# Conducting Polymer Composite Detector Arrays


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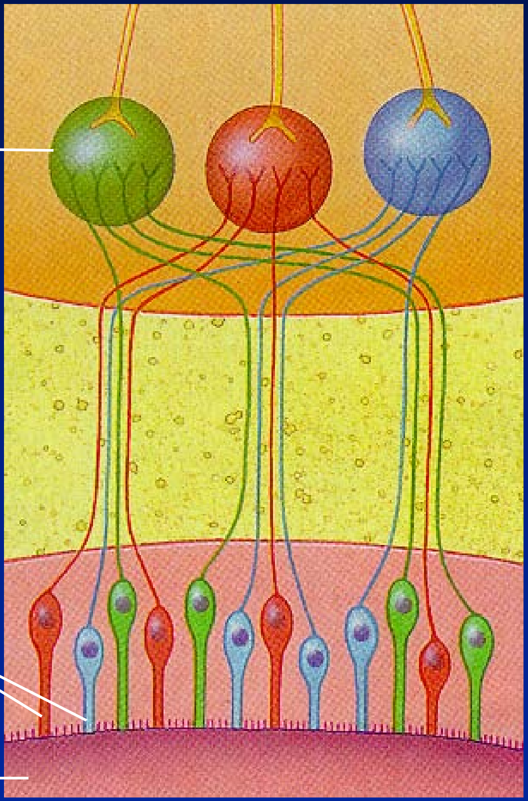
**JPL-Mike Burl**
Signal Processing
**Aerovironment**
Phil Tokumaru CFD

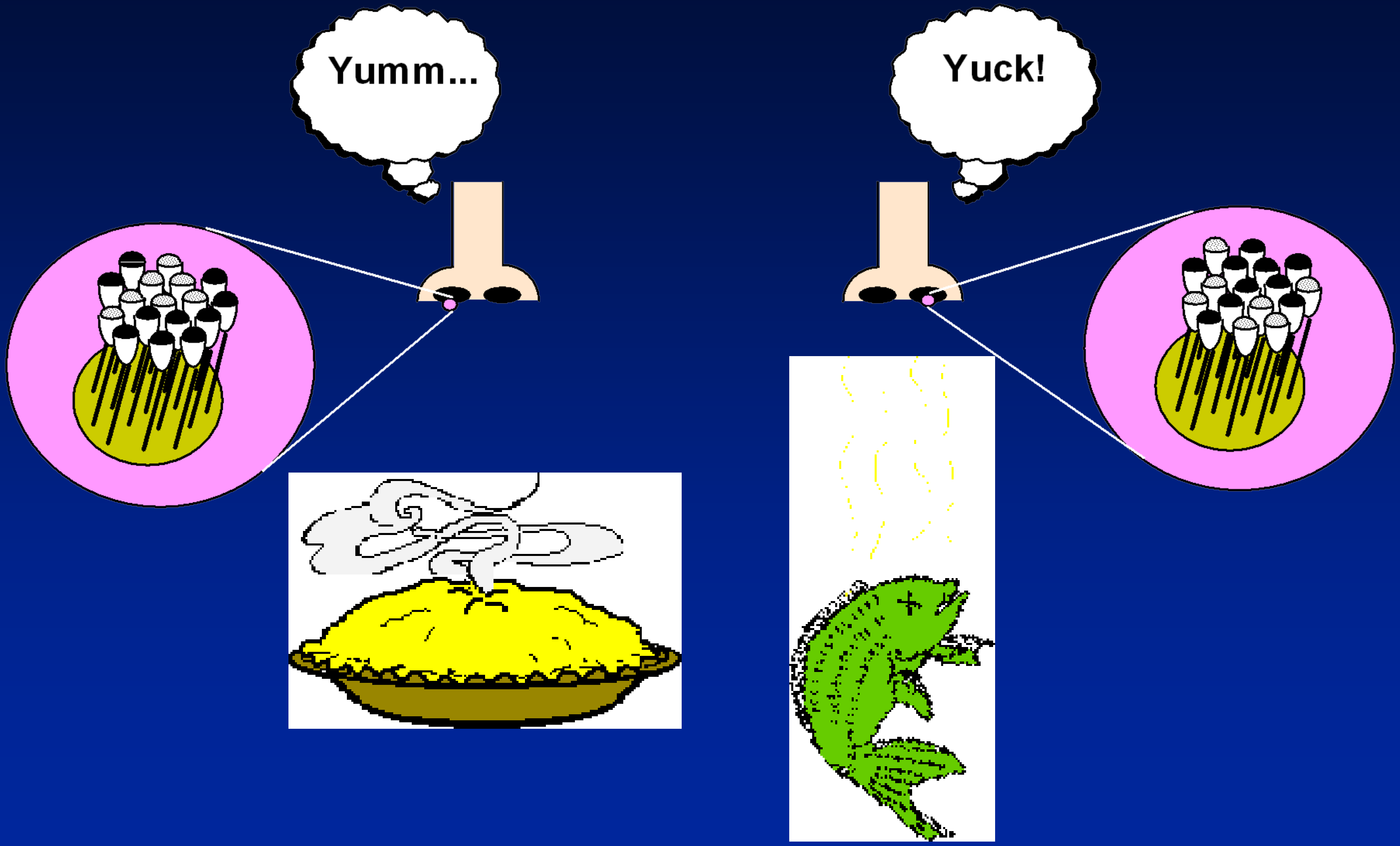
# Mammalian Olfaction

*(Axel and Buck, 1995-1999)*




- Mammals have ≈ $10^3$ chemically different types of odorant receptor proteins
- A single receptor recognizes multiple odorants
- A single odorant is recognized by multiple receptors
- Odorants may be identified by combinatorial patterns of activated receptors

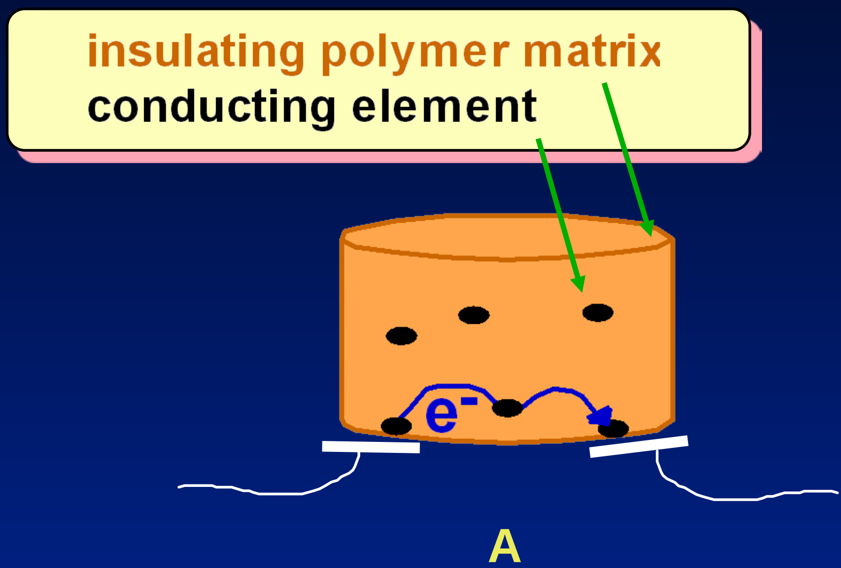
# Olfactory Pattern Recognition

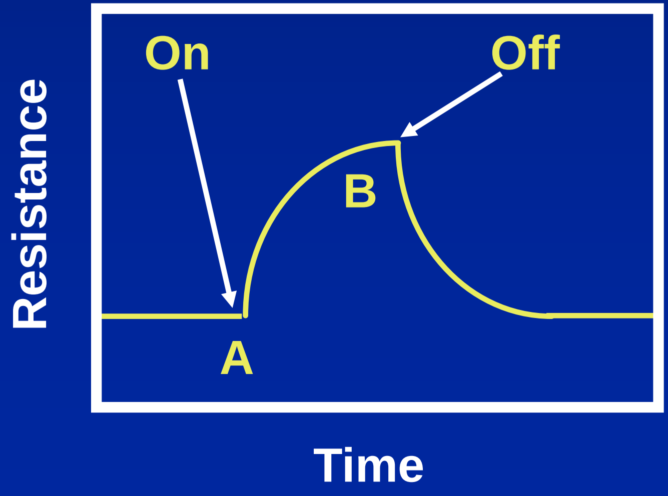


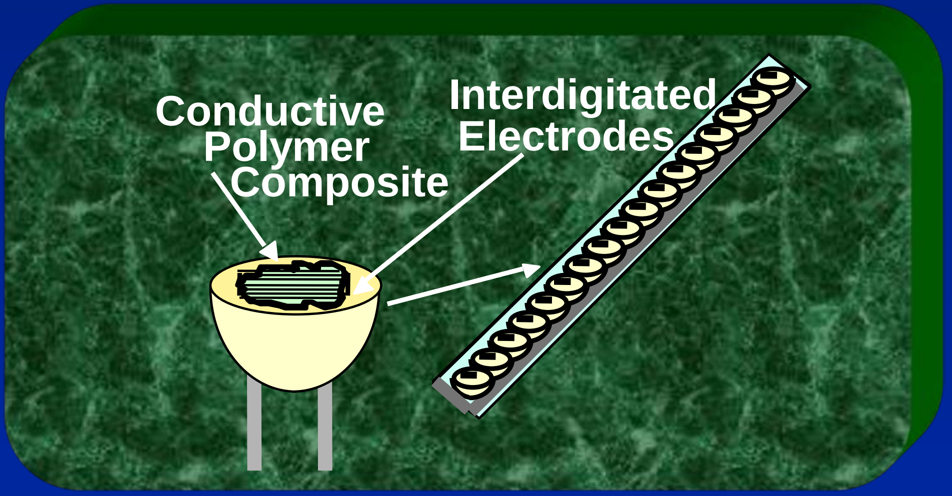
# Outline

- **Principles of Array Formation**
- Approach
  - Basic Detector Characteristics
  - Classification Performance
  - Sensitivity
- High-Pixel Density Chips
  - Combinatorial Arrays
  - Vapor Map Signatures
  - Correlation Between Pixels
- Spatiotemporal Signals
- Semi-customizable Arrays

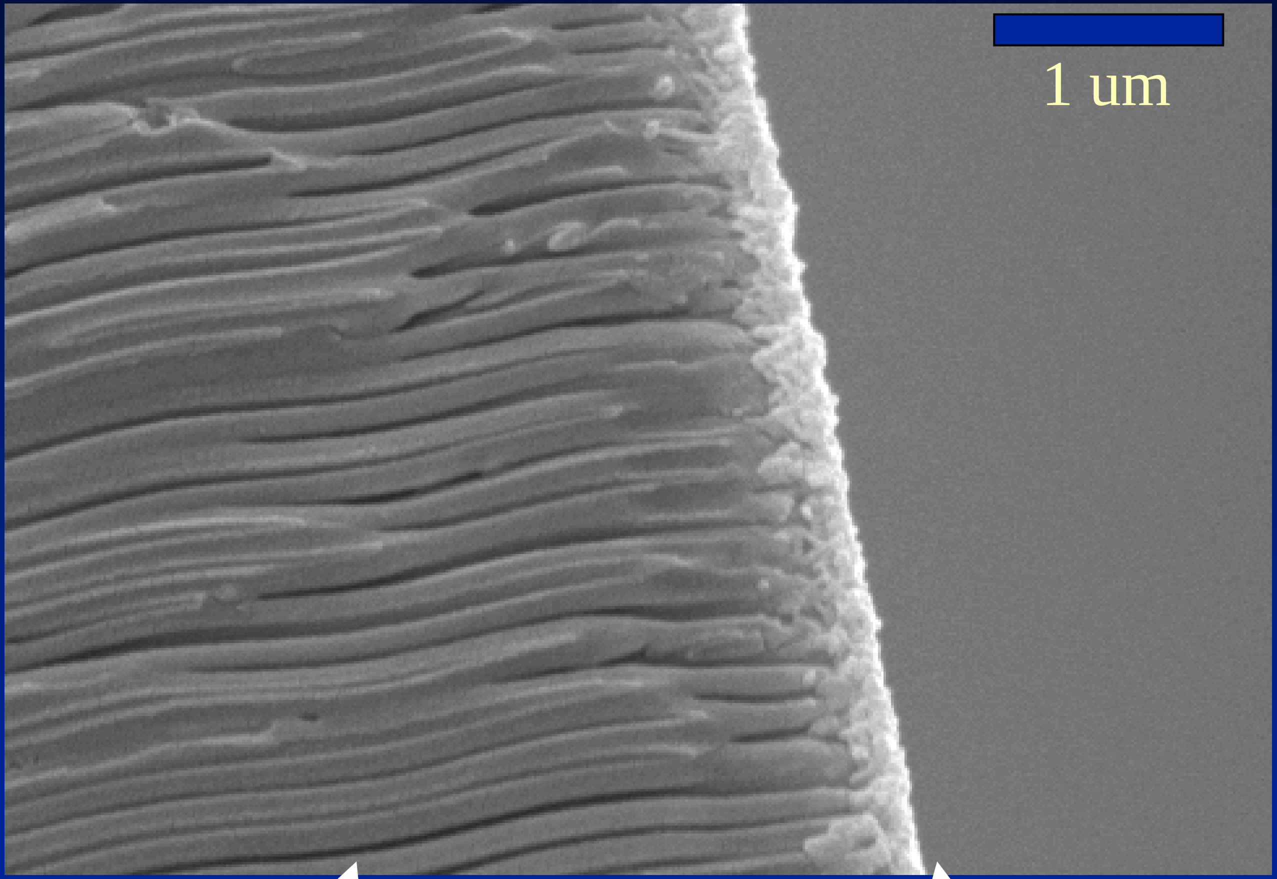
# Swelling-Induced Resistance Changes



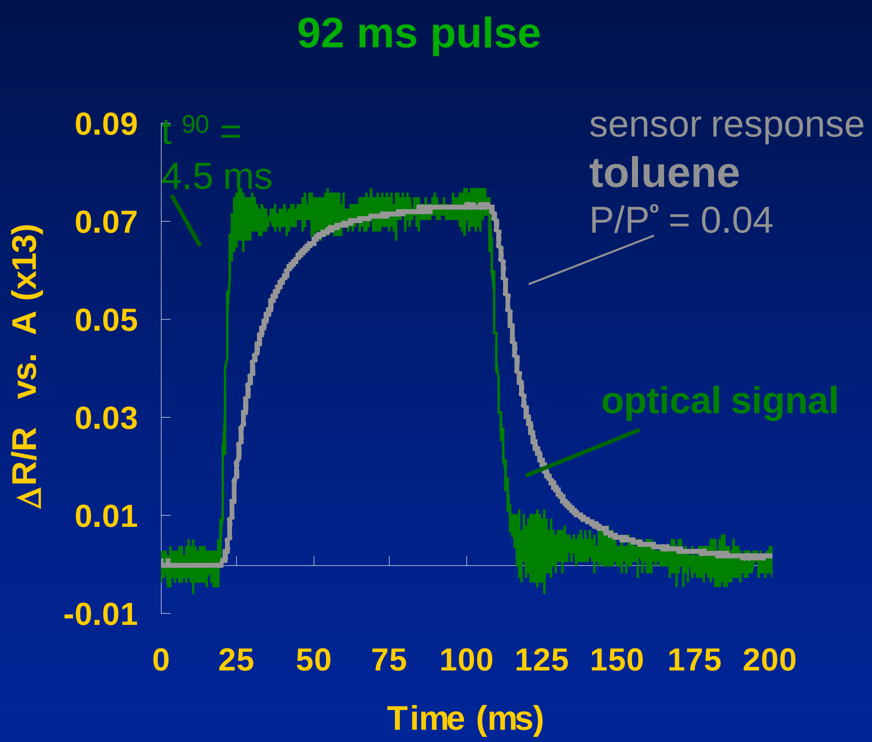
# SEM Image of Composite Membrane

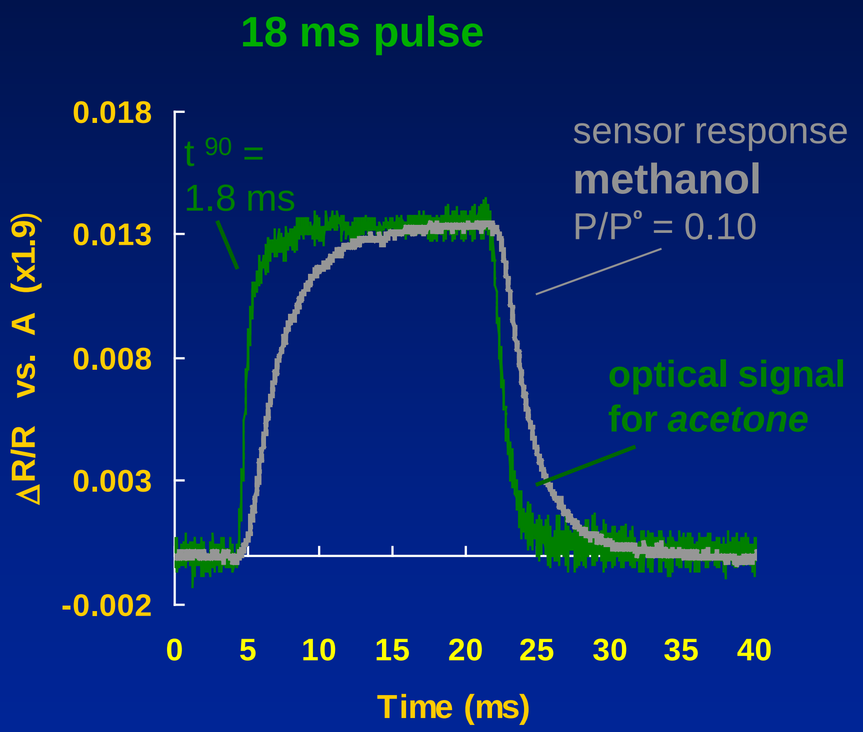



Porous Anopore support

Polymer/carbon black mix

# Time Response




*≈180 nm poly (ethylene co-vinyl acetate) film*

# Different Polymers Have Different Properties

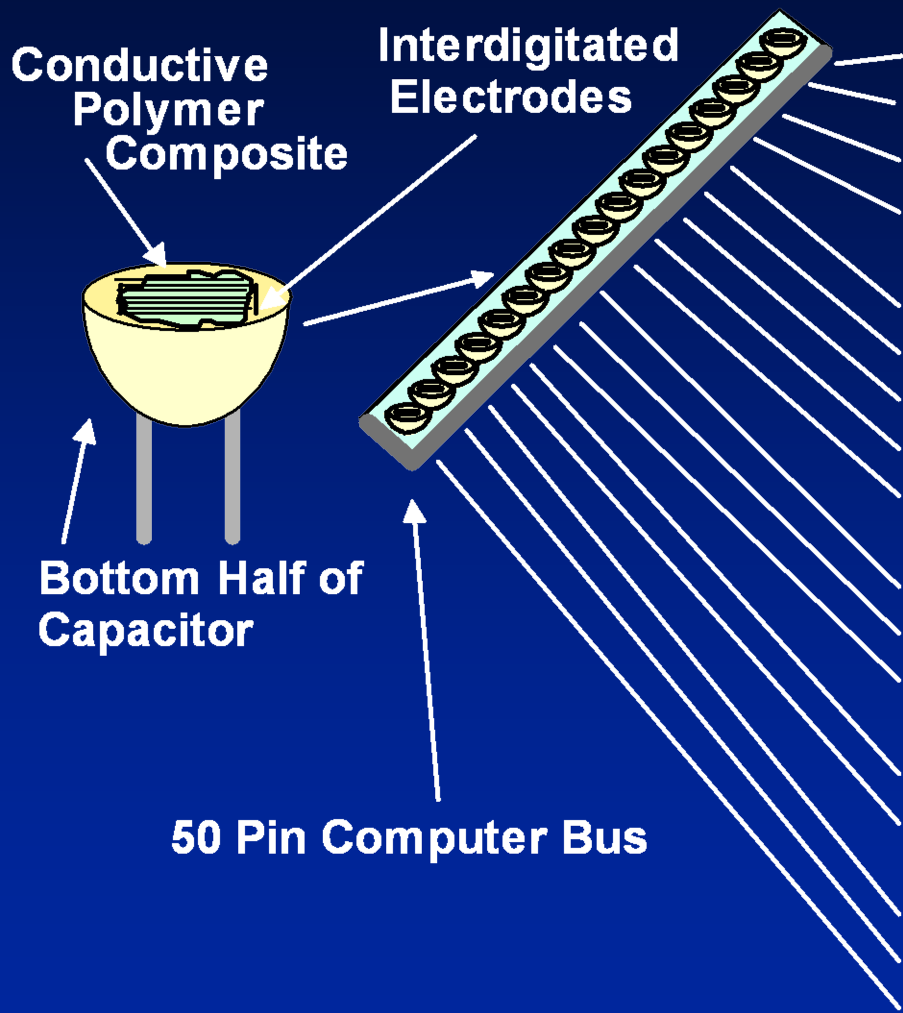
likes water

does not like water

## Insulating Polymer

poly(4 - vinyl phenol)
poly(*N* - vinyl pyrrolidone)
poly(ethylene oxide)
poly(caprolactone)
poly(methyl vinyl ether - *co* - maleic anhydride)
poly(styrene - *co* - maleic anhydride)
poly(vinylidene chloride - *co* - acrylonitrile)
poly(styrene - *co* - allyl alcohol)
poly(vinyl butyral)
poly(sulfone)
poly(vinyl acetate)
poly(methyl methacrylate)
poly(ethylene -*co* - vinyl acetate)
poly(carbonate bisphenol A)
poly($\alpha$ - methyl styrene)
poly(styrene)
poly(vinyl chloride -*co* - vinyl acetate)

