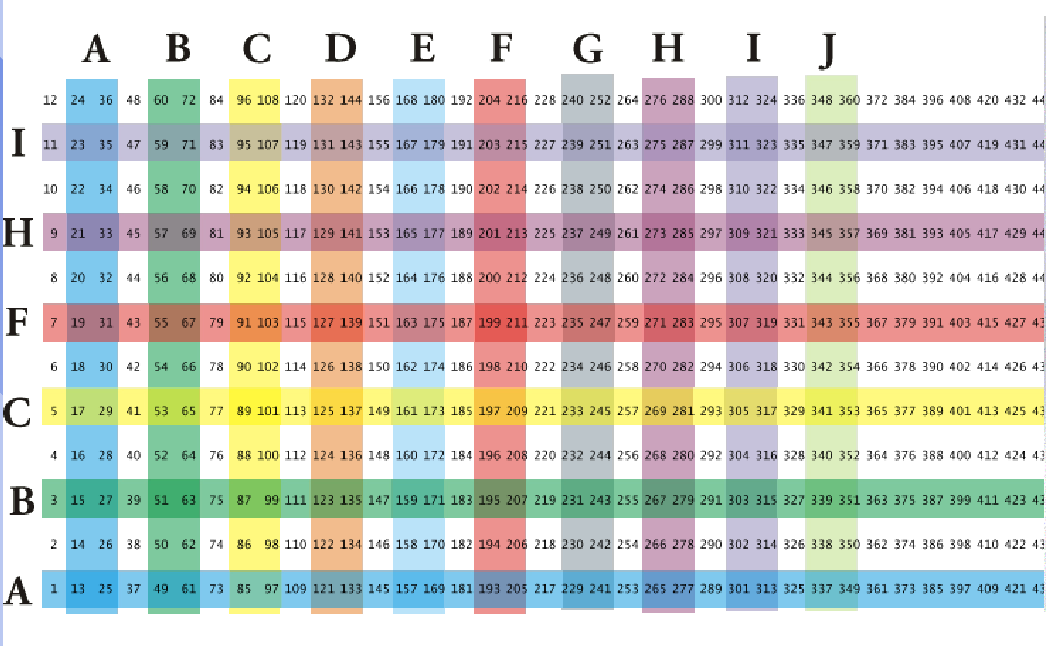




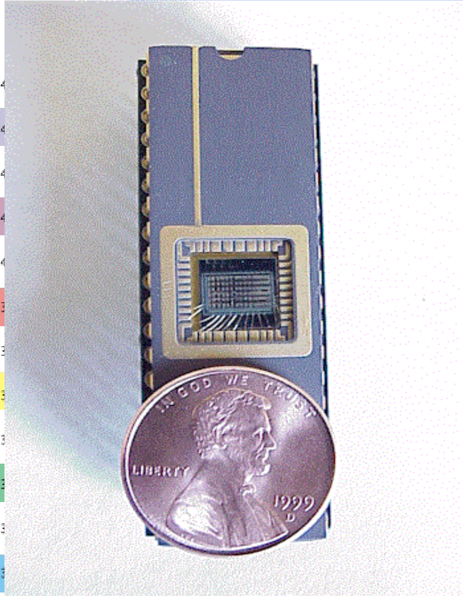




Combinatorial Pixel Array



		A			B			C			D			E			F			G			H			I			J								
	12	24	36	48	60	72	84	96	108	120	132	144	156	168	180	192	204	216	228	240	252	264	276	288	300	312	324	336	348	360	372	384	396	408	420	432	44
I	11	23	35	47	59	71	83	95	107	119	131	143	155	167	179	191	203	215	227	239	251	263	275	287	299	311	323	335	347	359	371	383	395	407	419	431	44
	10	22	34	46	58	70	82	94	106	118	130	142	154	166	178	190	202	214	226	238	250	262	274	286	298	310	322	334	346	358	370	382	394	406	418	430	44
H	9	21	33	45	57	69	81	93	105	117	129	141	153	165	177	189	201	213	225	237	249	261	273	285	297	309	321	333	345	357	369	381	393	405	417	429	44
	8	20	32	44	56	68	80	92	104	116	128	140	152	164	176	188	200	212	224	236	248	260	272	284	296	308	320	332	344	356	368	380	392	404	416	428	44
F	7	19	31	43	55	67	79	91	103	115	127	139	151	163	175	187	199	211	223	235	247	259	271	283	295	307	319	331	343	355	367	379	391	403	415	427	43
	6	18	30	42	54	66	78	90	102	114	126	138	150	162	174	186	198	210	222	234	246	258	270	282	294	306	318	330	342	354	366	378	390	402	414	426	43
C	5	17	29	41	53	65	77	89	101	113	125	137	149	161	173	185	197	209	221	233	245	257	269	281	293	305	317	329	341	353	365	377	389	401	413	425	43
	4	16	28	40	52	64	76	88	100	112	124	136	148	160	172	184	196	208	220	232	244	256	268	280	292	304	316	328	340	352	364	376	388	400	412	424	43
B	3	15	27	39	51	63	75	87	99	111	123	135	147	159	171	183	195	207	219	231	243	255	267	279	291	303	315	327	339	351	363	375	387	399	411	423	43
	2	14	26	38	50	62	74	86	98	110	122	134	146	158	170	182	194	206	218	230	242	254	266	278	290	302	314	326	338	350	362	374	386	398	410	422	43
A	1	13	25	37	49	61	73	85	97	109	121	133	145	157	169	181	193	205	217	229	241	253	265	277	289	301	313	325	337	349	361	373	385	397	409	421	43



A poly(ethylene oxide)

B PEVA 25

C poly(5-Butadiene)

D poly(vinyl-carbazole)

E poly(vinyl acetate)

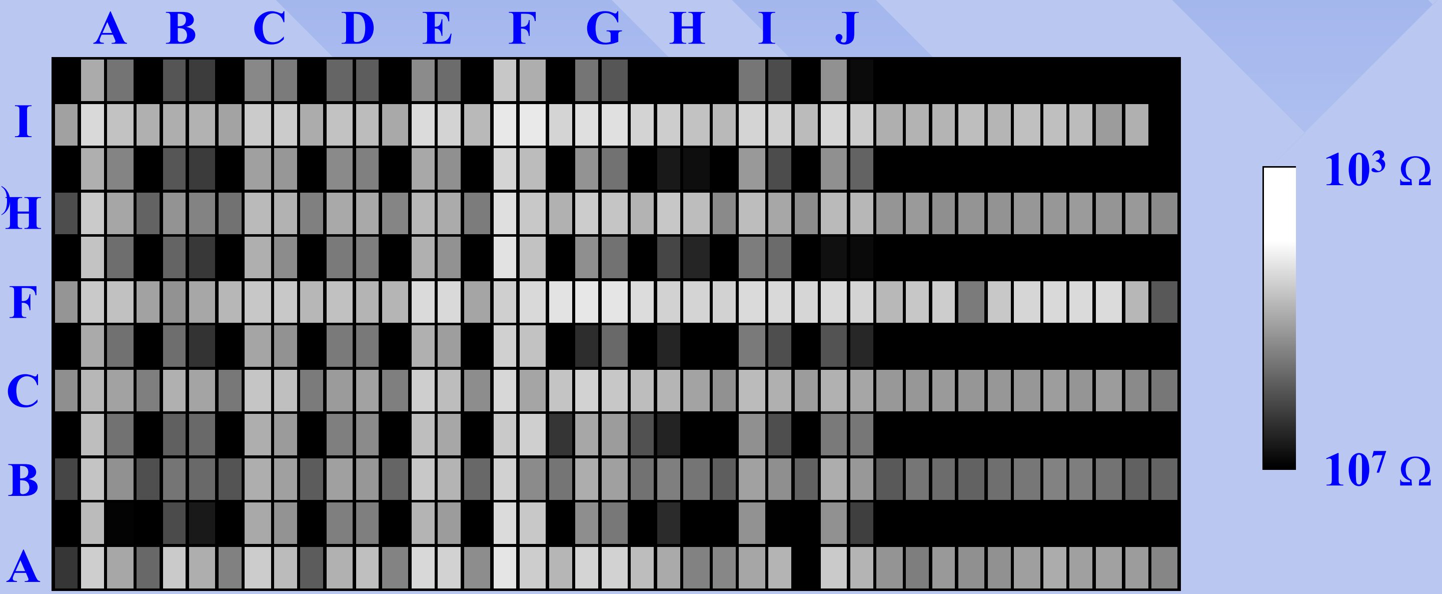
F poly(capralactone)

G poly(sulfone)

H poly(vinyl pyyrolidone)