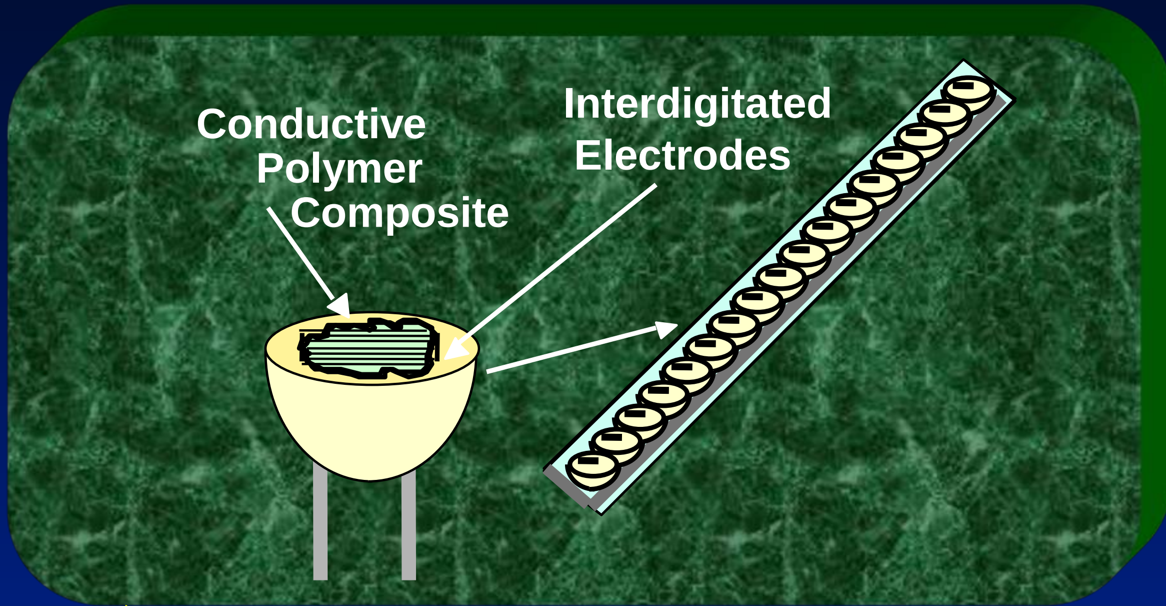
# Carbon Black Composite Sensor Array

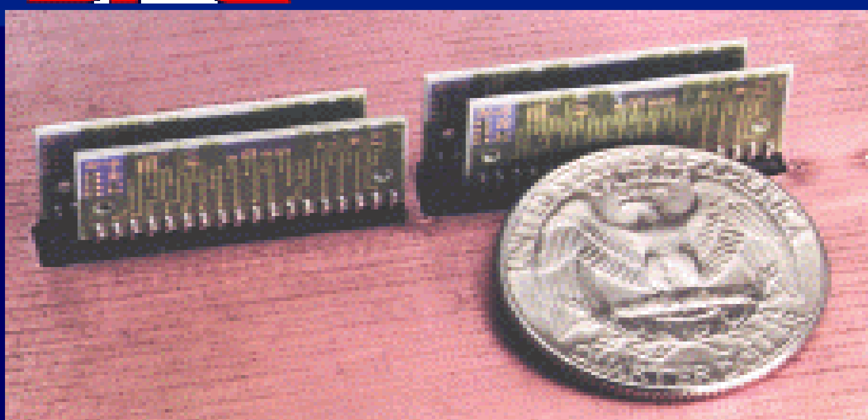



**Insulating polymer**

1. poly(4 - vinyl phenol)
2. poly(styrene -*co* - allyl alcohol)
3. poly($\alpha$ - methylstyrene)
4. poly(vinyl chloride - *co* - vinyl acetate)
5. poly(vinyl acetate)
6. poly(*N* - vinylpyrrolidone)
7. poly(carbonate bisphenol A)
8. poly(styrene)
9. poly(styrene - *co* - maleic anhydride)
10. poly(sulfone)
11. poly(methyl methacrylate)
12. poly(methyl vinyl ether - *co* - maleic anhydride)
13. poly(vinyl butyral)
14. poly(vinylidene chloride - *co* - acrylonitrile)
15. poly(caprolactone)
16. poly(ethylene -*co* - vinyl acetate)
17. poly(ethylene oxide)

# Early Technology Insertion

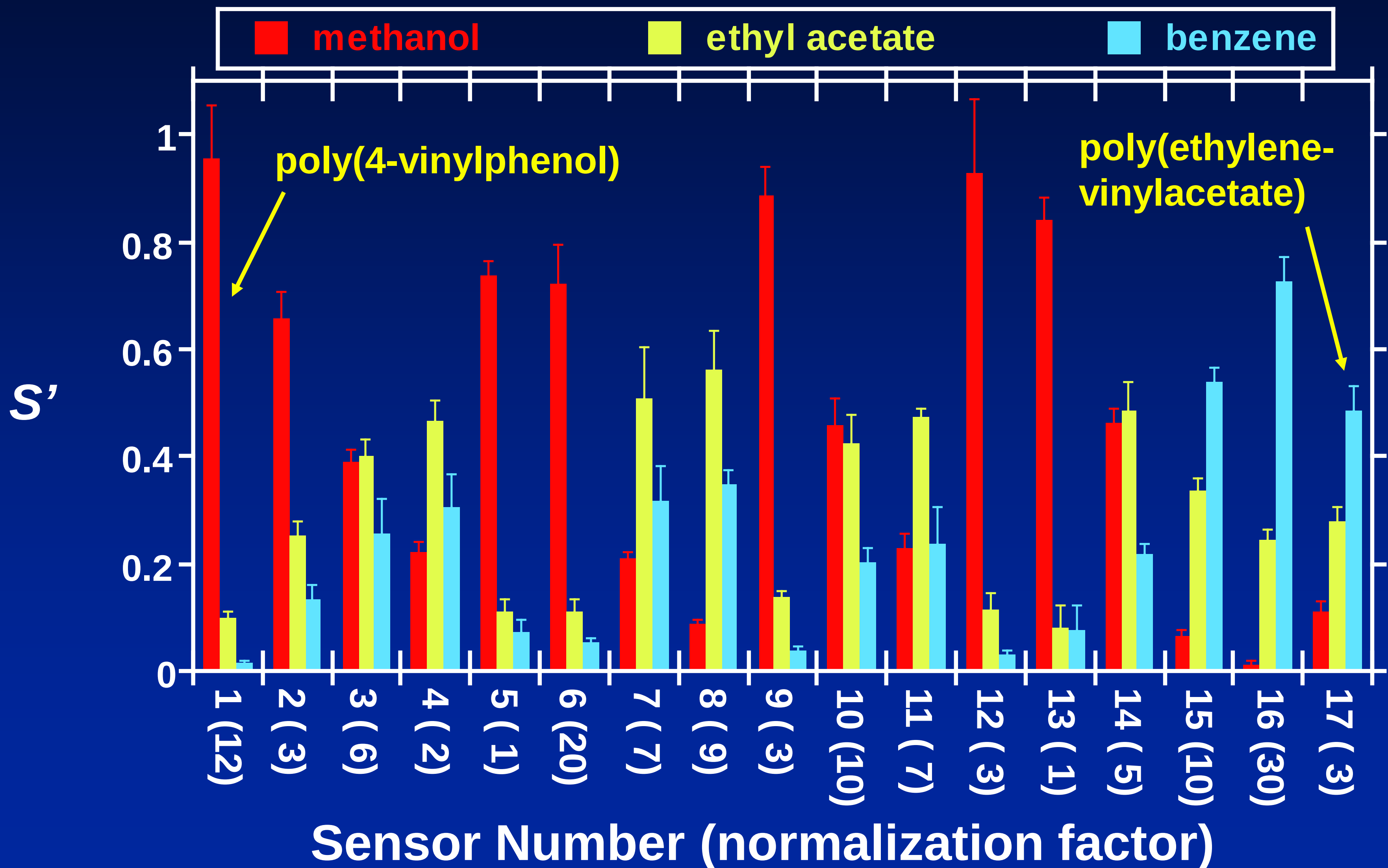


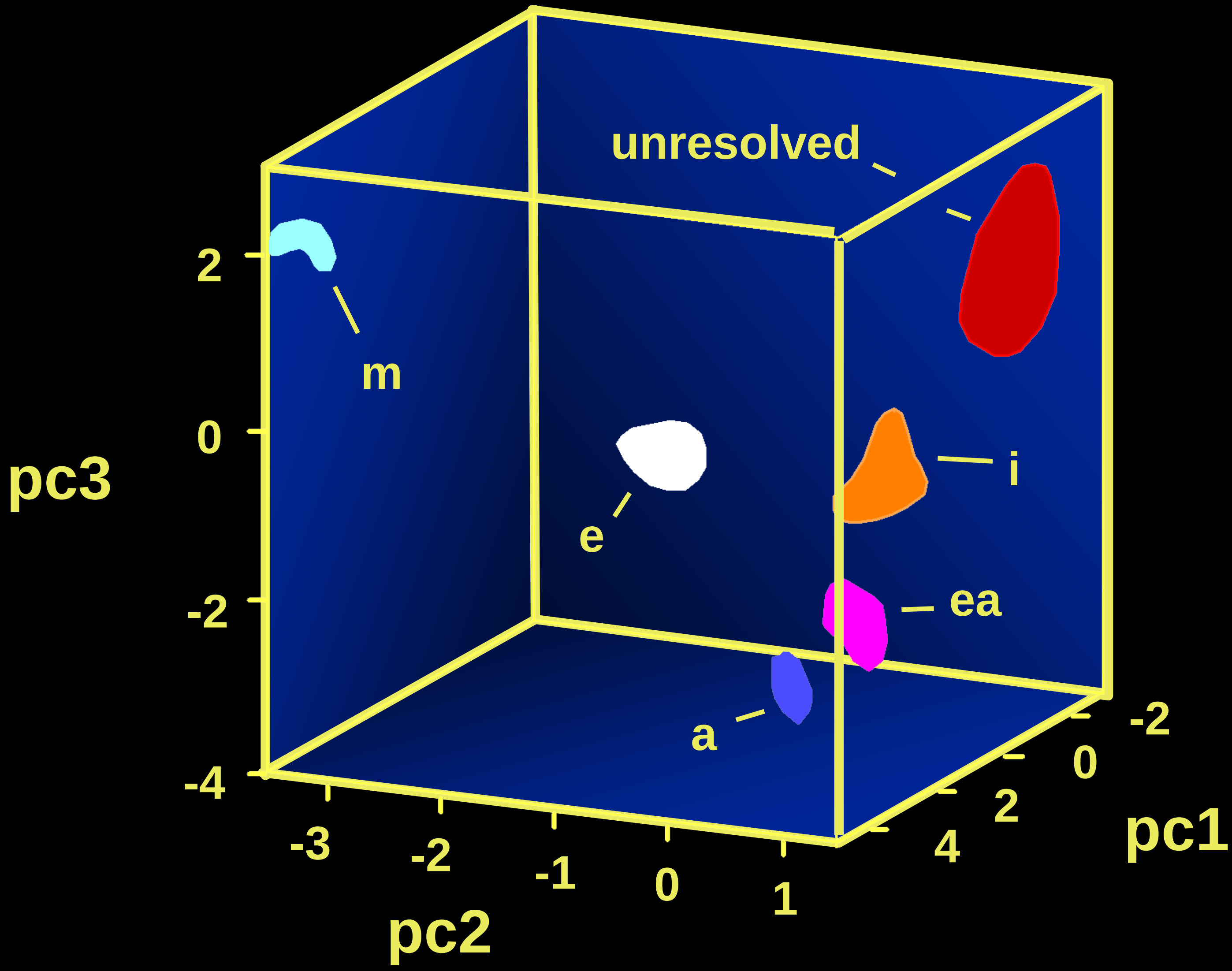
Sensor Array

STS-95

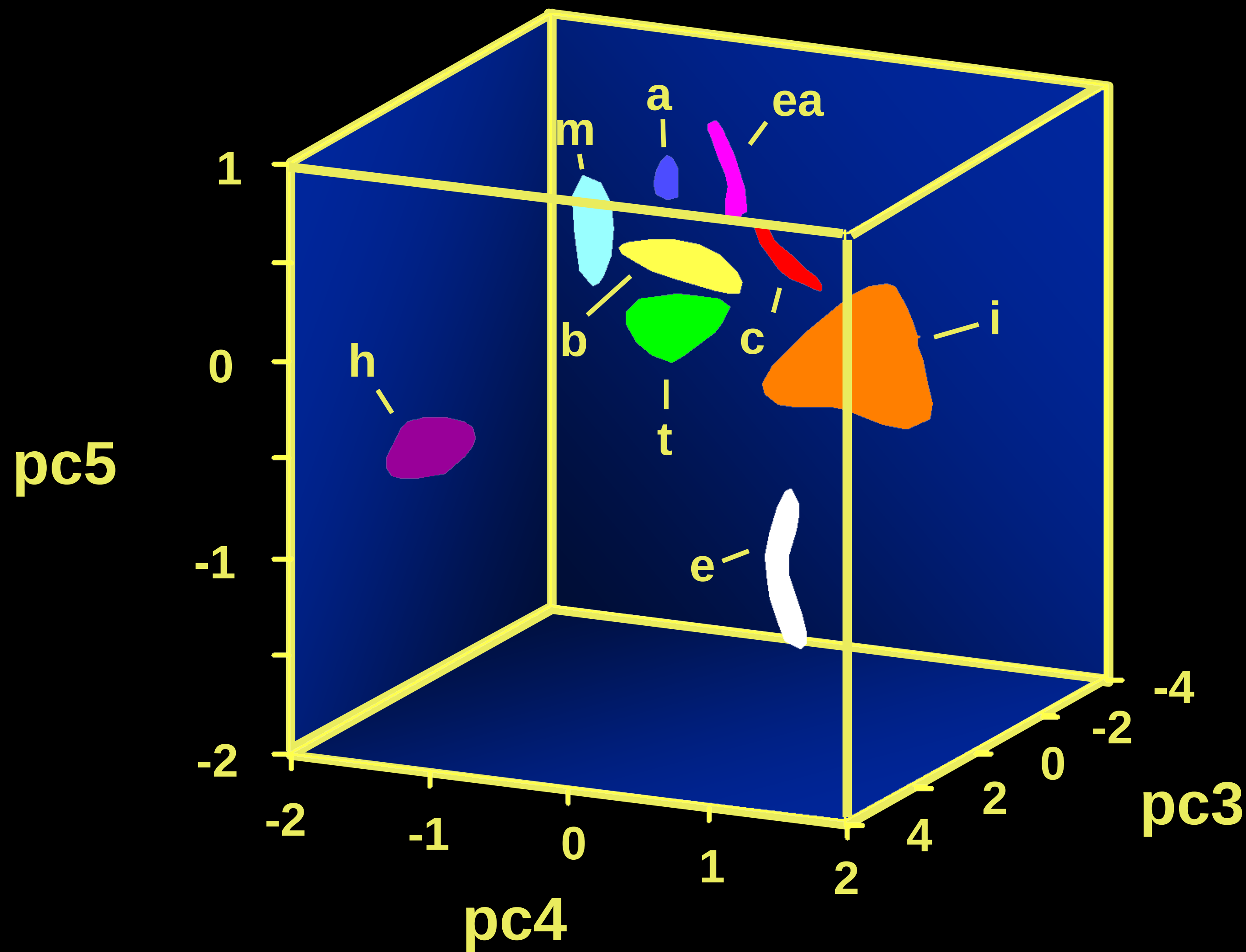
# Different Patterns for Different Vapors



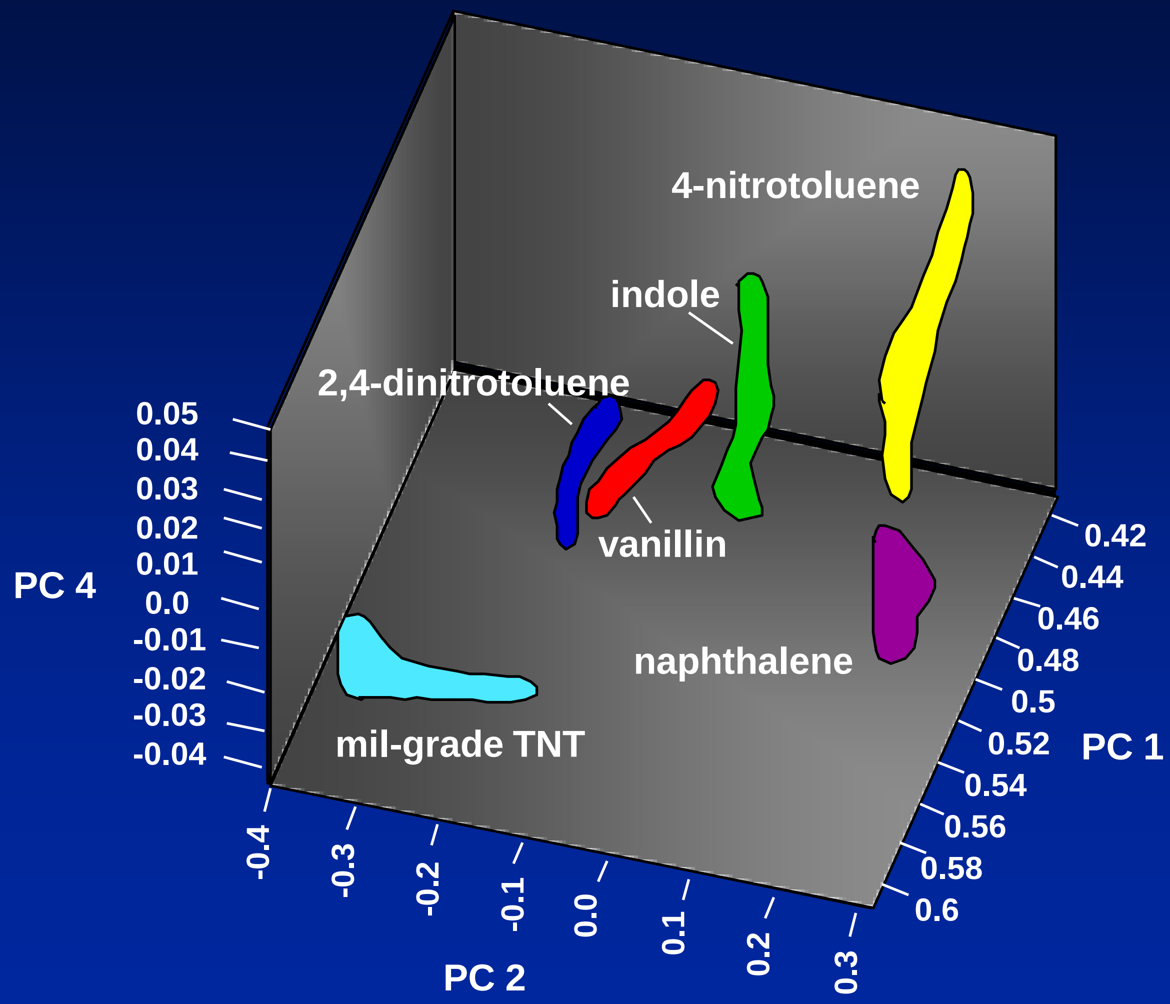
# Carbon Black-Based Array



# Carbon Black-Based Array



# Separation of Solid-Source Vapors



# Outline

- Principles of Array Formation
- **Approach**

  Basic Detector Characteristics

  Classification Performance

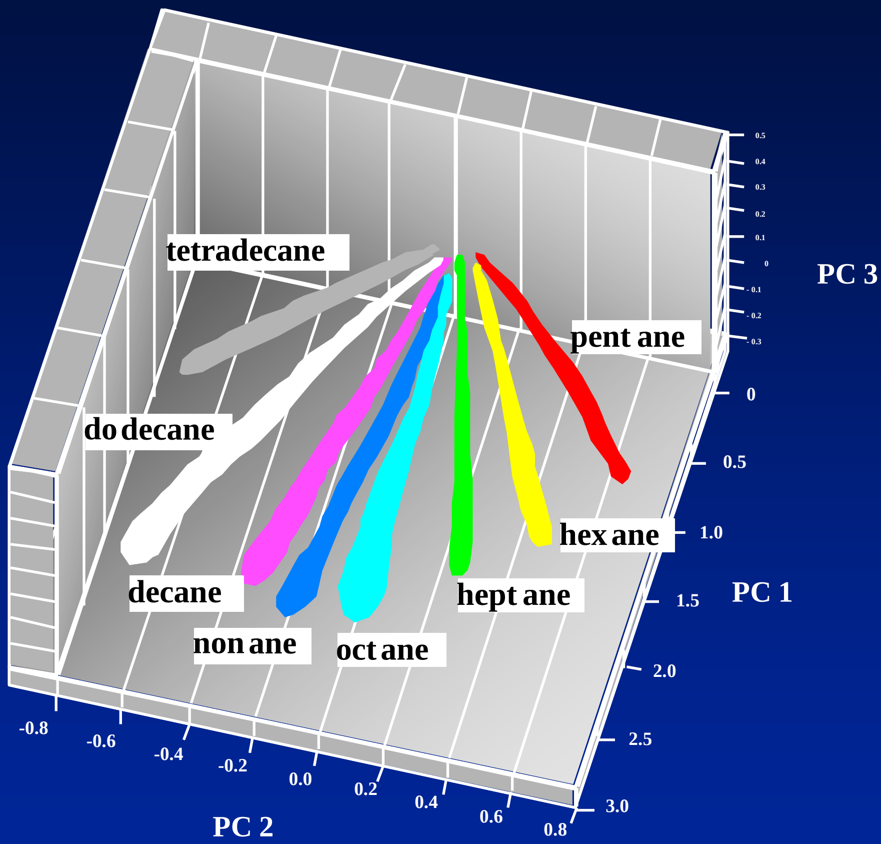
  Sensitivity
- High-Pixel Density Chips

  Combinatorial Arrays

  Vapor Map Signatures

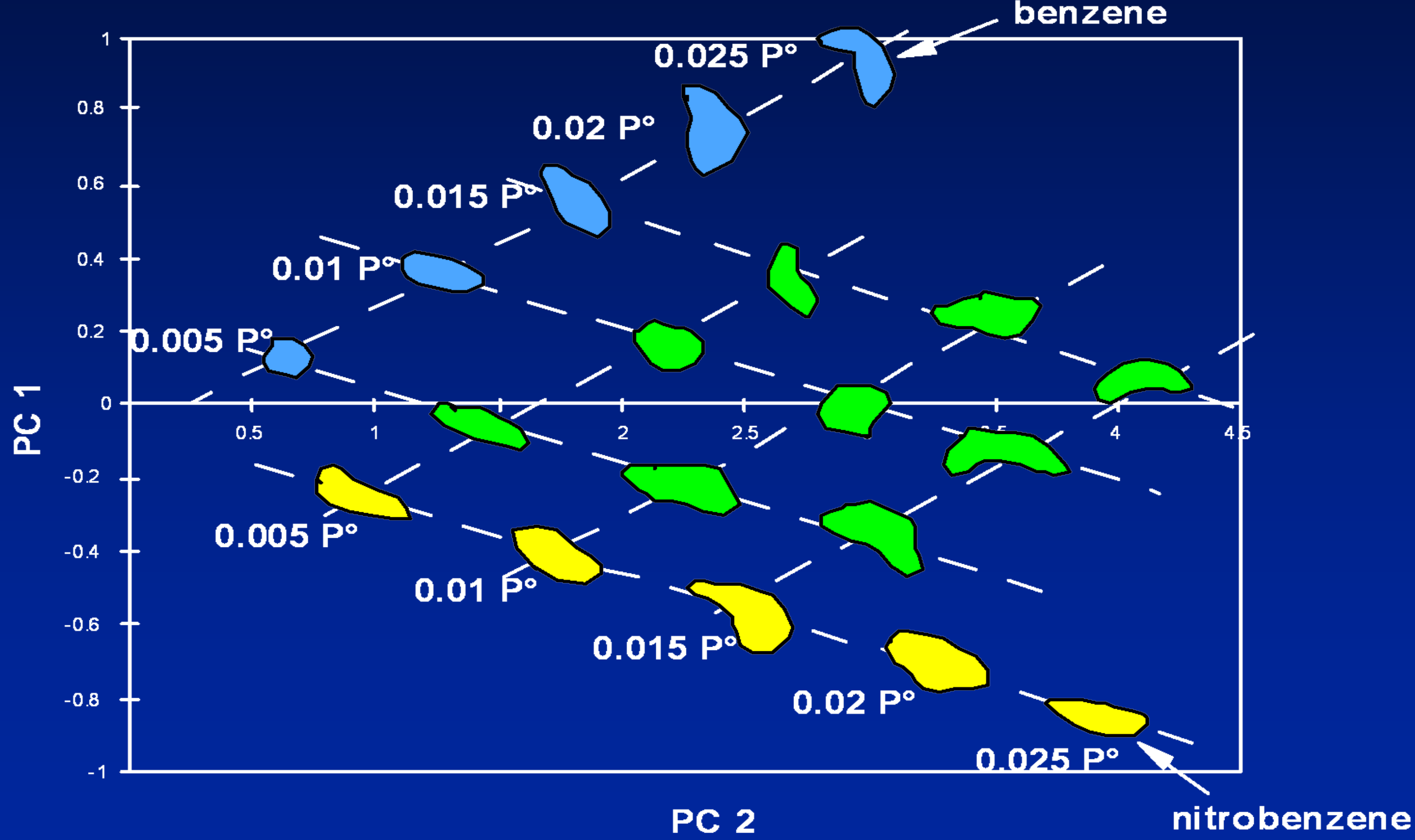
  Correlation Between Pixels
- Spatiotemporal Signals
- Semi-customizable Arrays

# Linearity of Response vs Concentration




*n-Alkanes from 0.005 - 0.03 P/P°*

# Exposure to Binary Mixtures



# Independence of Background

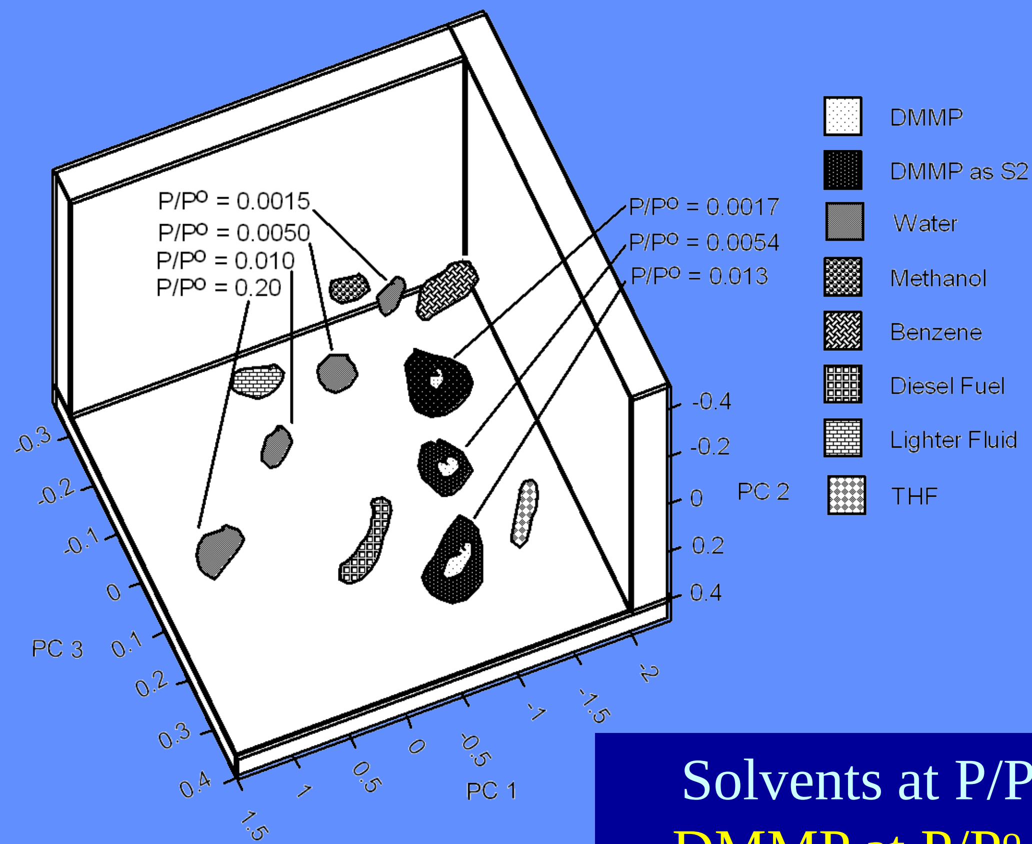
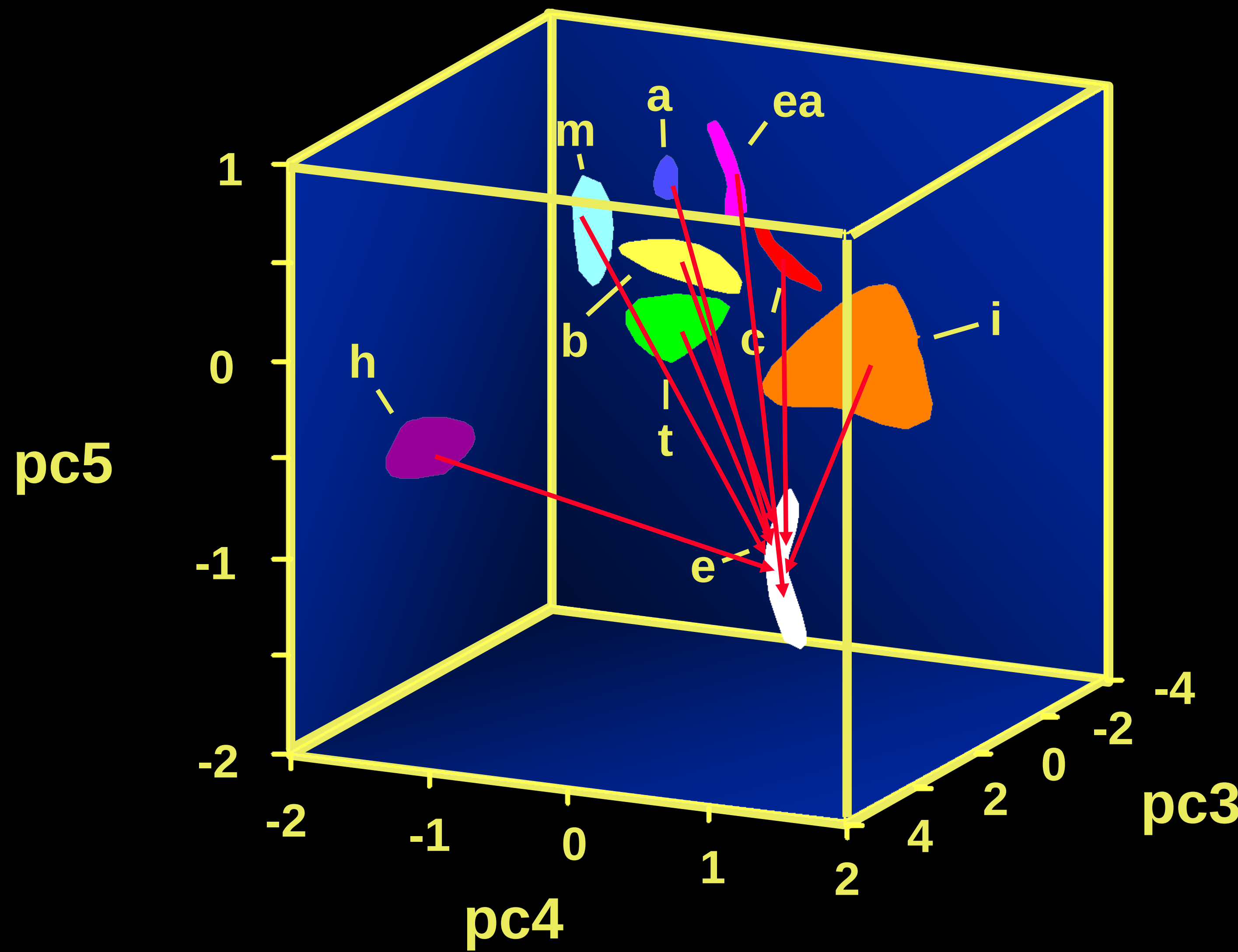


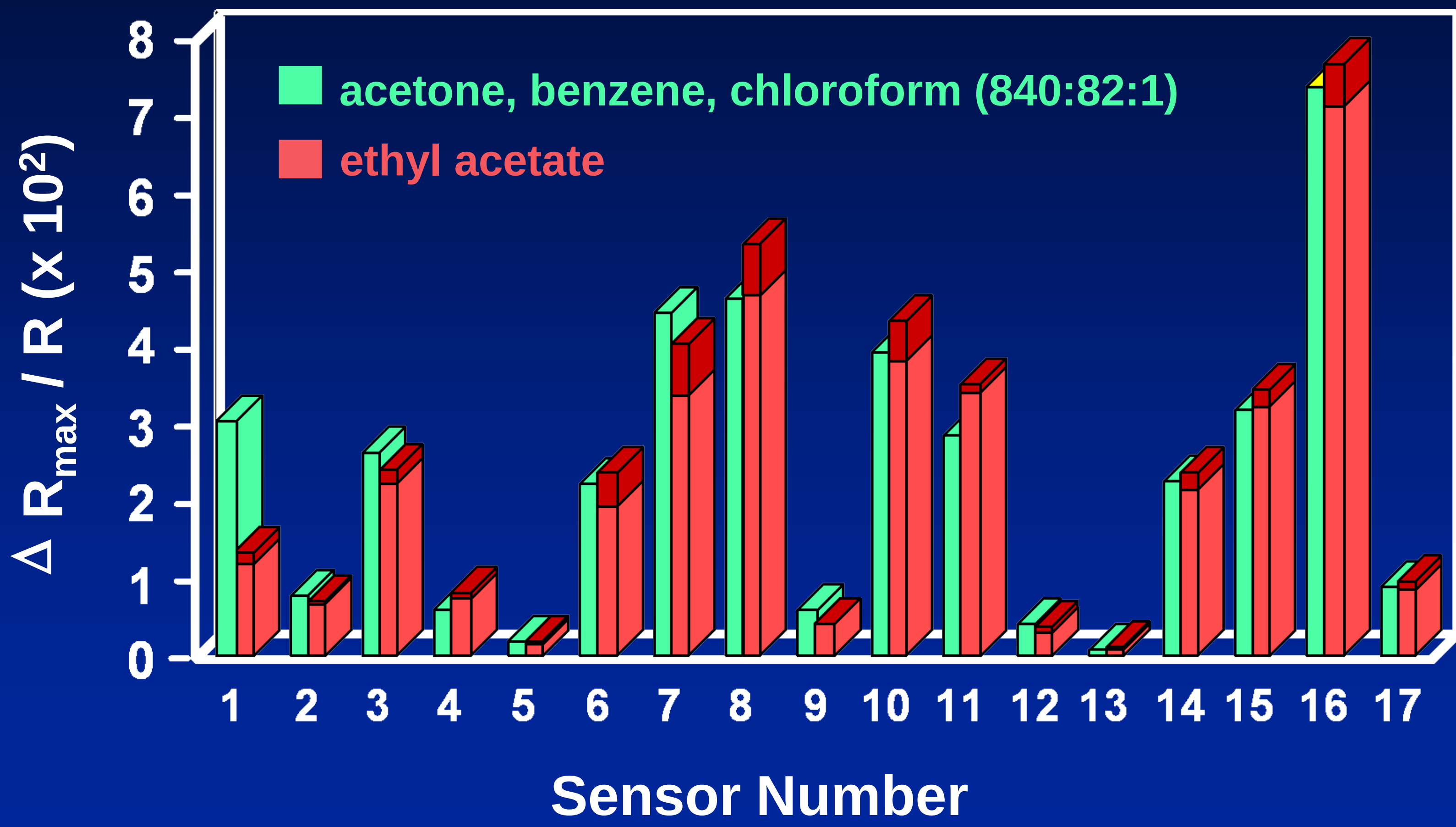

Figure 6.

Solvents at P/P$^{o}$=0.010 (1000 mg m$^{-3}$);
DMMP at P/P$^{o}$ = 0.0017 (2.56 mg m$^{-3}$), 0.0054 and 0.013
LOD 50 µg m$^{-3}$