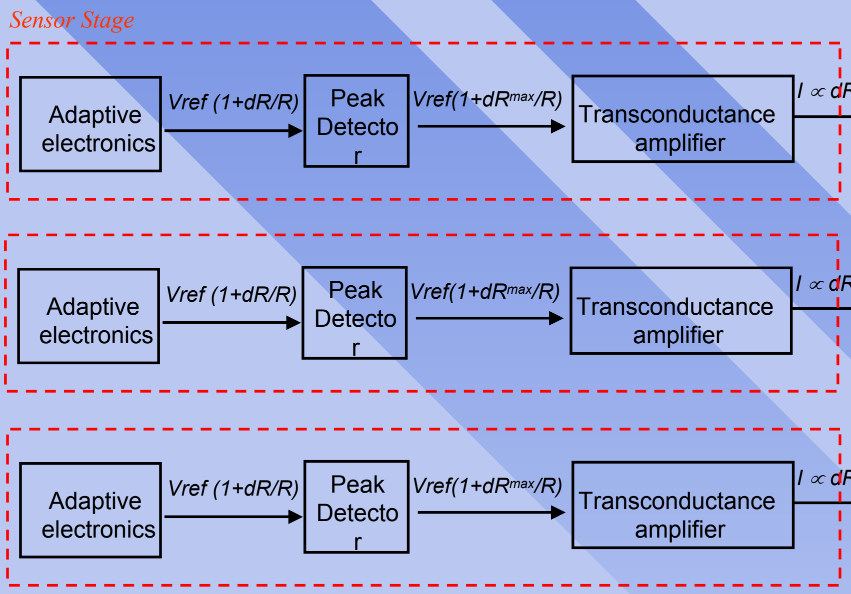
I poly(4-vinyl phenol)

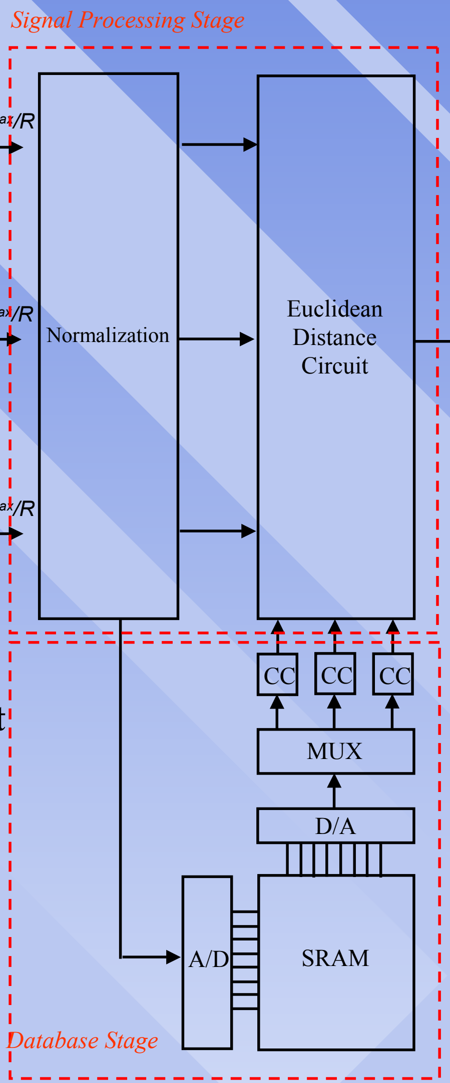
J poly(methyloctadecyl-siloxane)

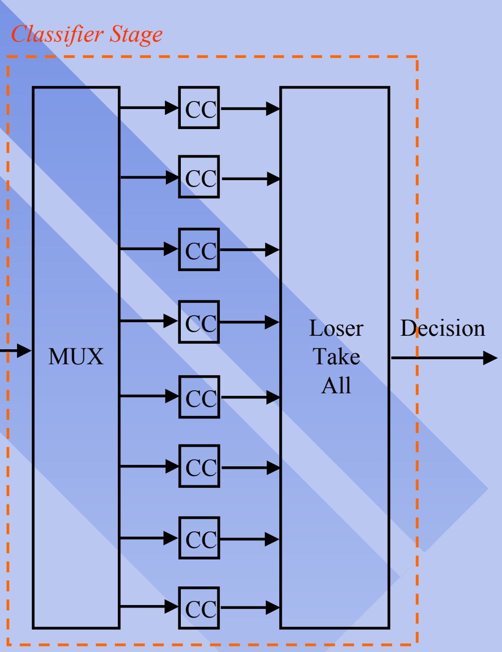


Rod Goodman

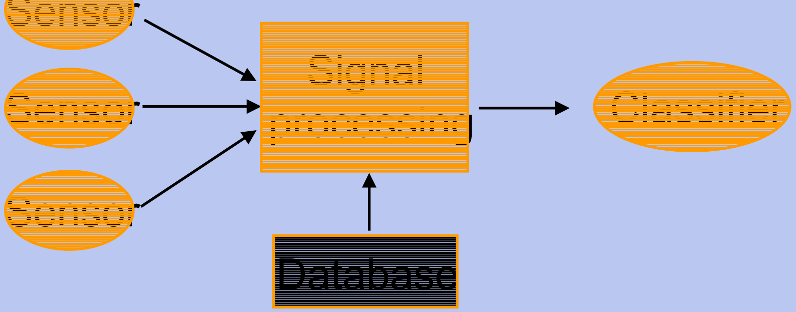
Hybrid Analog/Digital Integration of a complete nose-on-a-chip neuromorphic processor – interfaces to sensor array chips



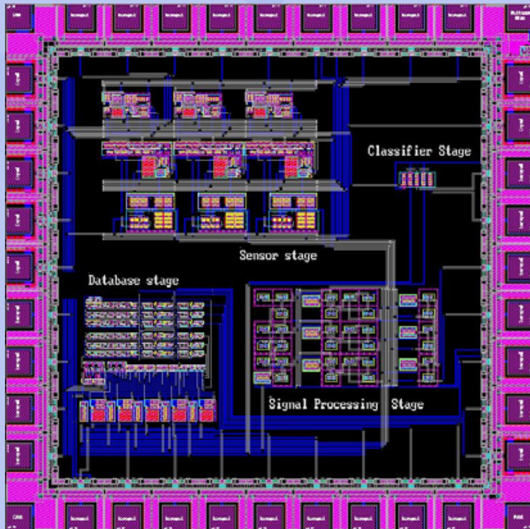




- Sensor stage – baseline adapt, ΔR/R out
- Signal processing stage – normalize & E.dist
- Database stage - pattern training and recall
- Classifier stage – Euclidean distance NN