# Carbon Black-Based Array

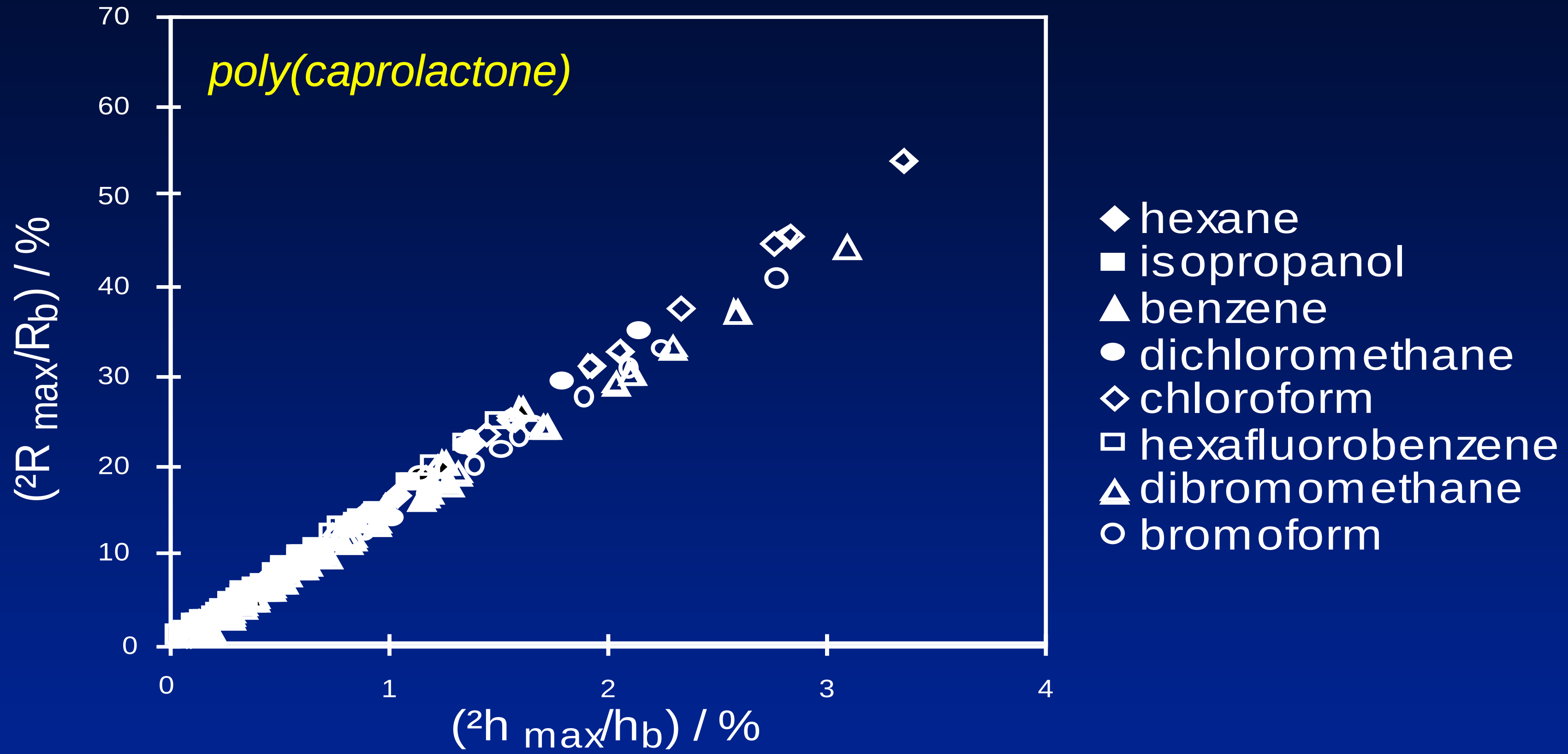


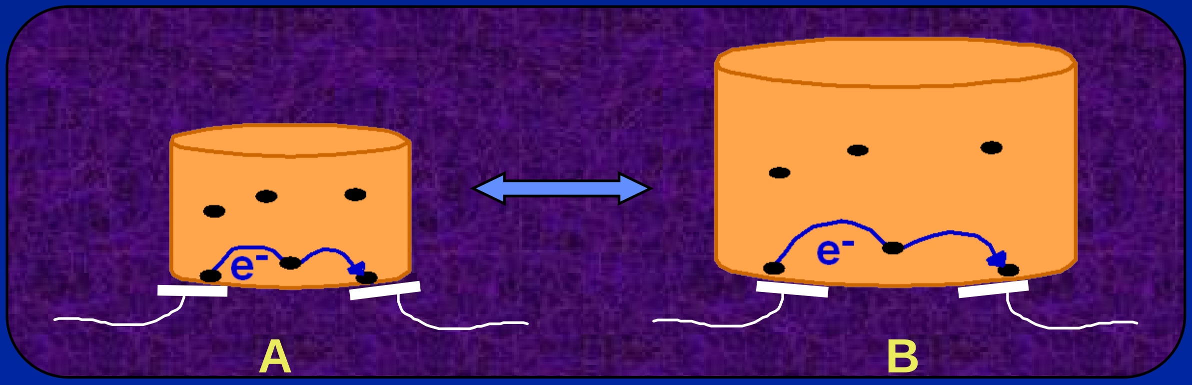
# Mixtures vs. New Vapors



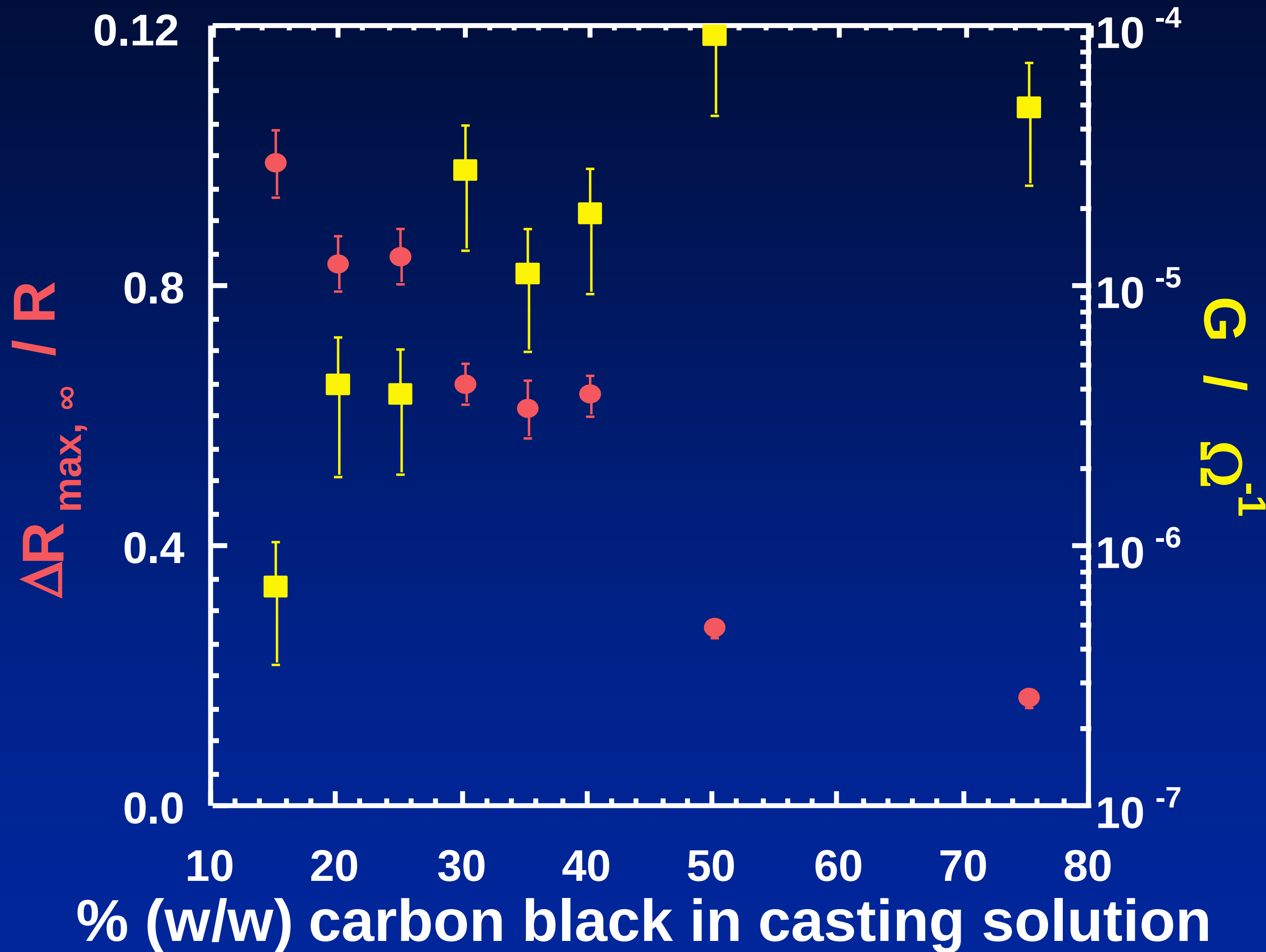

*17-element CB array*

# Resistance vs. Thickness Response



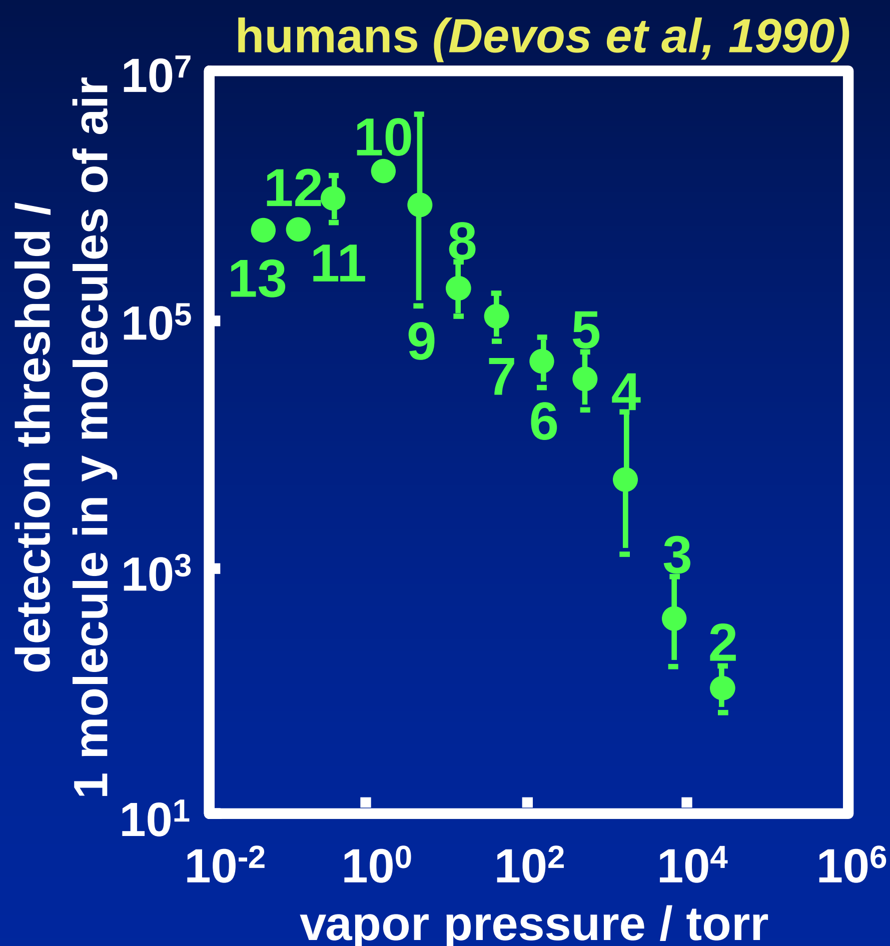



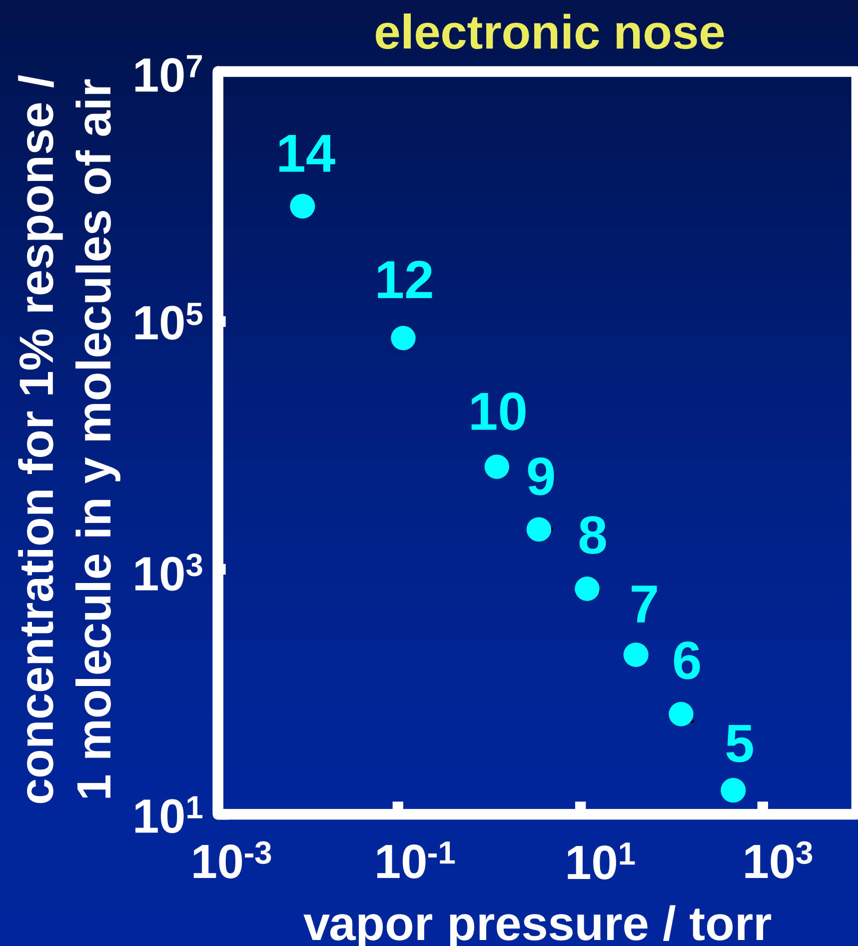
# Response vs. Carbon Black Content




*Poly(ethylene-co-vinylacetate-Carbon Black*
*Exposed to Benzene (10 ppt)*

# Sensitivity Trends for Humans vs. the Electronic Nose (n-Alkanes)



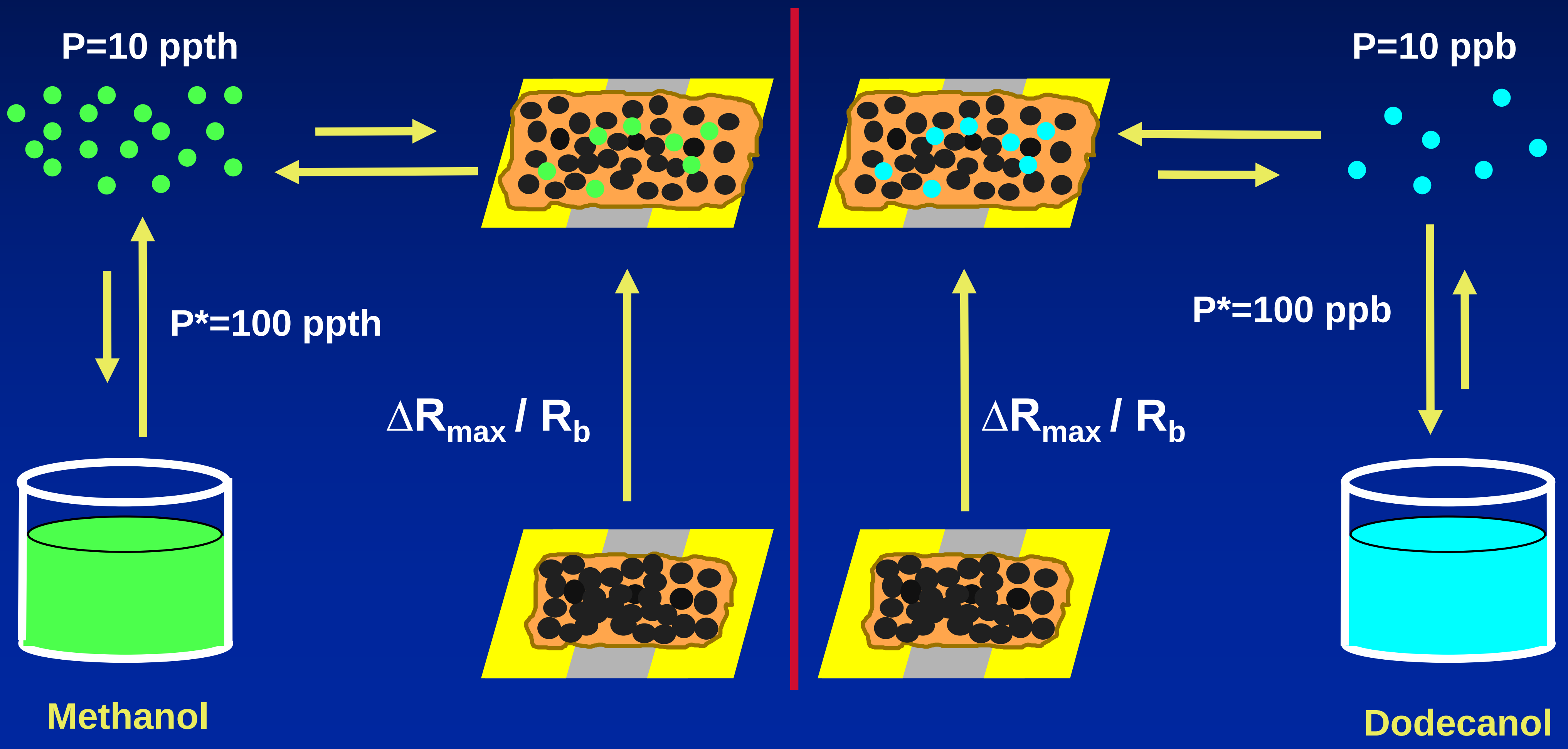



# Natural Preference for Low Vapor Pressure Odorants

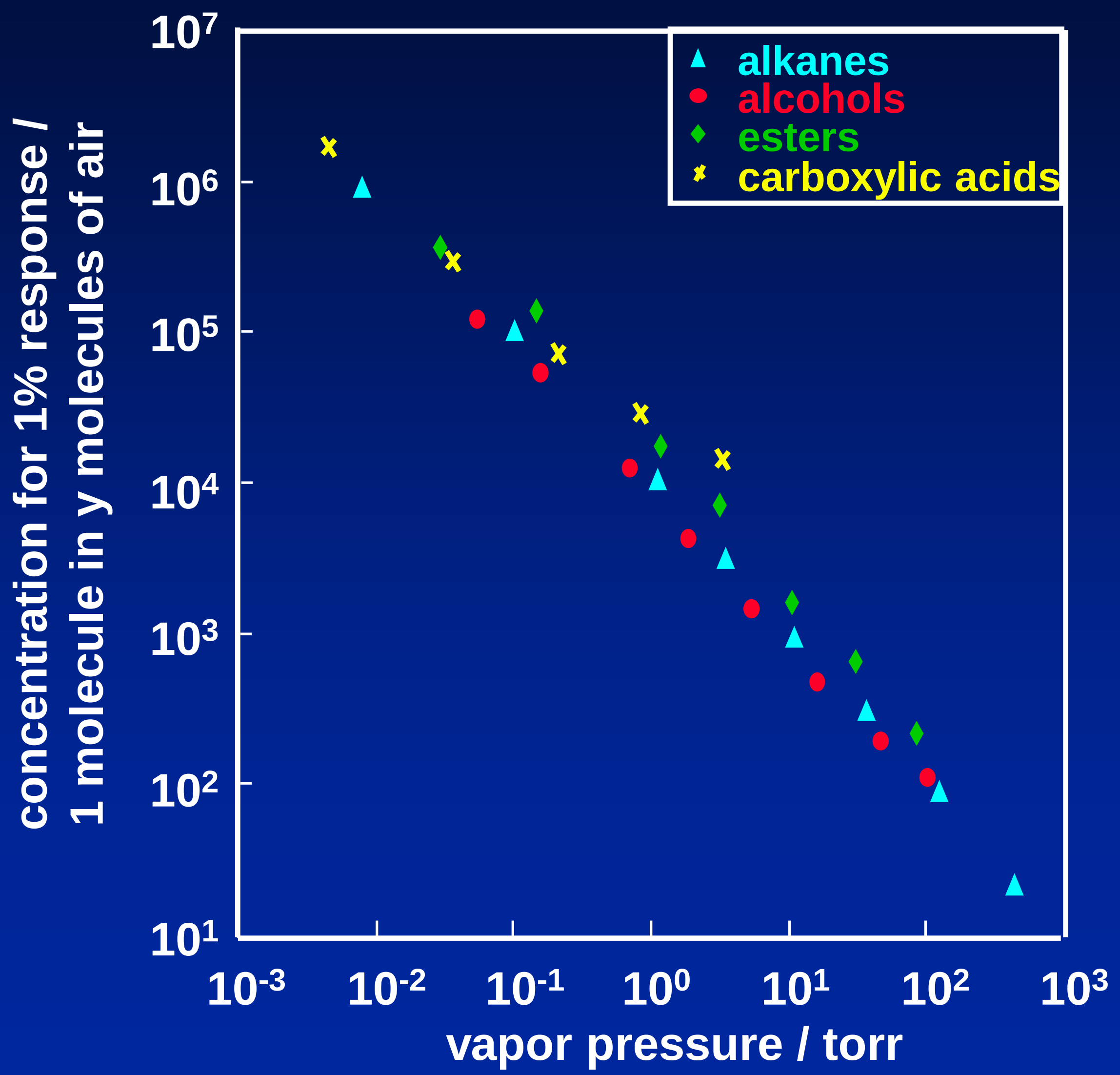
$$\frac{P}{P^*} = \gamma\chi$$

**case 1: high P* odorant**

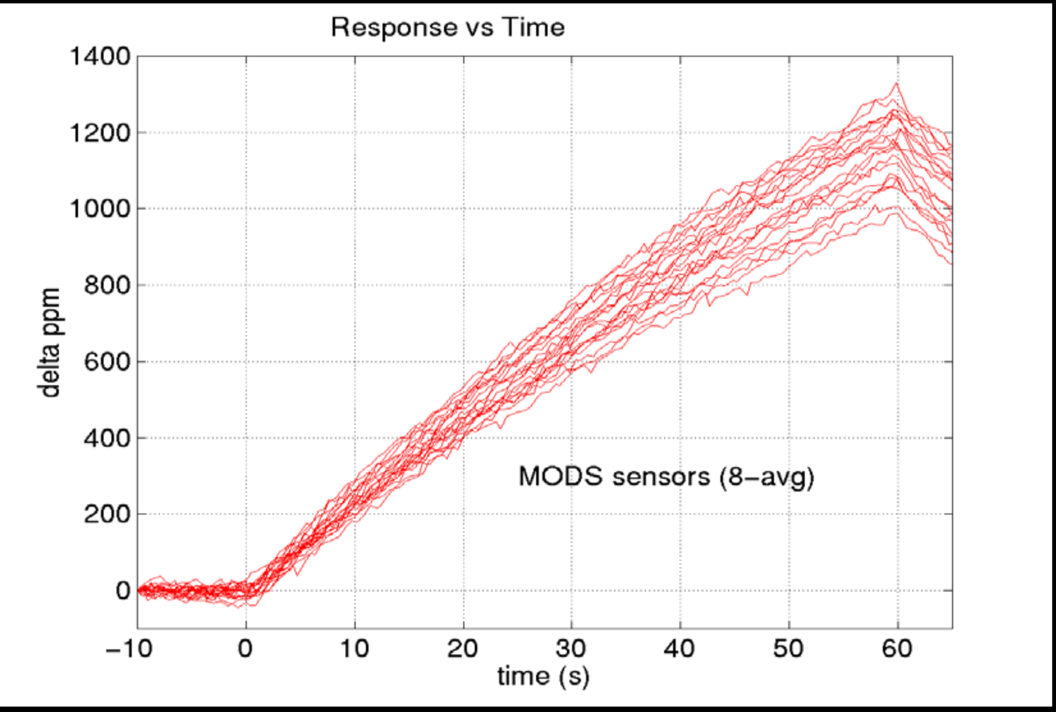
**case 2: low P* odorant**

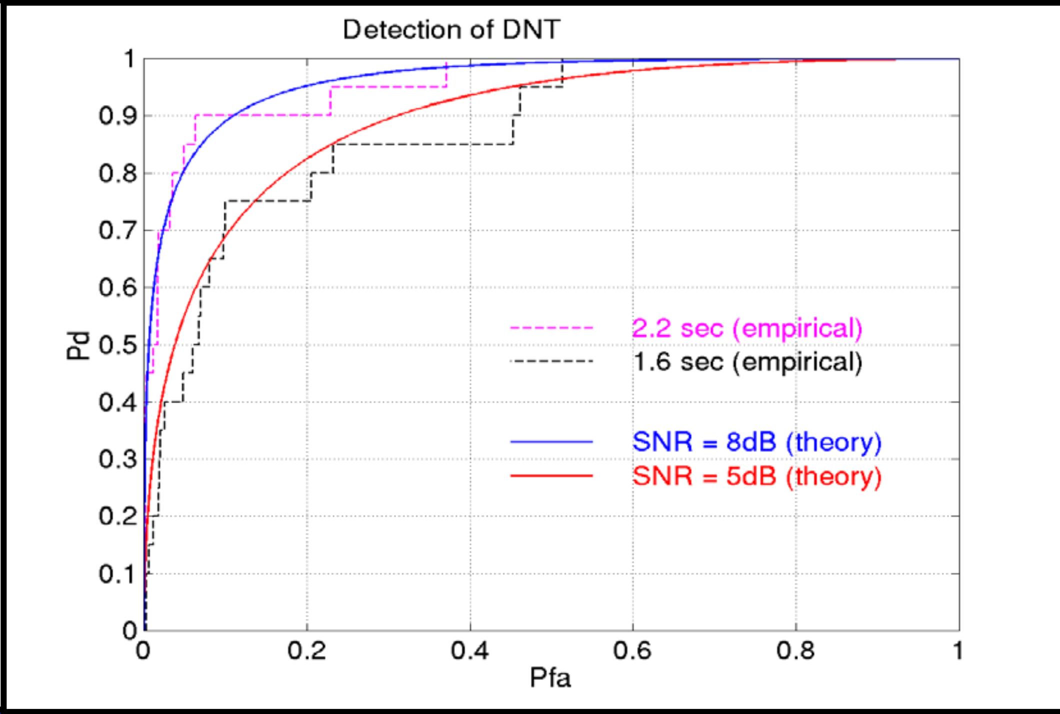


# Electronic Nose Sensitivity vs. Vapor Pressure



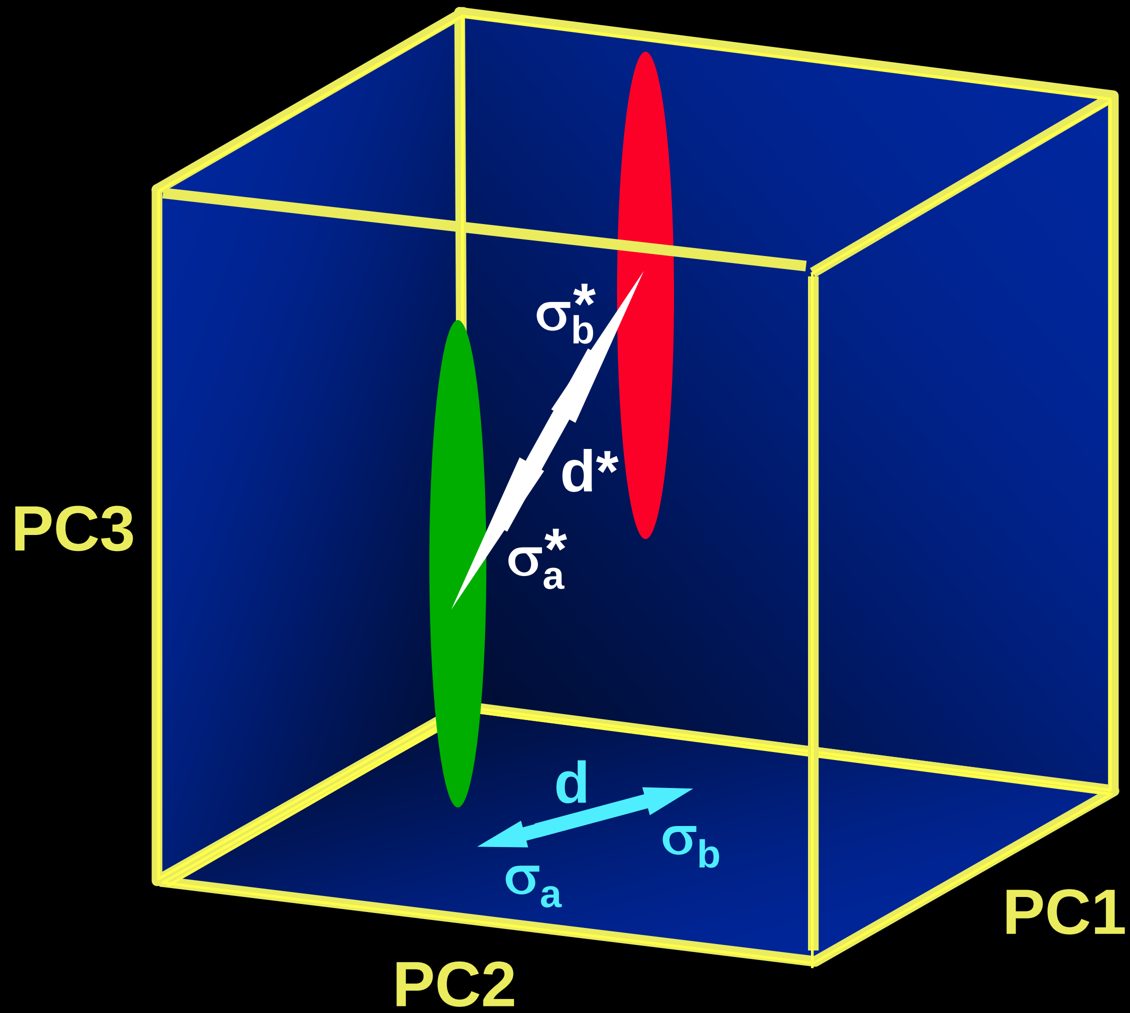
# DNT Detection




*0.2 ppb DNT in air, 20 C*

# Resolution Factors




$$rf = \frac{d}{\sqrt{\sigma_a^2 + \sigma_b^2}}$$

rf* = resolution factor along vector between cluster centroids

rf = maximized resolution factor along optimal vector (Fisher's methodology)

rf ≥ rf*

# Resolution Factors

*average rf = 145*

*14-detector carbon black-polymer array* *worst rf = 23*

| | acetone | acetonitrile | anisole | benzene | butylamine | chloroform | cyclohexane | dichloromethane | ethanol | ethyl acetate | isopropanol | methanol | n-heptane | n-pentane | tetrahydrofuran | toluene | triethylamine | trifluorotoluene |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1,2-dimethoxyethane | 121 | 194 | 71 | 49 | 58 | 95 | 287 | 130 | 135 | 164 | 184 | 230 | 156 | 354 | 130 | 179 | 73 | 119 |
| acetone | | 51 | 102 | 98 | 44 | 106 | 88 | 42 | 58 | 93 | 107 | 41 | 95 | 172 | 42 | 227 | 138 | 198 |
| acetonitrile | | | 154 | 173 | 54 | 153 | 152 | 73 | 58 | 171 | 207 | 75 | 119 | 135 | 88 | 317 | 174 | 200 |
| anisole | | | | 106 | 23 | 178 | 146 | 130 | 107 | 126 | 131 | 129 | 140 | 182 | 145 | 59 | 78 | 60 |
| benzene | | | | | 52 | 65 | 177 | 132 | 117 | 58 | 140 | 202 | 112 | 195 | 102 | 229 | 47 | 82 |
| butylamine | | | | | | 55 | 63 | 53 | 48 | 36 | 82 | 86 | 76 | 54 | 48 | 41 | 57 | 65 |
| chloroform | | | | | | | 123 | 102 | 122 | 133 | 126 | 204 | 92 | 231 | 159 | 303 | 146 | 180 |
| cyclohexane | | | | | | | | 109 | 103 | 180 | 108 | 151 | 202 | 152 | 153 | 528 | 132 | 312 |
| dichloromethane | | | | | | | | | 57 | 121 | 60 | 72 | 132 | 54 | 63 | 489 | 246 | 384 |
| ethanol | | | | | | | | | | 119 | 102 | 57 | 77 | 77 | 51 | 279 | 125 | 137 |
| ethyl acetate | | | | | | | | | | | 88 | 201 | 123 | 181 | 59 | 253 | 122 | 151 |
| isopropanol | | | | | | | | | | | | 135 | 161 | 119 | 73 | 313 | 218 | 206 |
| methanol | | | | | | | | | | | | | 107 | 58 | 87 | 401 | 308 | 260 |
| n-heptane | | | | | | | | | | | | | | 177 | 161 | 380 | 156 | 90 |
| n-pentane | | | | | | | | | | | | | | | 217 | 556 | 171 | 343 |
| tetrahydrofuran | | | | | | | | | | | | | | | | 359 | 93 | 178 |
| toluene | | | | | | | | | | | | | | | | | 246 | 180 |
| triethylamine | | | | | | | | | | | | | | | | | | 168 |

# Discrimination of $H_2O$ and $D_2O$

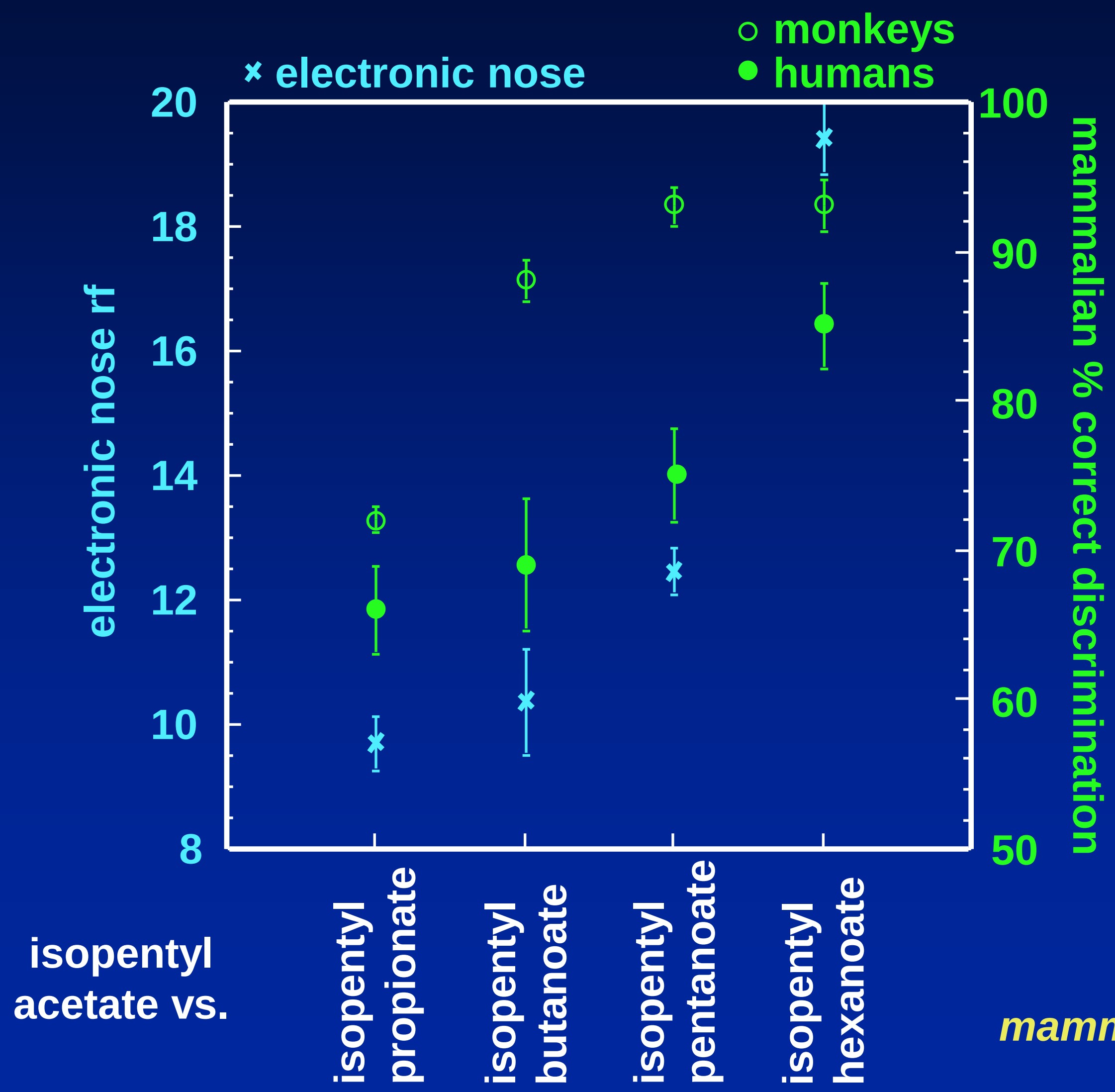
- **Four bubblers, 2 each of $H_2O$ and $D_2O$**
- **50 exposures from each bubbler**

**resolution factors:**

| | $H_2O$ | $D_2O$ | $H_2O$ | $D_2O$ |
|---|---|---|---|---|
| $H_2O$ | 0.0 | | | |
| $D_2O$ | 8.2 | 0.0 | | |
| $H_2O$ | 2.1 | 8.1 | 0.0 | |
| $D_2O$ | 9.3 | 1.8 | 10.1 | 0.0 |

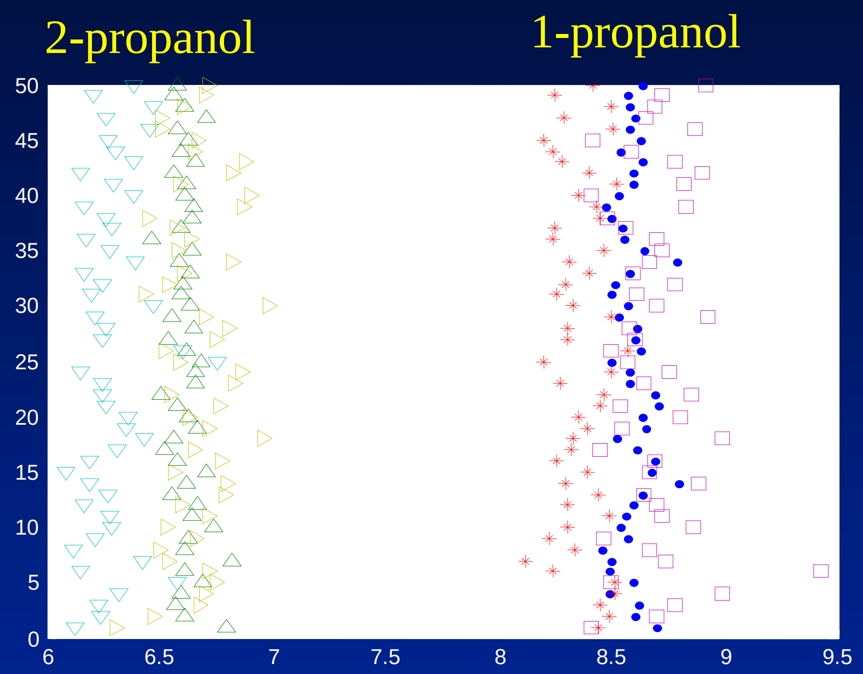
- **Trained on one set, tested on the other**
- **All 200 correctly classified**

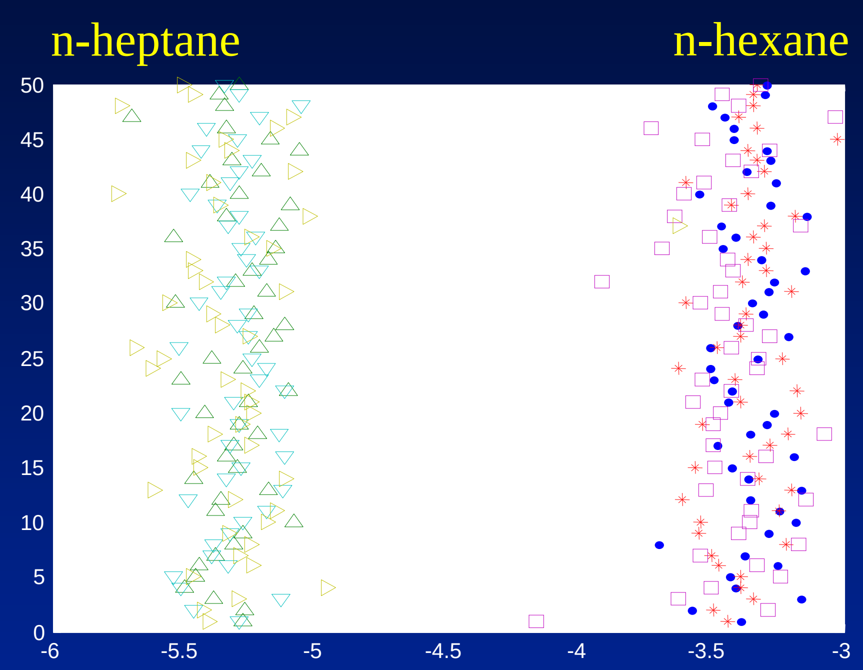
# Odorant Discrimination Trends for Mammals and the Electronic Nose (Esters)




*mammalian data courtesy of Laska et al, 1997*

# Effects of Detector Drift




Weights Based on First Day

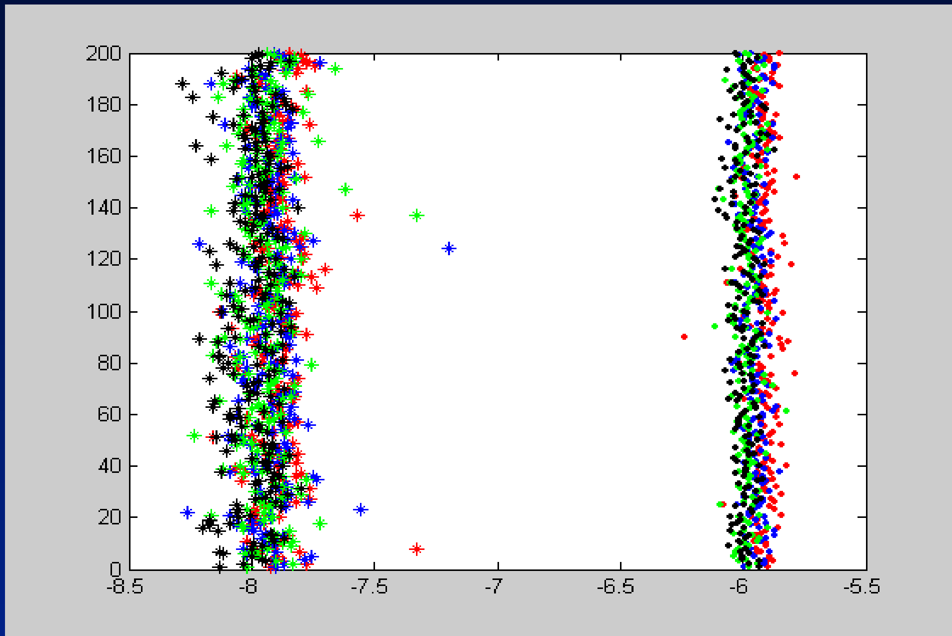
| Day | Resolution |
|---|---|
| 1 | 20.01 |
| 2 | 12.16 |
| 3 | 8.67 |