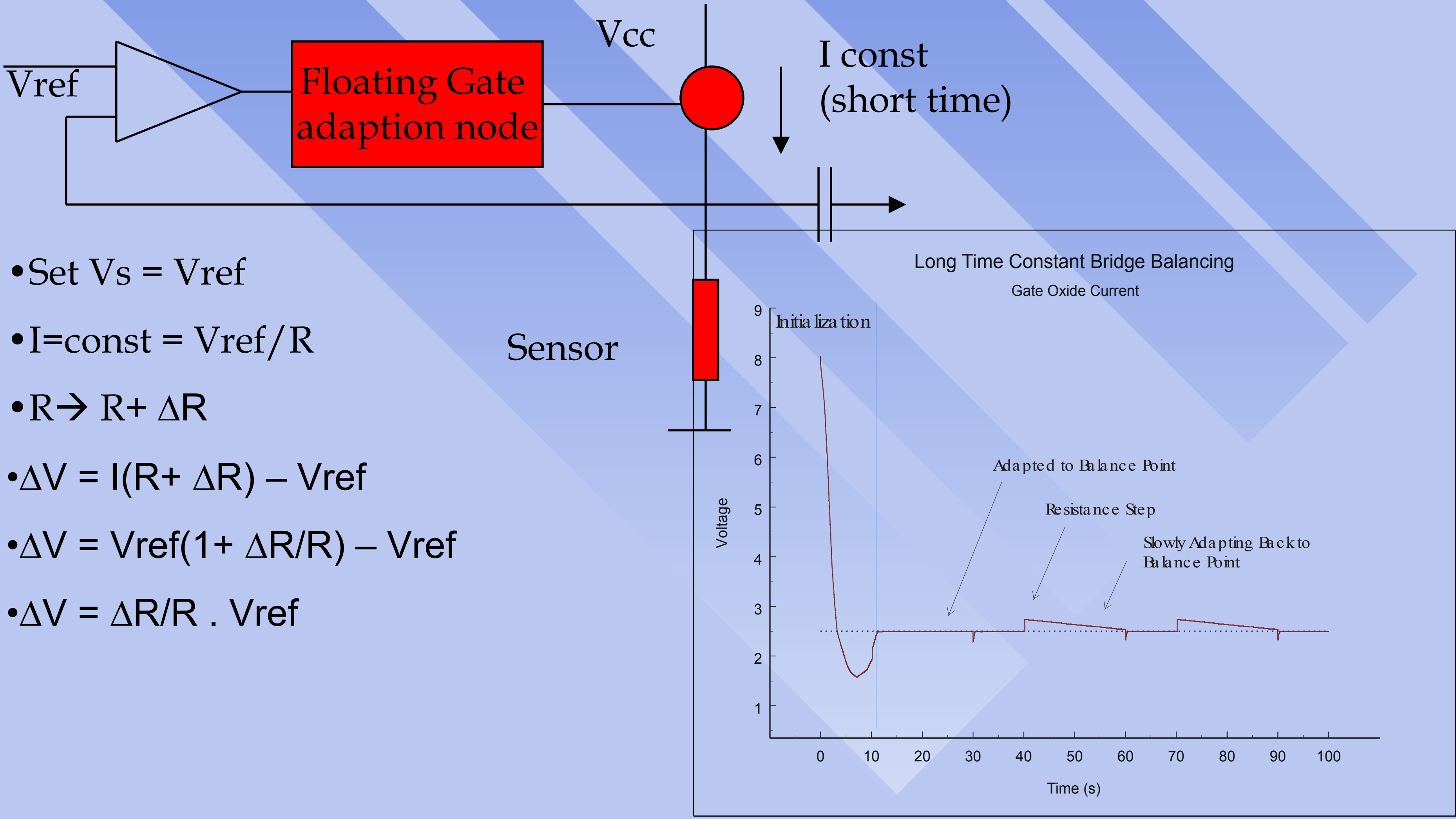


MOSIS AMI 1.2um process



Adaptive Baseline Tracking

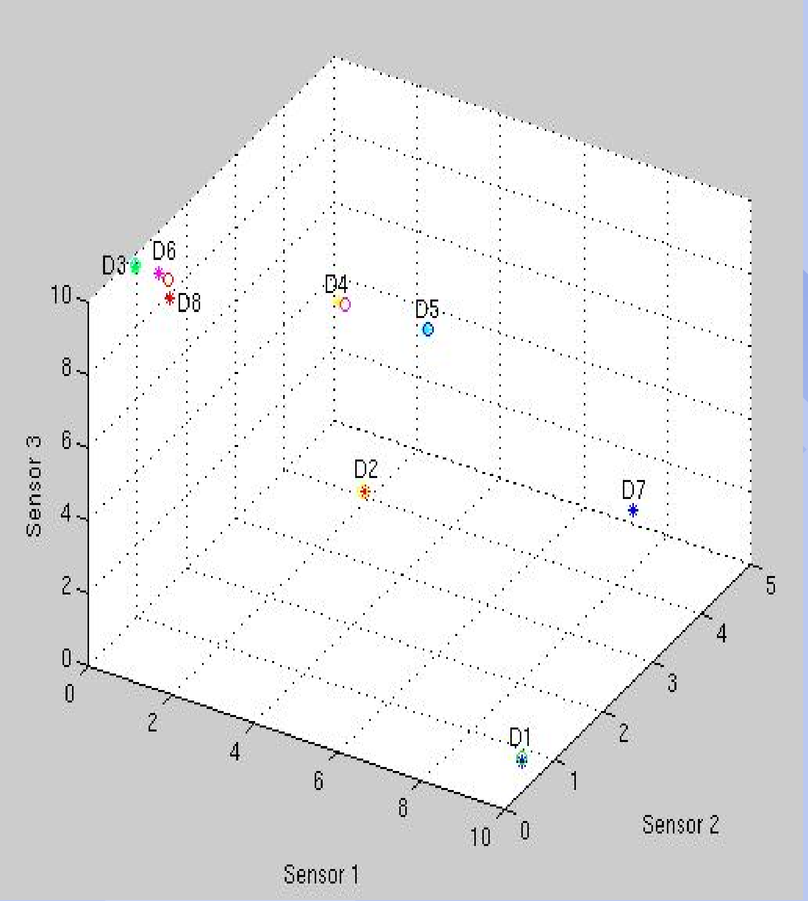
- Adaptive bias circuit provides baseline tracking, ratiomentric output and ac coupling in one simple circuit.



- Set Vs = Vref
- I=const = Vref/R
- R→ R+ ΔR
- ΔV = I(R+ ΔR) – Vref
- ΔV = Vref(1+ ΔR/R) – Vref
- ΔV = ΔR/R . Vref

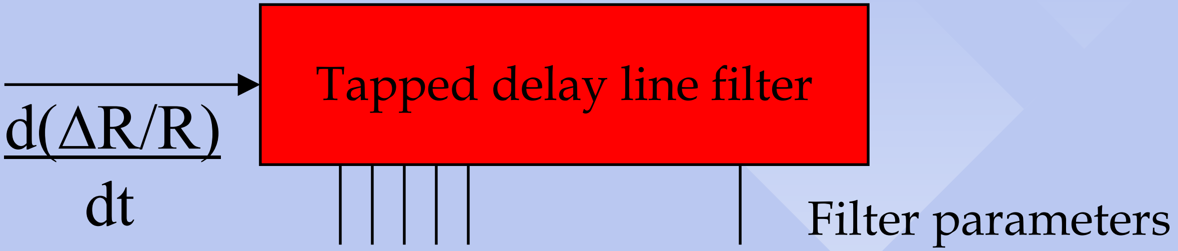
Chip Performance

- First five of the six test patterns can be classified to the correct classes respectively
- The sixth test pattern does not belong to any group, which is true because the chip did not learn the odor
- Test patterns
  - T1 - methanol
  - T2 - 2-propanol
  - T3 - hexane
  - T4 - ethyl acetate
  - T5 - acetone
  - T6 - benzene



Response time

- Different polymer-odorant pairs have different time responses for ΔR/R .
- This can be used to aid recognition.
- But it’s a complex function and noisy.
- Direct use of rate does not help discrimination much.
- Indirect approach where we use a “matched filter” approach to dynamically model the rate as it changes and then match the filter parameters showing promise.



$$\frac{d(\Delta R/R)}{dt}$$

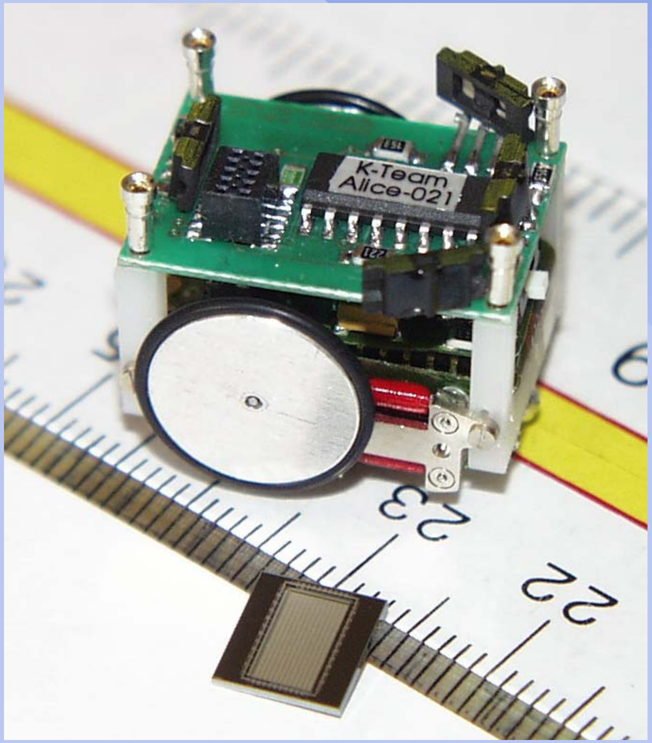
Tapped delay line filter

Filter parameters

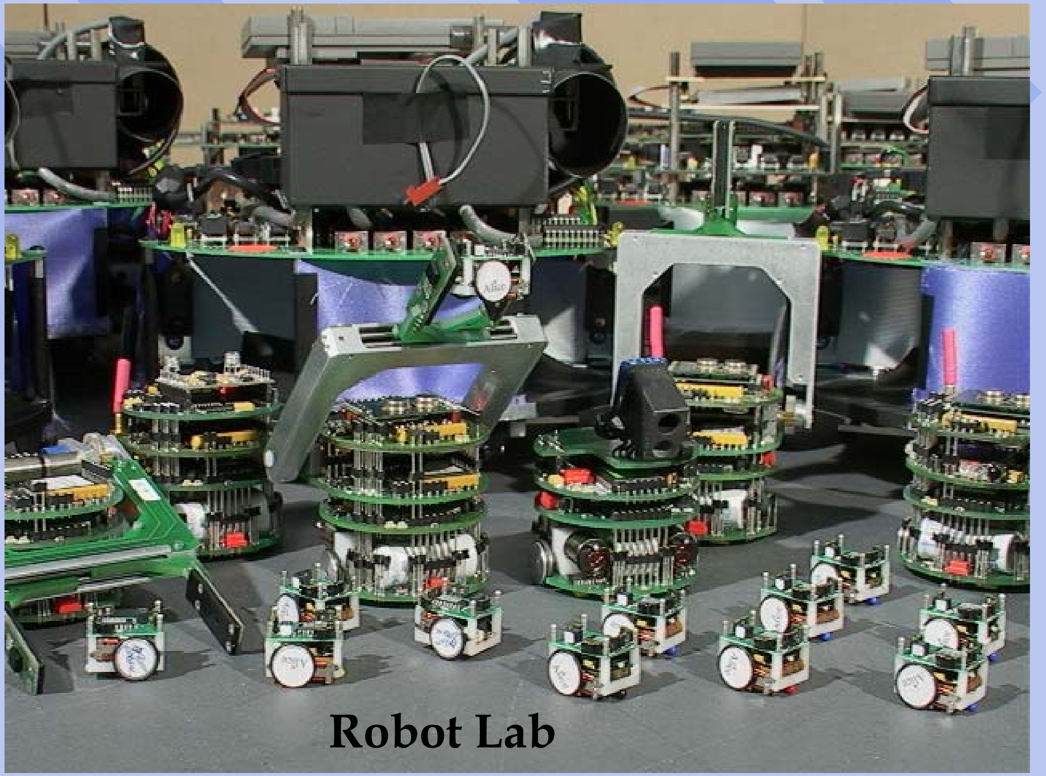
Mobile Robot Noses

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

Alice microrobots



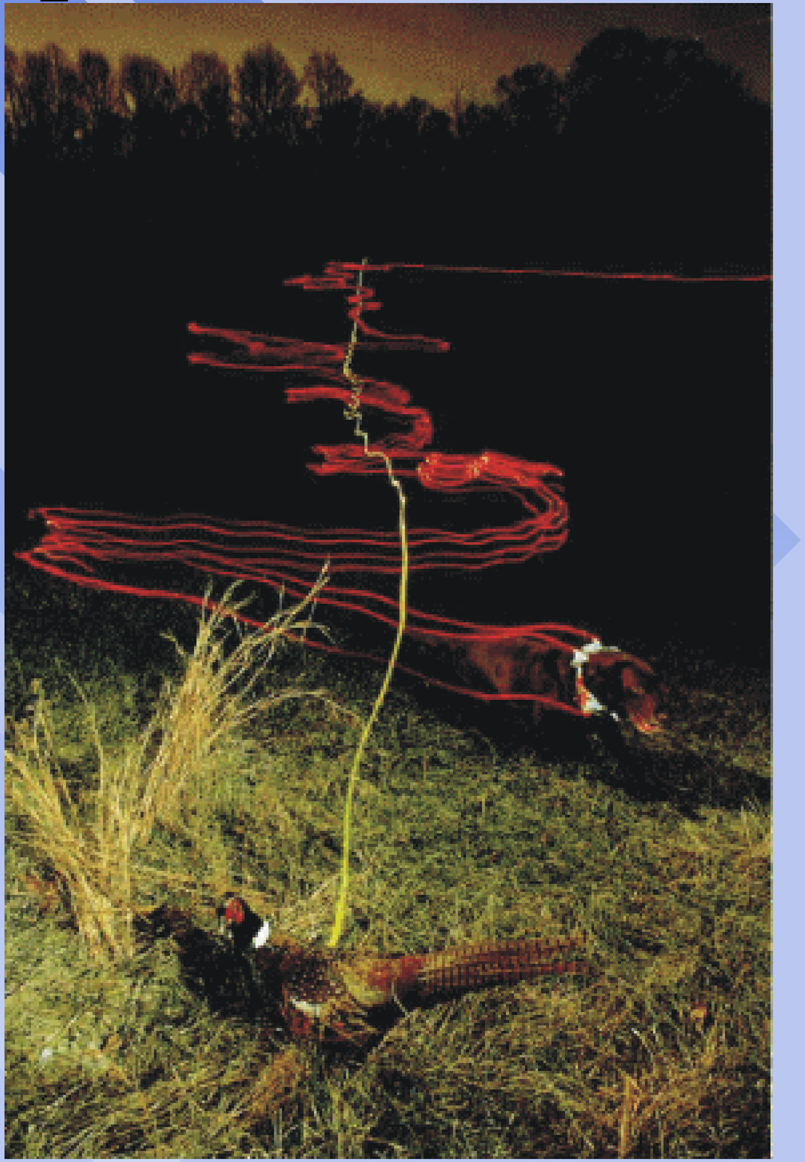
Alice with 18x18 nose chip



Robot Lab

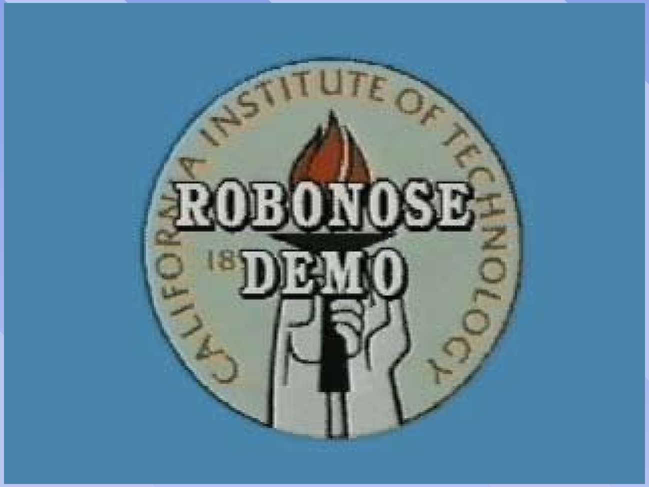
Biological Inspiration

- Animals are capable of impressive performance in classifying, localizing, tracking, and tracing odor trails and plumes.
- Moths can use single-molecule hits of pheremone 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?