Weights Based on First Day

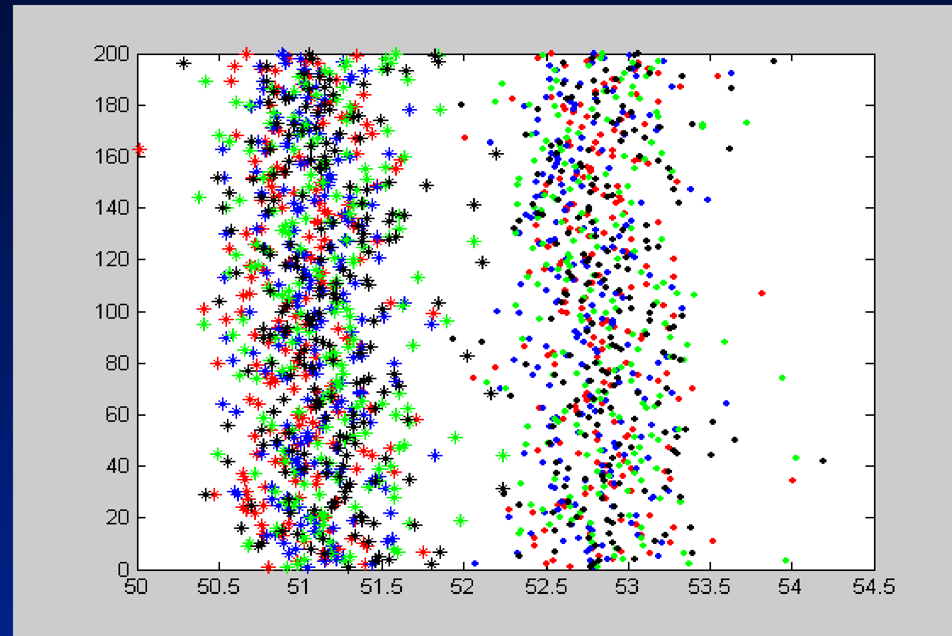
| Day | Resolution |
|---|---|
| 1 | 10.85 |
| 2 | 11.13 |
| 3 | 5.24 |

# Effects of Detector Drift

2-propanol toluene



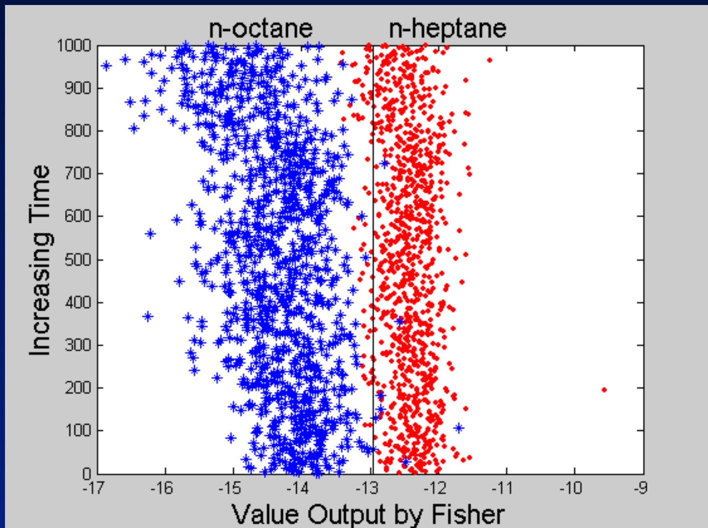

ethanol methanol




| Date | Correct/400 | Fisher RF |
|---|---|---|
| 12/16 | 400 | 19.1 |
| 12/30 | 400 | 7.4 |
| 1/4 | 400 | 17.7 |
| 1/11 | 400 | 19.5 |

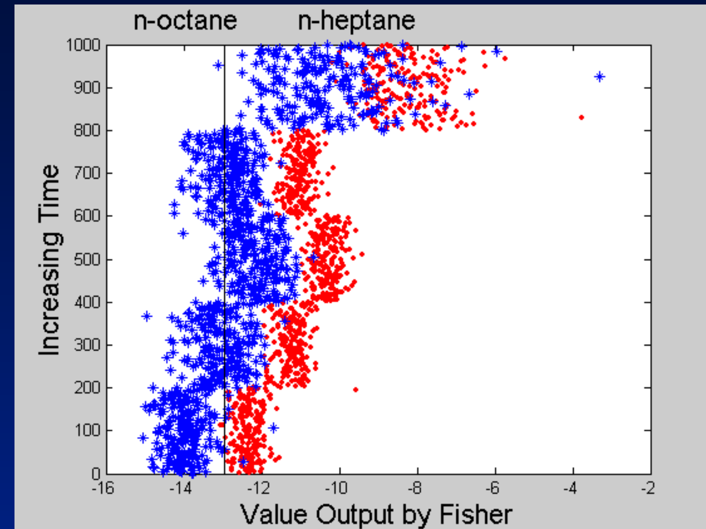
| Date | Correct/400 | Fisher RF |
|---|---|---|
| 12/16 | 400 | 4.63 |
| 12/30 | 400 | 4.52 |
| 1/4 | 395 | 2.89 |
| 1/11 | 394 | 3.66 |

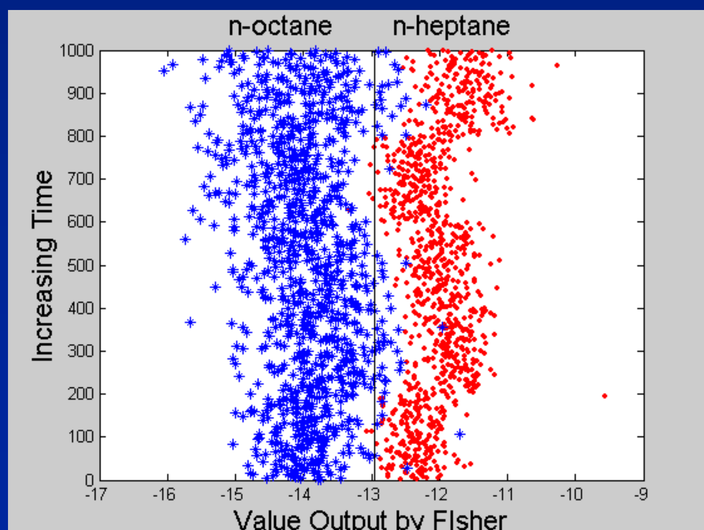
# Drift Calibration with Various "Standards"




Calibration with n-hexane

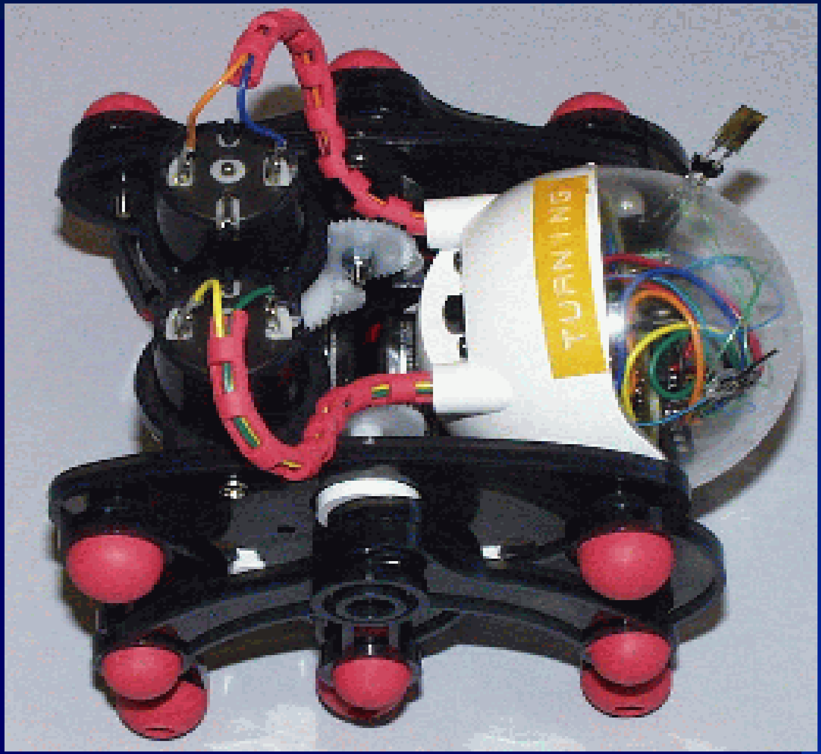
Calibration with i-octane

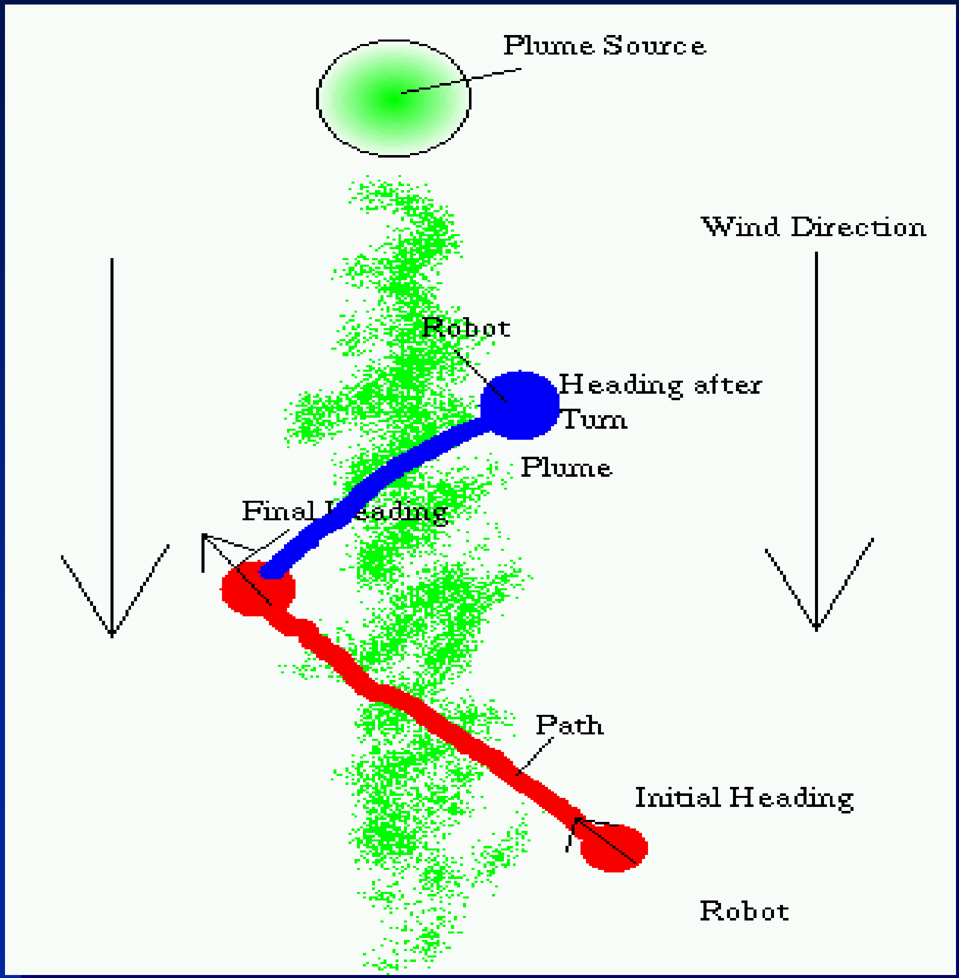



Calibration with THF, EtOH, and EtOAc

# Technology Migration
# DARPA Plume Tracing Program



# Plume Tracing

QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

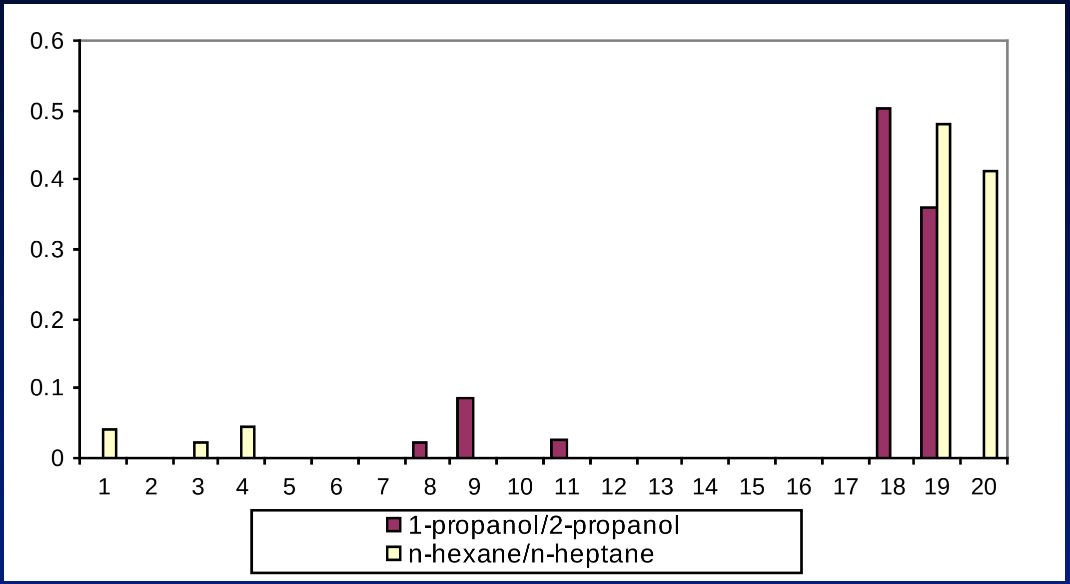
# Plume Tracing

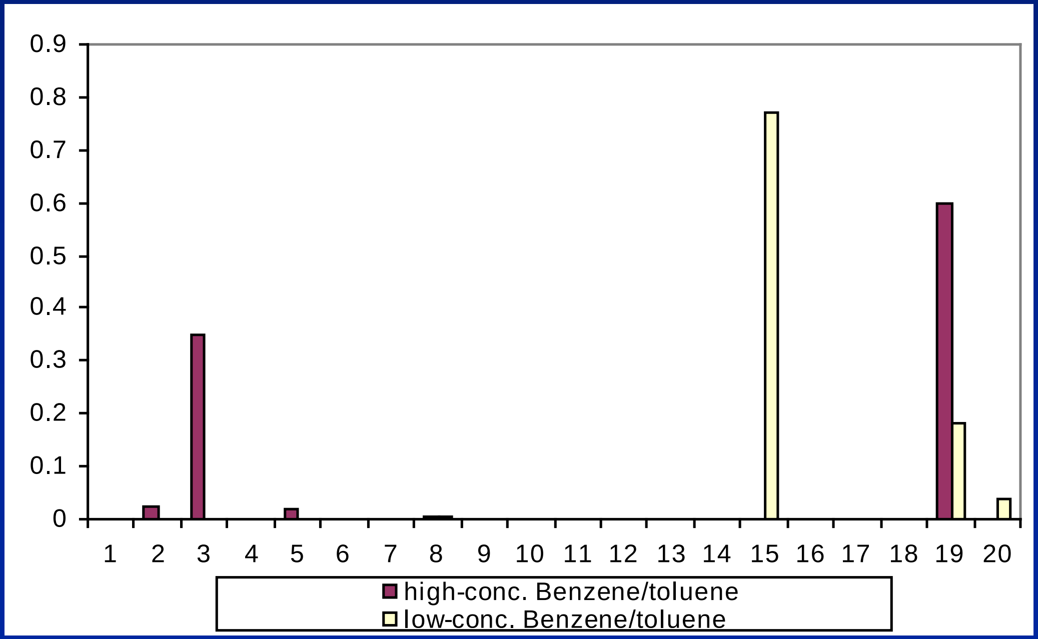
QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

# Outline

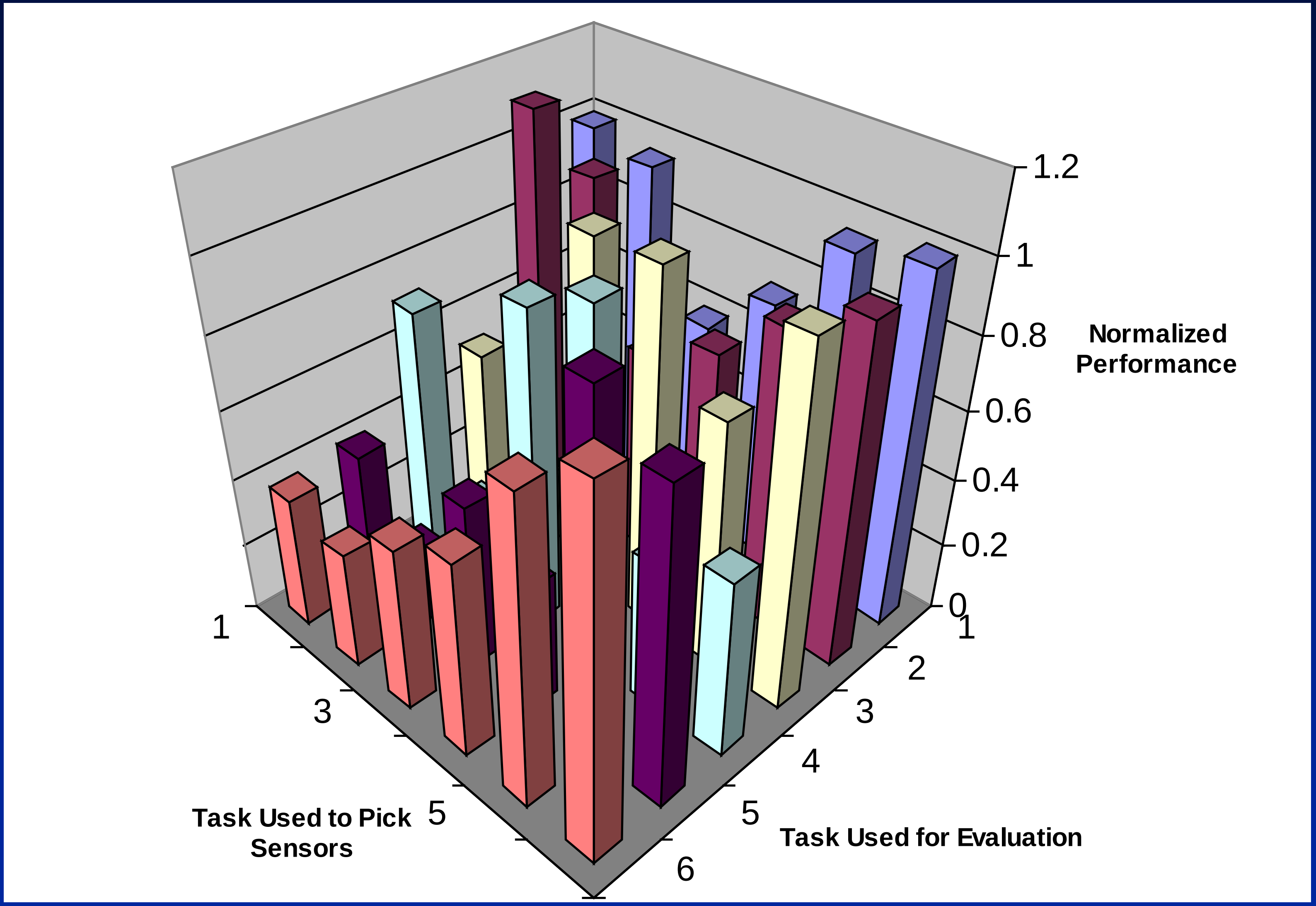
- Principles of Array Formation
- Approach
  - Basic Detector Characteristics
  - Classification Performance
  - Sensitivity
- **High-Pixel Density Chips**
  - Combinatorial Arrays
  - Vapor Map Signatures
  - Correlation Between Pixels
- Spatiotemporal Signals
- Semi-customizable Arrays