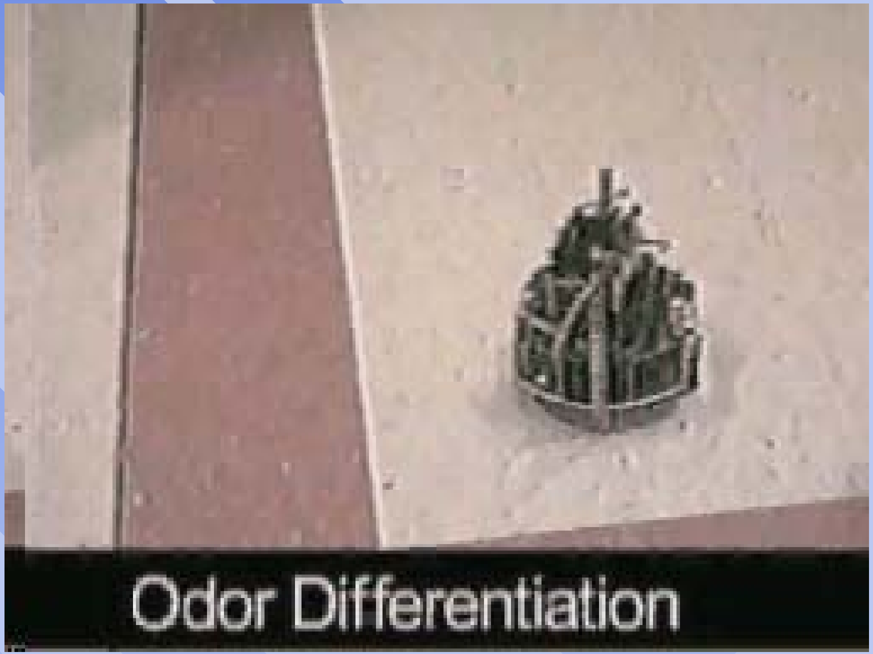


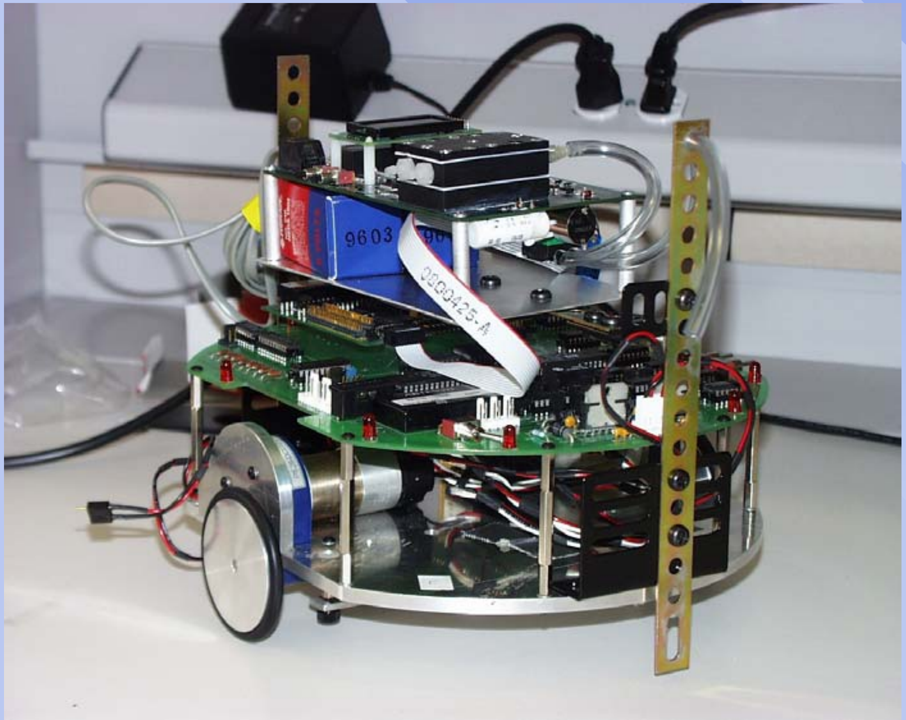
Rod Goodman

Early steps- Chemotaxis



Early steps - Odor Discrimination

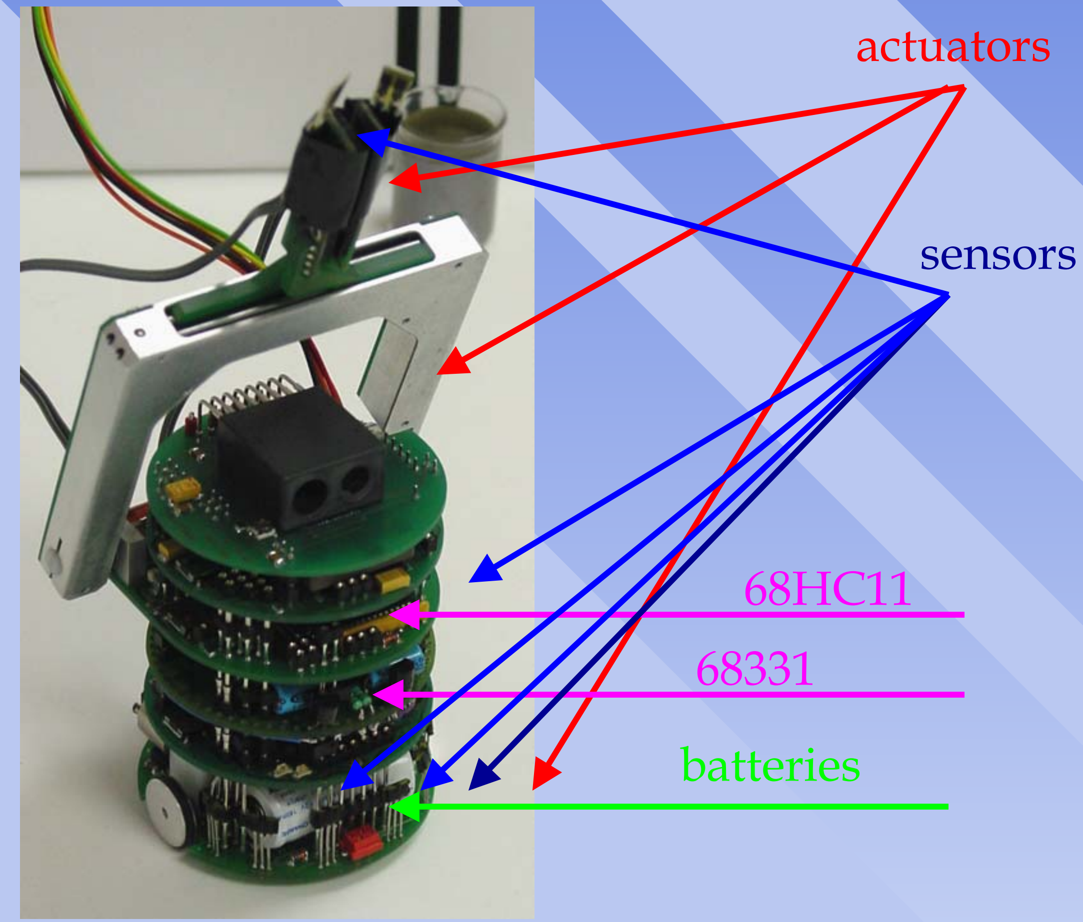


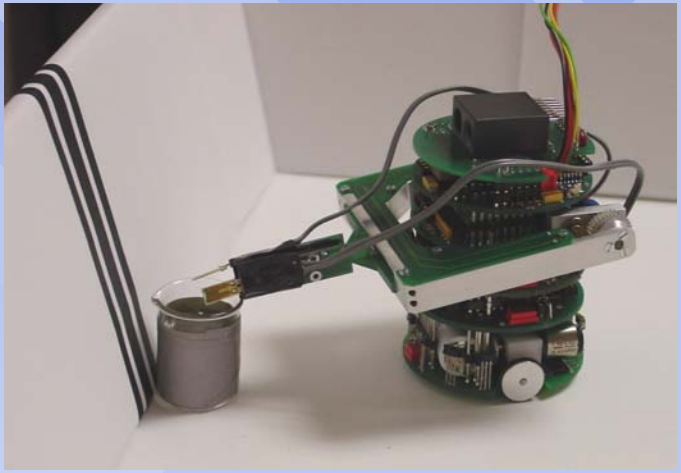


Moorebot with prototype
32 sensor Cyrano e-nose

Early steps- Integration of Odor and Vision Sensing

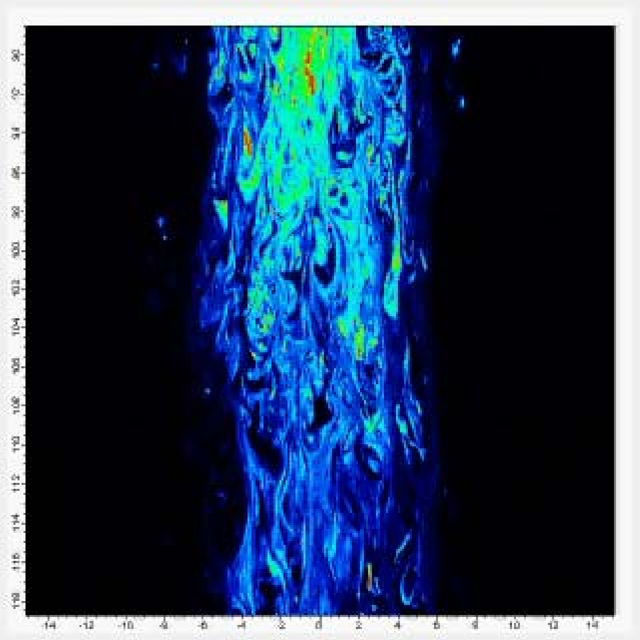
Khepera robot equipped with (2) odor sensors and 1D vision system



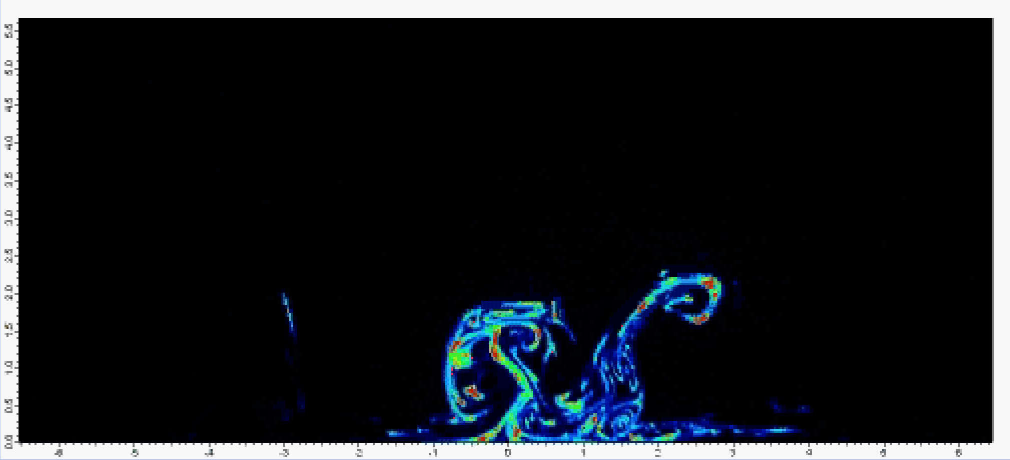


- •The ultimate objective is to use vision to search for “interesting features” in the environment and then smell them.
- •Compare with rat search strategies in collaboration with Bower lab in Biology.

Characteristics of a Plume



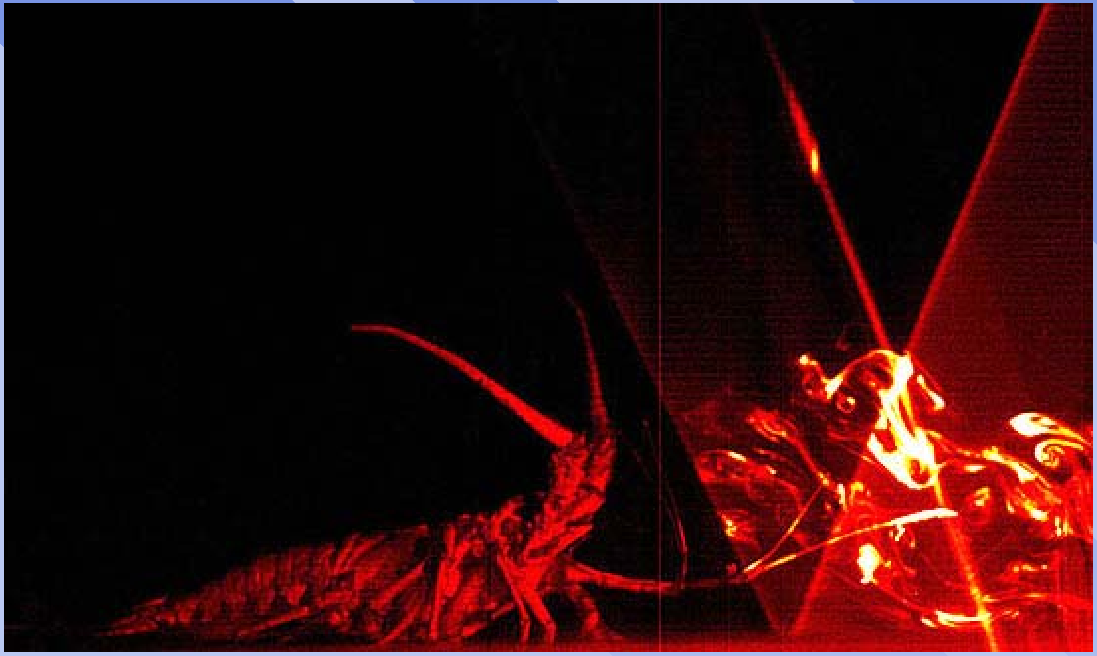
- Plume has complex dynamic “packet” structure.
- Not a simple gradient-following task.
- Instantaneous concentration far downstream can be as high as near the source.
- Yes, one can stop at a location, time average to get an estimate of local concentration, then move up-gradient.
- That takes a lot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



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.