# Different Detector Sets for Different Tasks



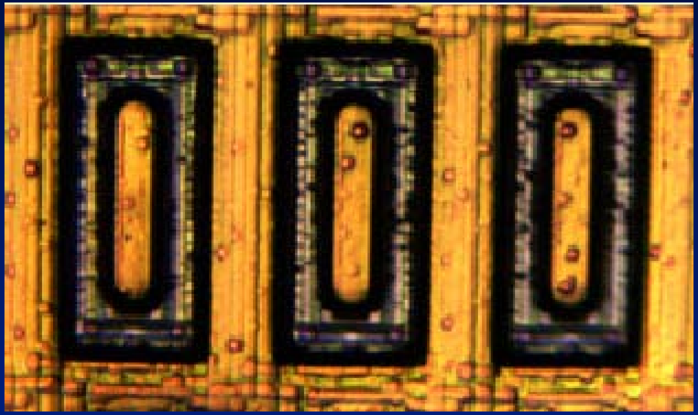



# Detector Set Performance for Different Tasks

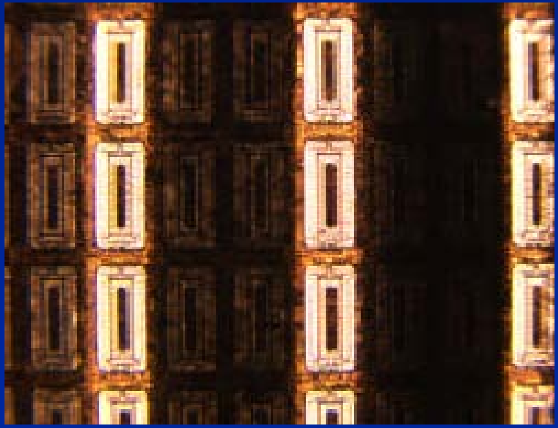


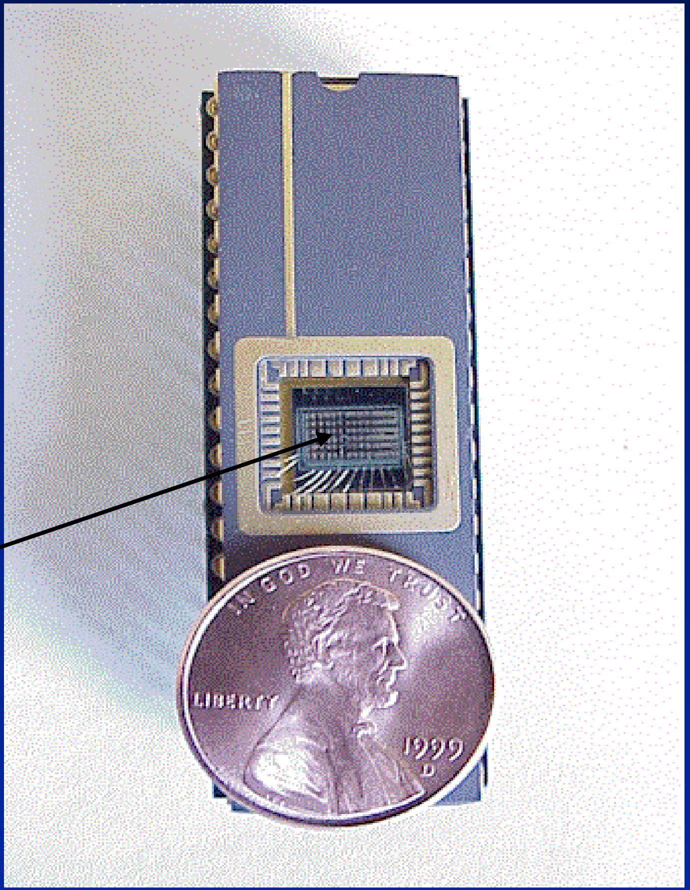
# Nose Chip Pixels

Guard Ring Pixels



Spray Pixels with Sensor Film





# Combinatorial Pixel Array

**A** poly(ethylene oxide)

**B** PEVA 25

**C** poly(5-Butadiene)

**D** poly(vinyl-carbazole)

**E** poly(vinyl acetate)

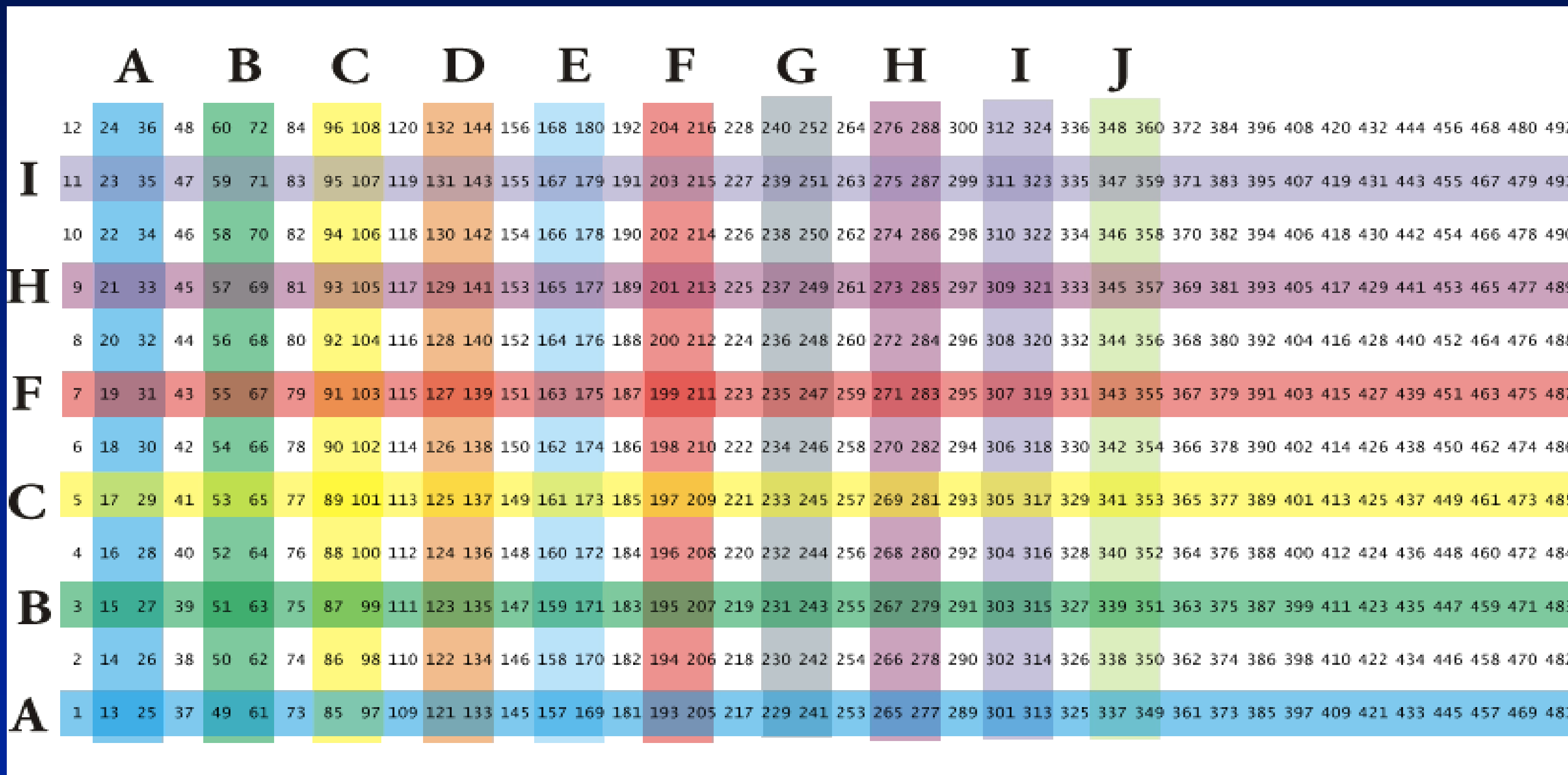
**F** poly(capralactone)

**G** poly(sulfone)

**H** poly(vinyl pyyrolidone)

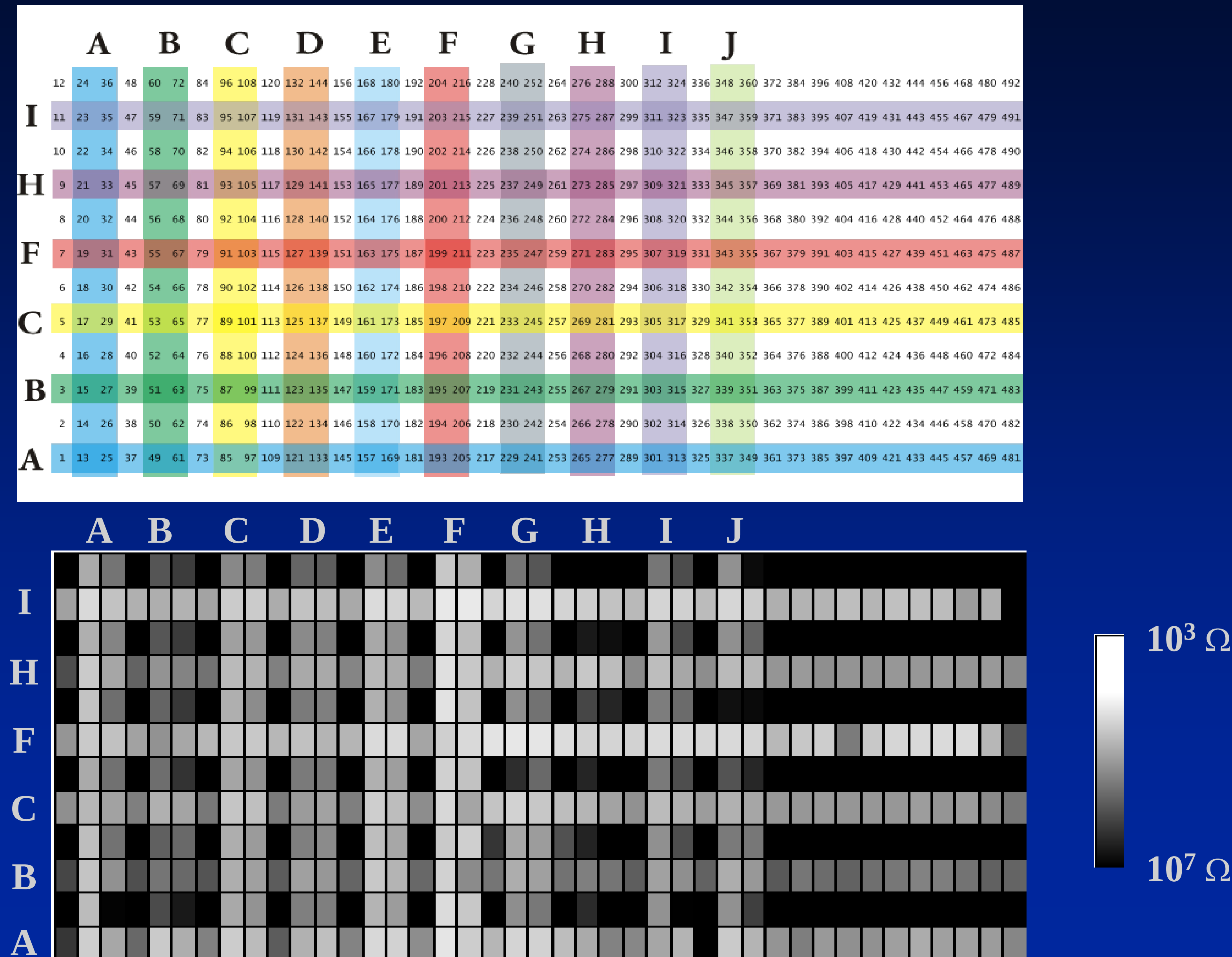
**I** poly(4-vinyl phenol)

**J** poly(methyloctadecyl-
siloxane)

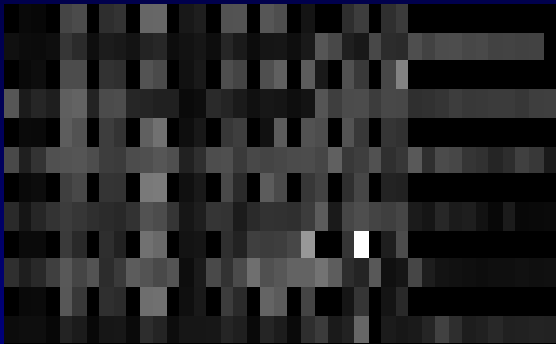



*Columns sprayed first, so sensor 23 is* ***surface/A/I/vapor***

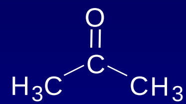
# Resistance Map

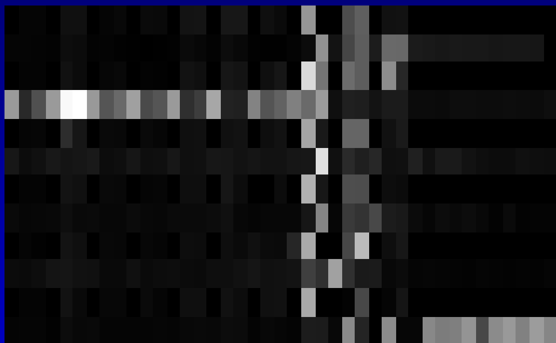


# ΔR/R Responses Mapped onto Chip



1 Acetone

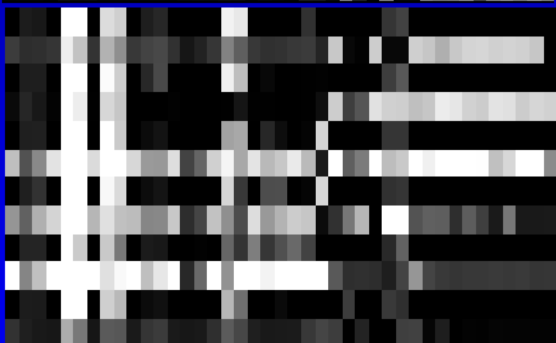


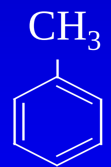
2 Methanol

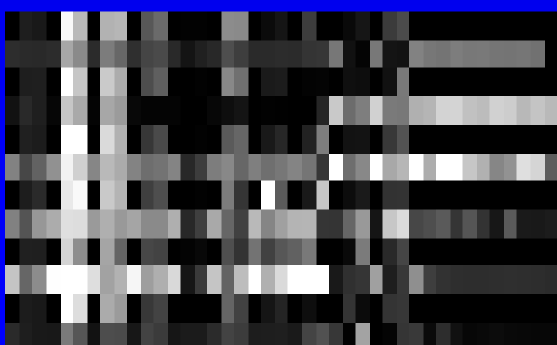
$CH_3OH$

QuickTime™ and a
Microsoft Video 1 decompressor
are needed to see this picture.

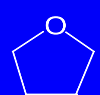


3 Toluene



4 Tetrahydrofuran



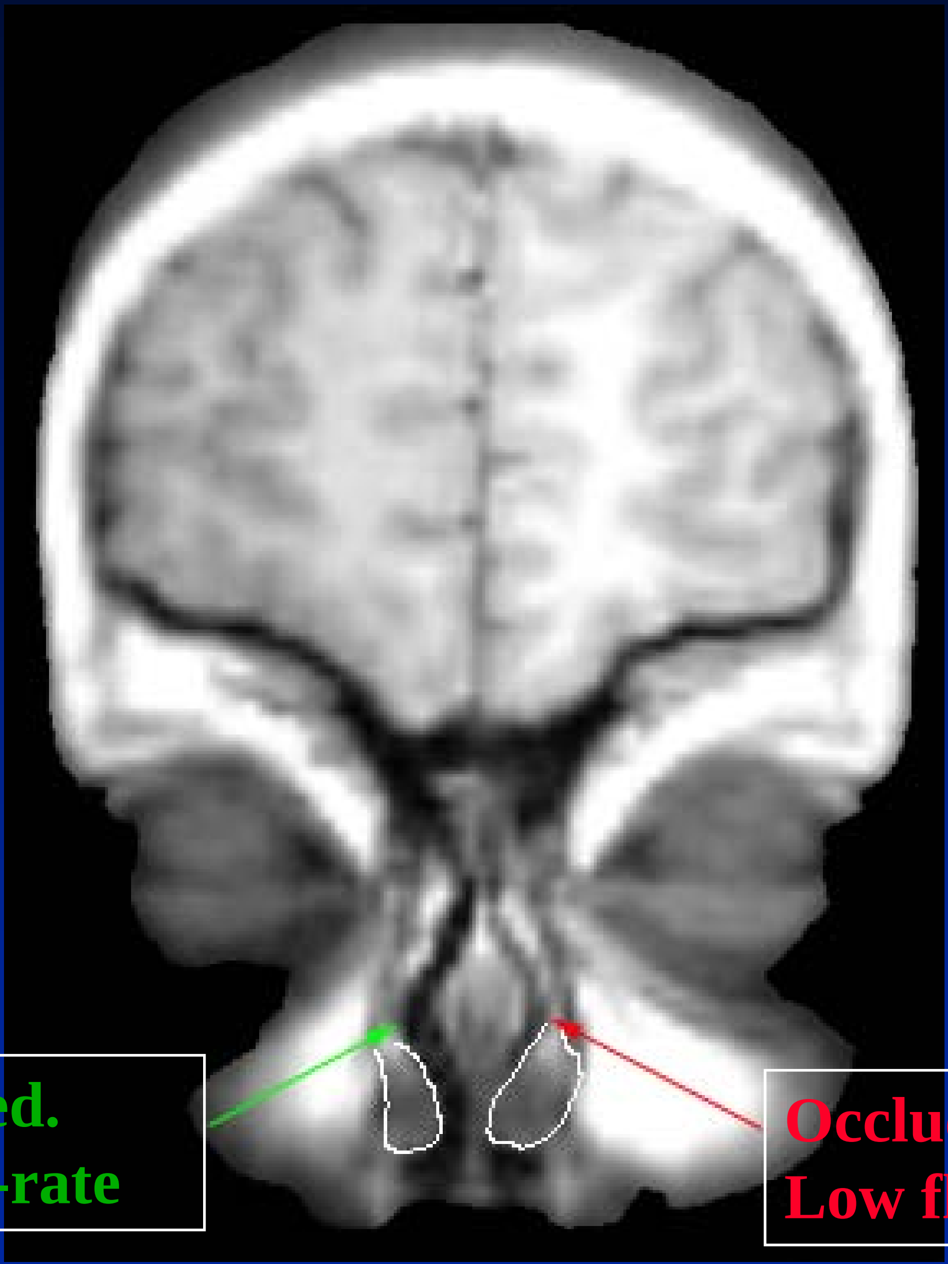
# Outline

- Principles of Array Formation
- Approach
    - Basic Detector Characteristics
    - Classification Performance
    - Sensitivity
- High-Pixel Density Chips
    - Combinatorial Arrays
    - Vapor Map Signatures
    - Correlation Between Pixels
- **Spatiotemporal Signals**
- Semi-customizable Arrays