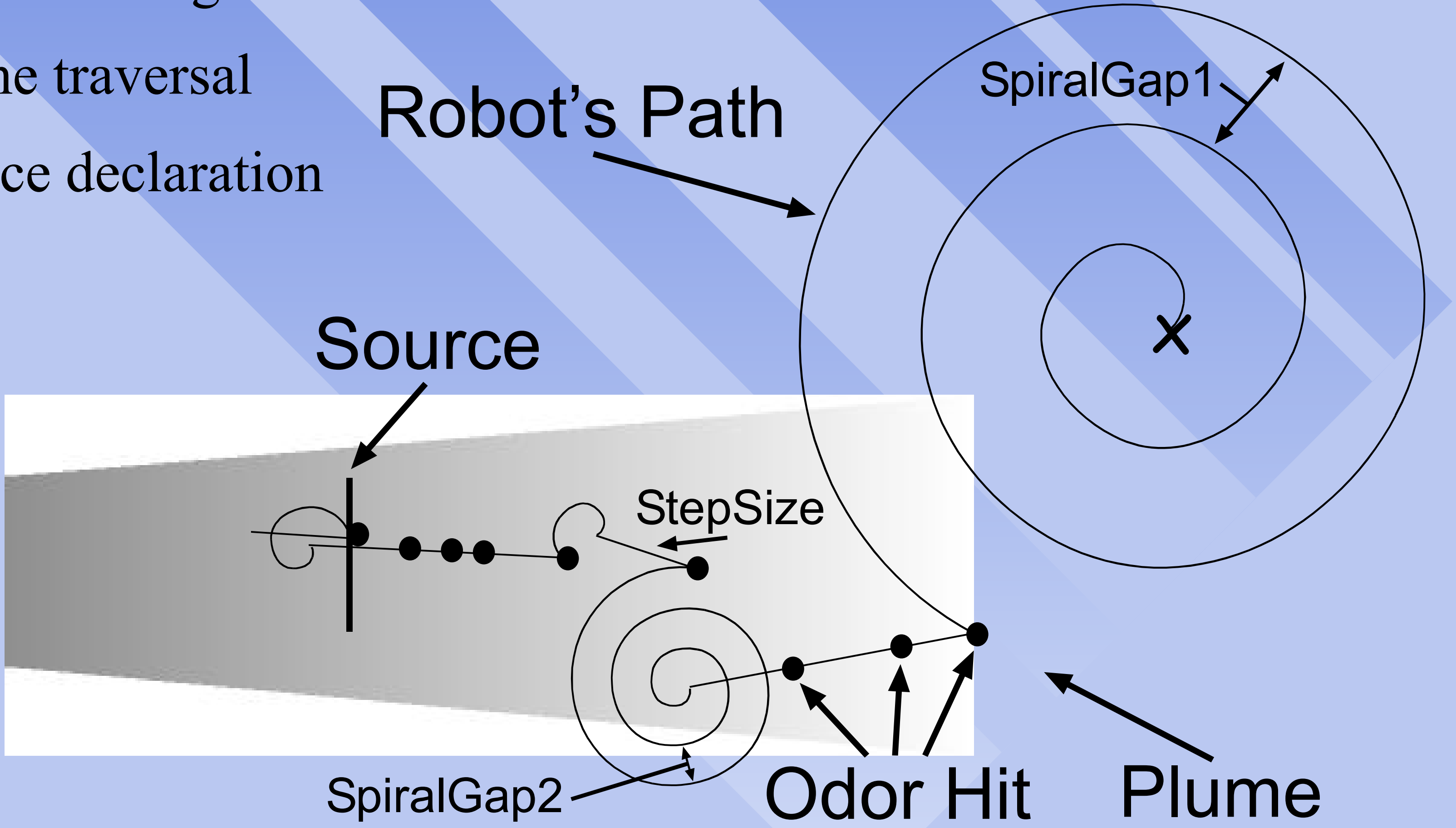
Rod Goodman

Plume edge following - Wagbot

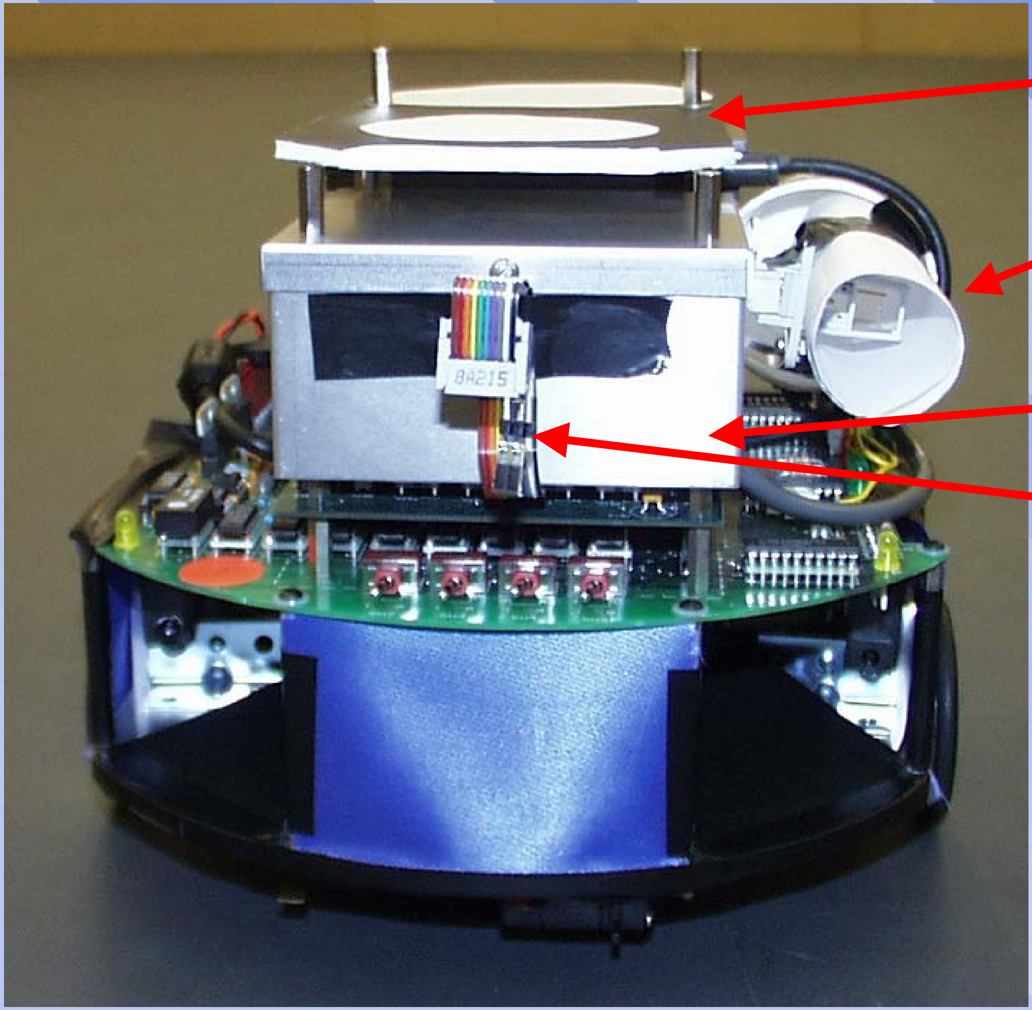
- Uses a simple Braitenberg controller to detect the left or right edge of the plume and turns “inwards”.
- Uses the “physics” of the problem:
  - waggly antennae break the boundary layer.
  - Sufficient difference in sensor facing upstream vs downstream to decode up from down with simple time delays.

Spiral Surge Plume Tracking

- Task Decomposition
  - –Plume finding
  - –Plume traversal
  - –Source declaration



6-smell channel Moorebot with Integrated Wind Sensor

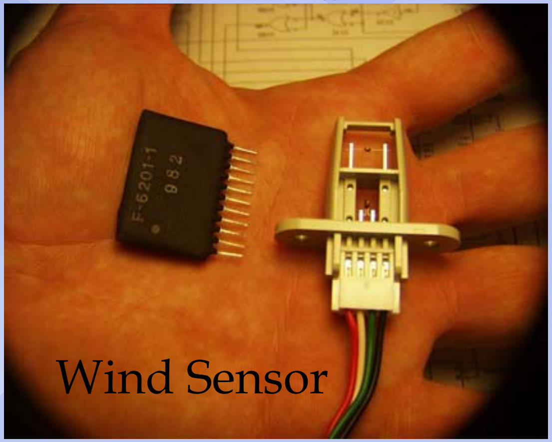


Tracking Hat for Overhead Vision System

Wind Sensor

Interface Electronics with Adaptive Baseline Tracking

6-channels of smell sensor
Uses discrete or chip sensors

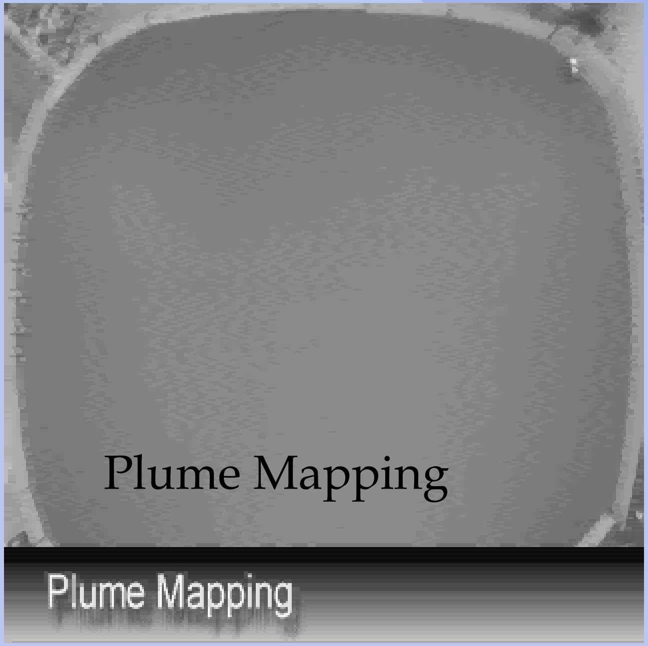


Range: 0.05m/s to 20m/s
Resolution: 5 degrees

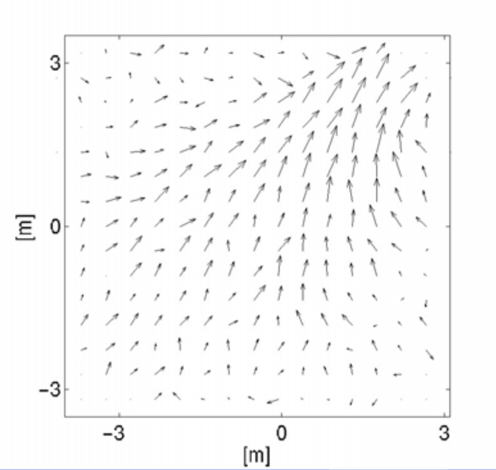
Odor Tracking and Mapping

Odor Visualization

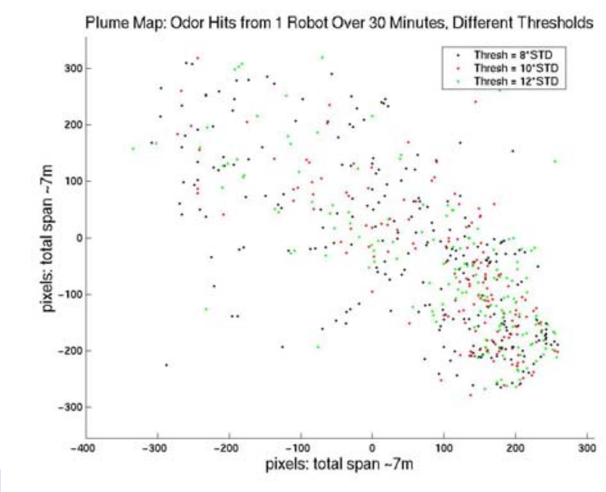
Single Robot Odor Finder



Plume Mapping



Wind direction map



Plume map

Rod Goodman

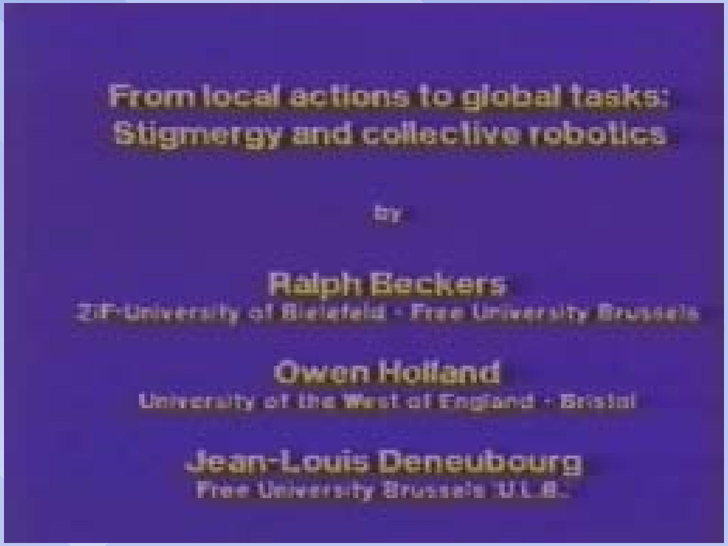
Multiple Collaborating Robots- collective robotics

Multiple robots offer significant advantages over single robots:

- Simultaneous sensing and action in multiple places
- Task dependent reconfigurability
- Enhanced system performance through work division
- Robustness through redundancy
- Task enabling if the task could not be solved by an individual

The challenge:

How can we design and control collective systems consisting of up to thousands of units?



From local actions to global tasks:
Stigmergy and collective robotics

by

Ralph Beckers
ZiF-University of Bielefeld · Free University Brussels

Owen Holland
University of the West of England · Bristol

Jean-Louis Deneubourg
Free University Brussels U.L.B.

S. Kazadi, A.Abdul-Khaliq, R. Goodman, "On the Convergence of Puck Clustering Systems," *Robotics and Autonomous Systems*, To appear.

Collective Plume Tracing

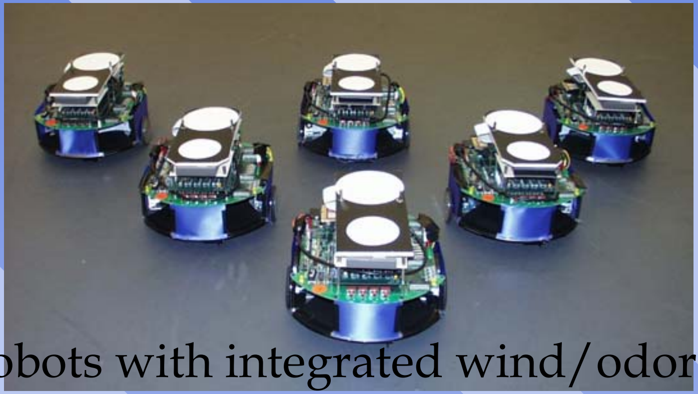
Steam Plume Visualization

- Behavioral priorities:
  1. obstacle avoidance
  2. trace following
  3. teammate following
  4. spiraling

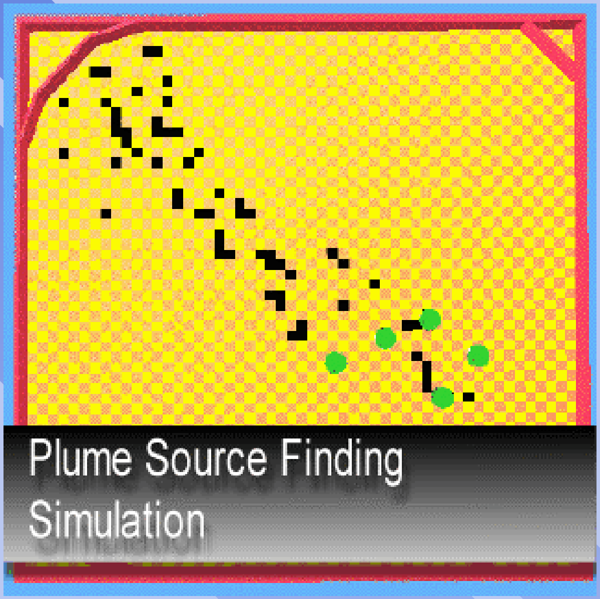
3 Robot Odor Localization

- Signaling with real IR hardware
- Equipped with “come to me” and “no hits here” beacons
- Dispersion and aggregation
- Robustness of the collective solution
- Uses spiral algorithm

Collective Plume Tracing

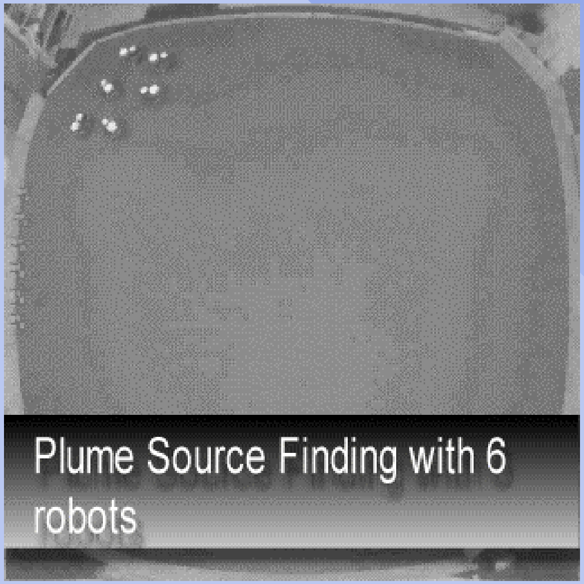


- Six robots with integrated wind/odor sensors



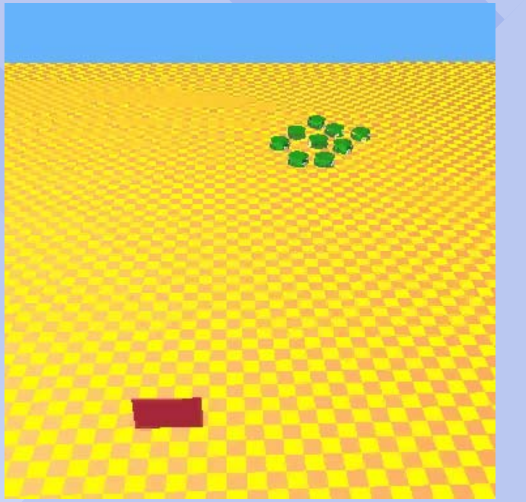
Plume Source Finding Simulation

Embodied Webots simulation – real lab plume data



Plume Source Finding with 6 robots

Overhead View



Embodied Webots simulation – Farrell simulated plume

- Signaling via virtual transceivers emulated via the overhead camera + radio LAN.
- No dispersion mechanism.
- [Hayes, Martinoli, Goodman, 2001]

Defining Performance

$$Q = \left(\frac{T_{sf}}{T_{min}}\right)^{\alpha} + \left(\frac{D_{sf}}{D_{min}}\right)^{\beta}$$

$$P = \frac{2}{E(Q)}$$

T_{sf}, D_{sf} - Time, Distance to find source

T_{min}, D_{min} - Optimum time and distance given environment

α,β - Weighting parameters

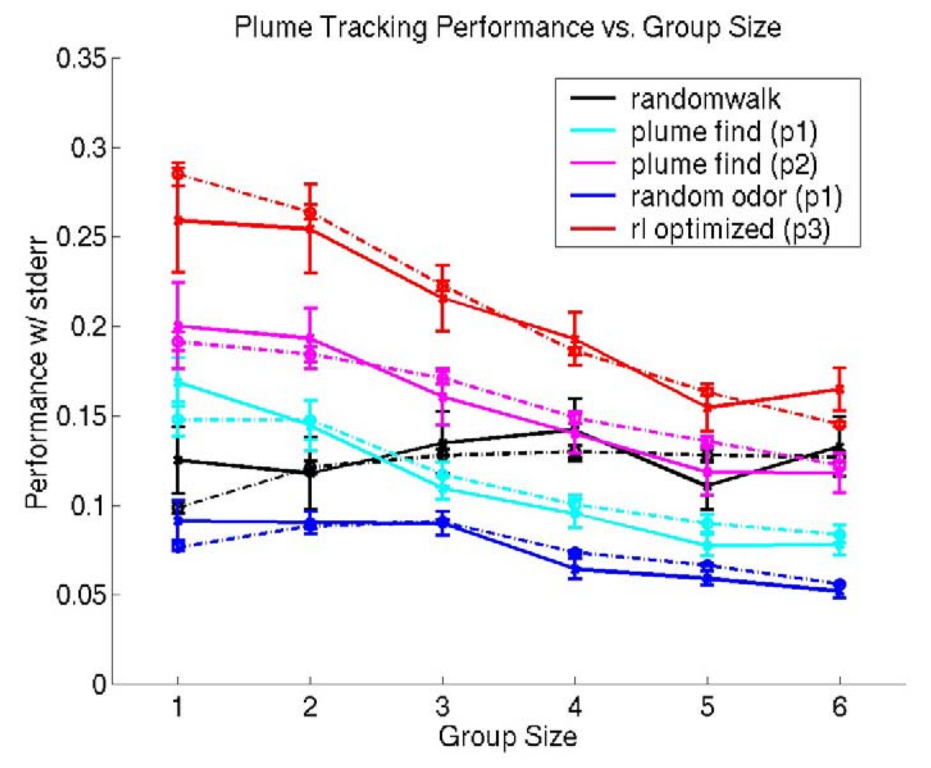
Algorithm Parameters

- **SpiralGap1** - Initial spiral gap width
- **SpiralGap2** - Plume reacquisition spiral gap width
- **StepSize** - Surge distance post odor hit
- **CastTime** - Time before reverting from reacquisition to initial spiral
- **SrcDecThresh** - Significance threshold between consecutive separate hits
- **SrcDecCount** - Number of differences before source declaration
- **CommRange** - Communication range

Odor Localization Results

Five different algorithms:

- Random turns at obstacles (30 trials/group size)
- Plume tracing spiral algorithm with two different sets of parameters (15 trials per group size)
- Spiral algorithm with randomly generated plume hits, to assess performance of pure 'wind tracking' (15 trials per group size)
- Plume tracing spiral algorithm with parameters optimized via reinforcement learning (15trialsper group size)



- Best (highest) performance recorded from plume tracing algorithm with reinforcement learning to optimize parameters.
- Poor performance with random odor hits demonstrates true plume information is being used, not just wind.
- Good performance of random walk algorithm at large group sizes indicates the exploration area is too small relative to plume extent and robot size.

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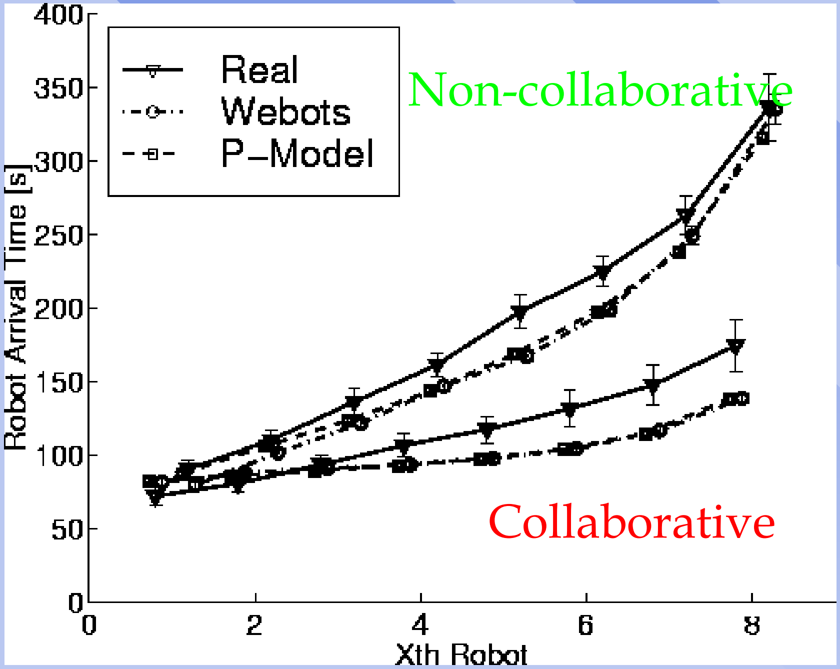
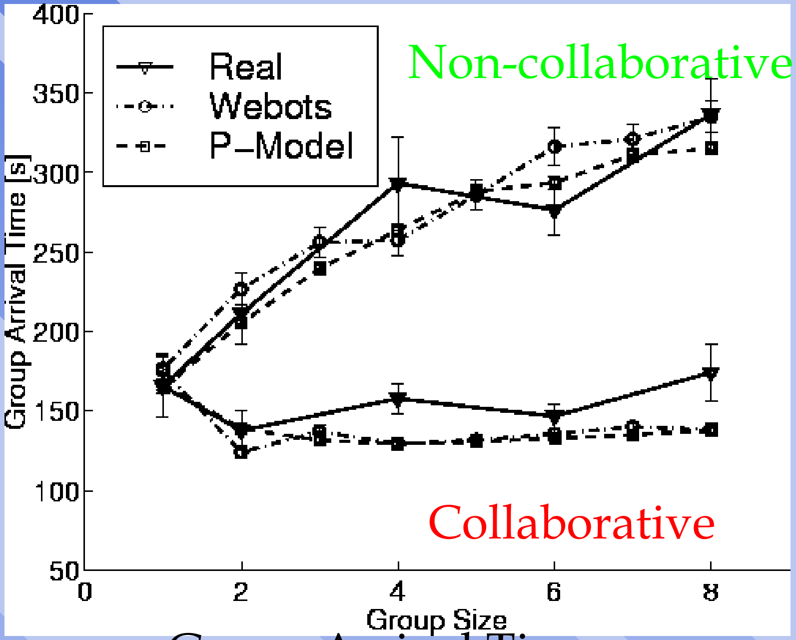
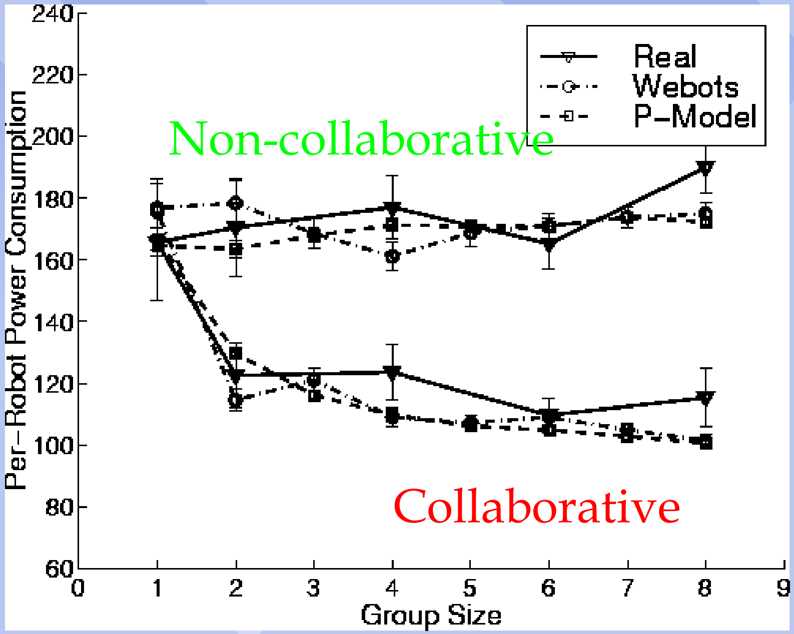
Collective Advantage



Robot Arrival Time



Group Arrival Time



Per Robot Power Consumption

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Challenges !

Get the Moorebots outside the lab!

FLYING NOSES!

In Collaboration with the University of the West of England:

- Owen Holland
- Alan Winfield
- Chris Melhuish

The Flying Flock