# T1 MR Image of Nasal Passage

HFR Nostril

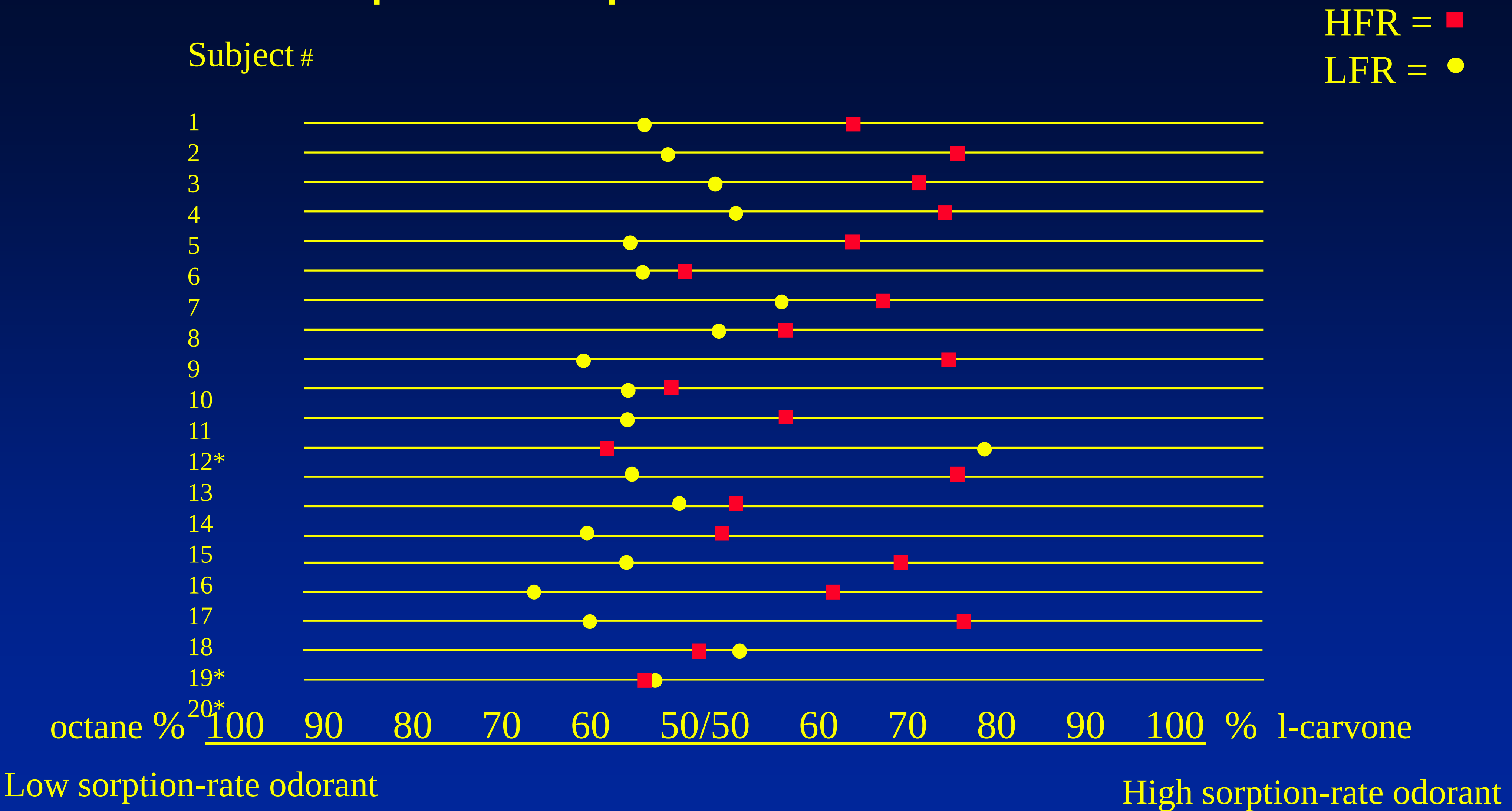
LFR Nostril



**Unoccluded.**
**High flow-rate**

**Occluded.**
**Low flow-rate**

# Perceptual Dependence on Air Flow




HFR judgment = 55% l-carvone and 45% octane

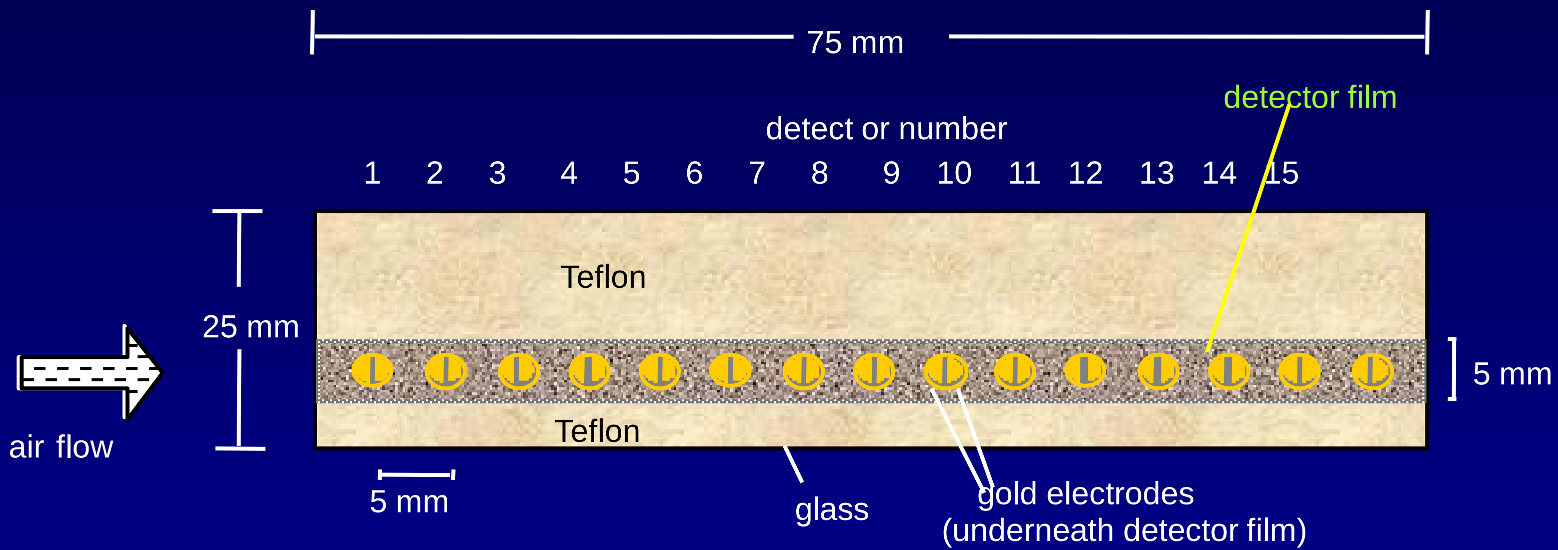
LFR judgment = 61% octane and 39% l-carvone

$t(19) = 3.74$, $p = .001$

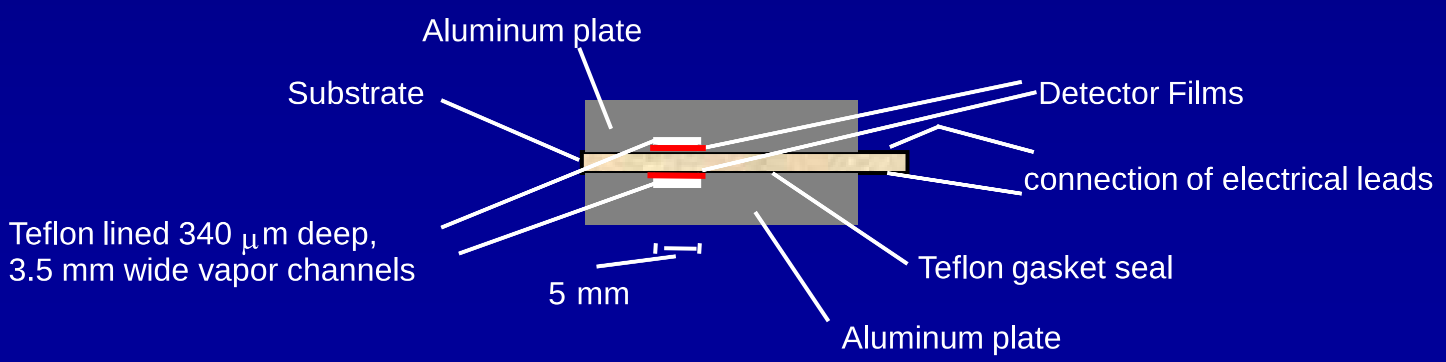
*Nature,11/ 1999*

# Linear Detector Array

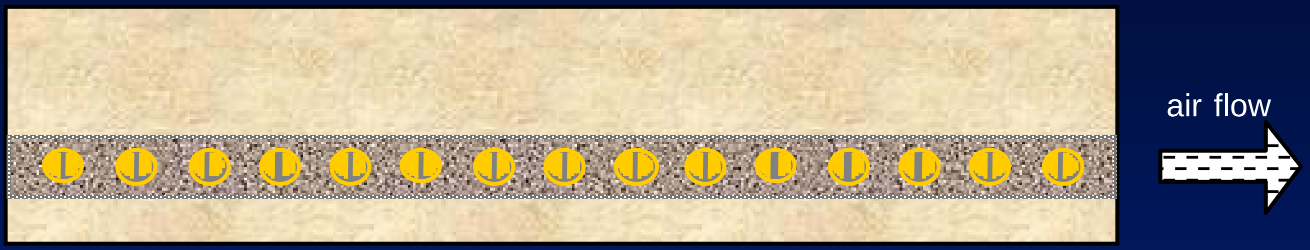
## Top-view of substrate




## End view cross section of substrate and sample chamber

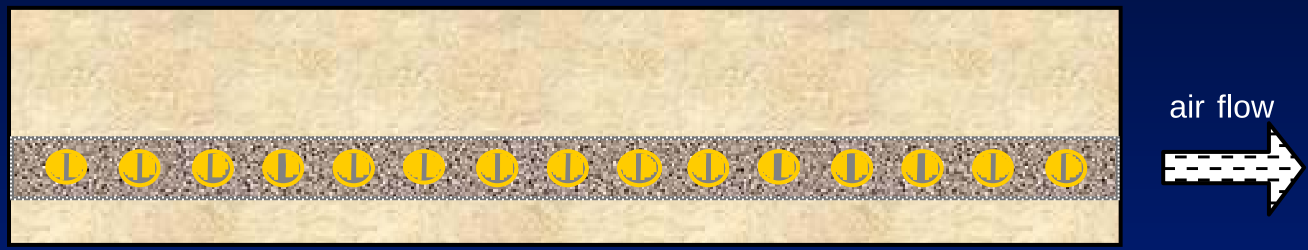


# Spatiotemporal Response on Linear Detector Array



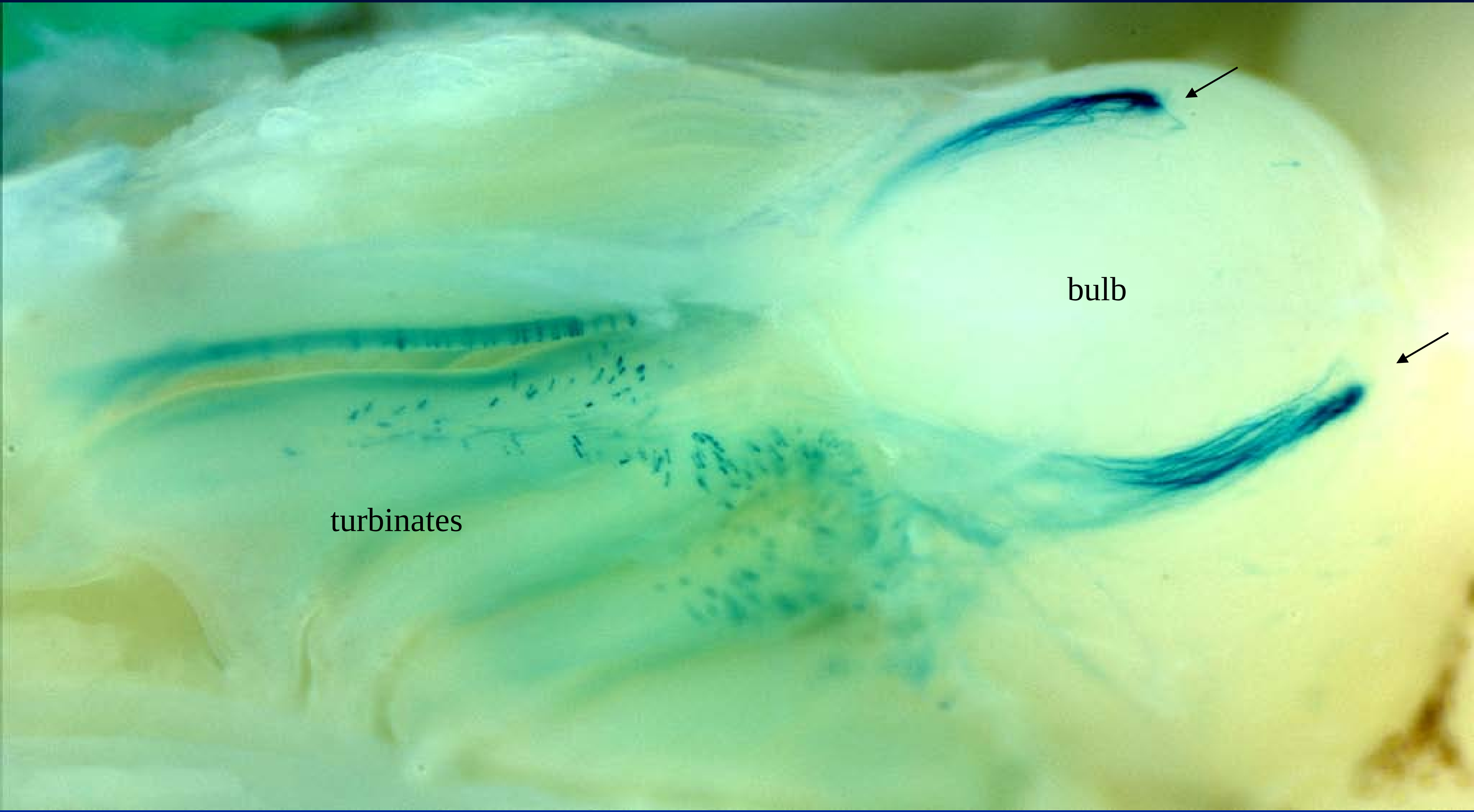

QuickTime™ and a
Microsoft Video 1 decompressor
are needed to see this picture.

# Spatiotemporal Response on Linear Detector Array

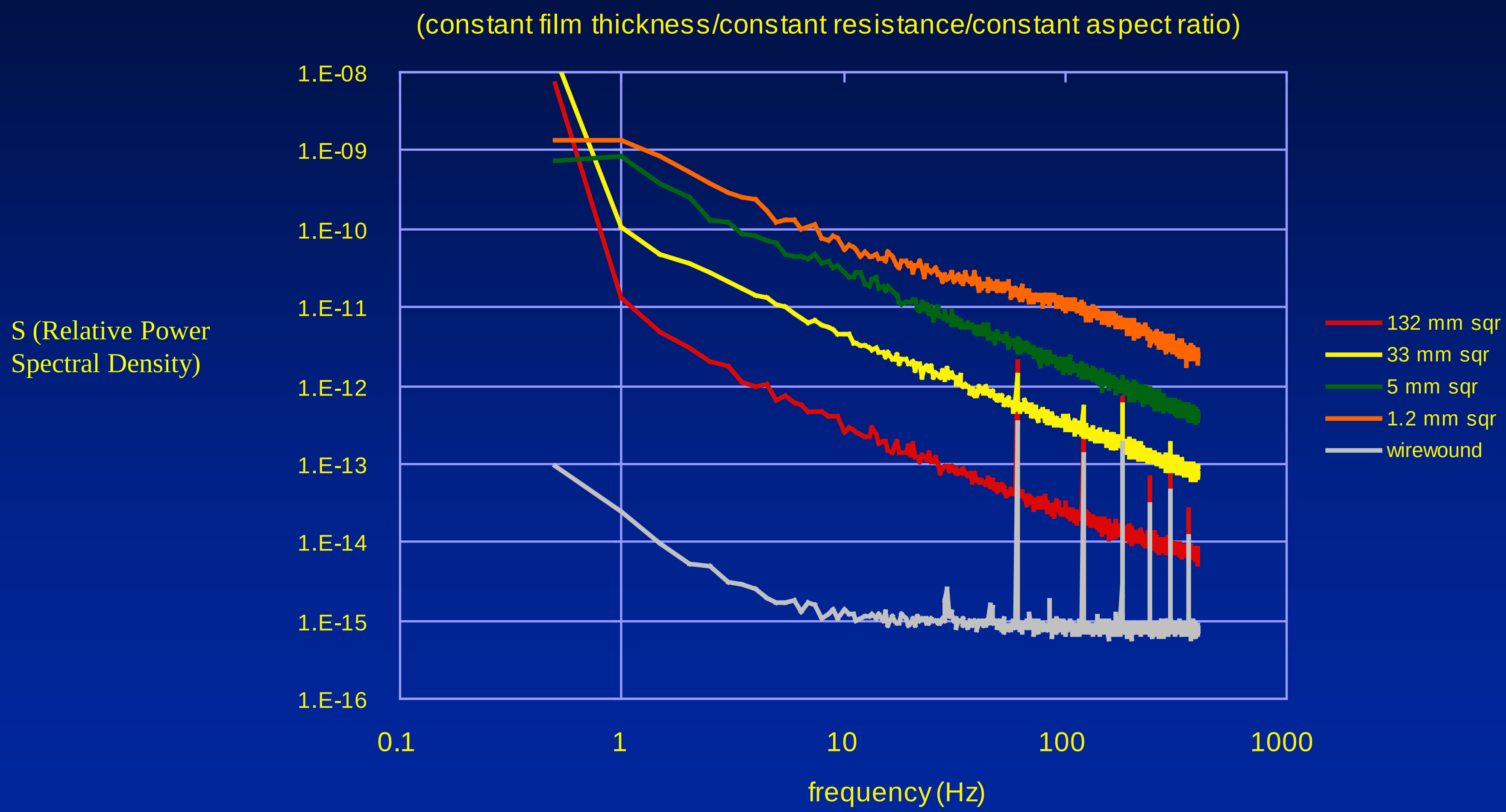



QuickTime™ and a
Microsoft Video 1 decompressor
are needed to see this picture.

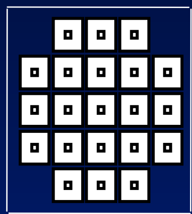
# A distinct neuron population projects onto two glomeruli

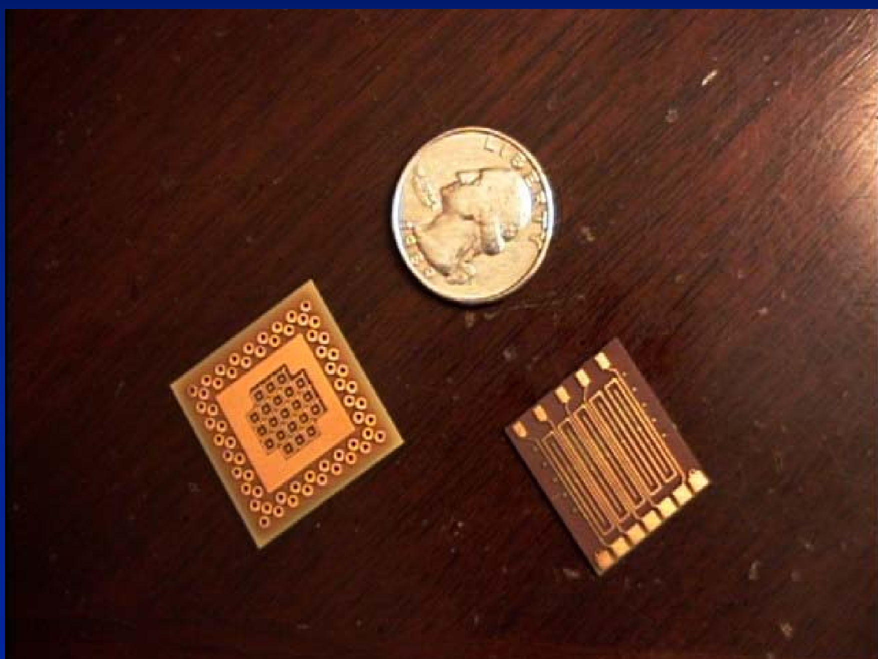


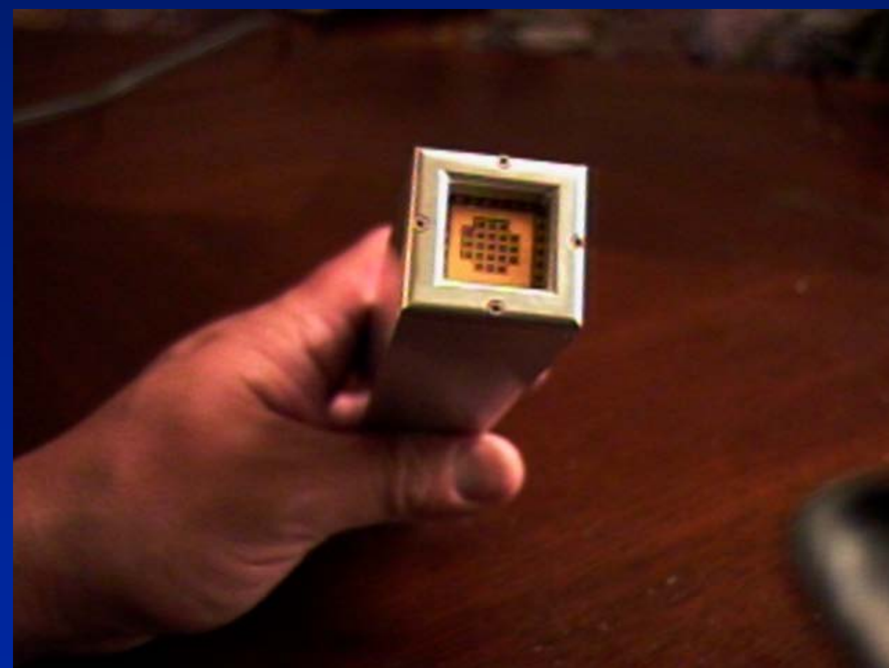
# Sensor Noise Changes with Area



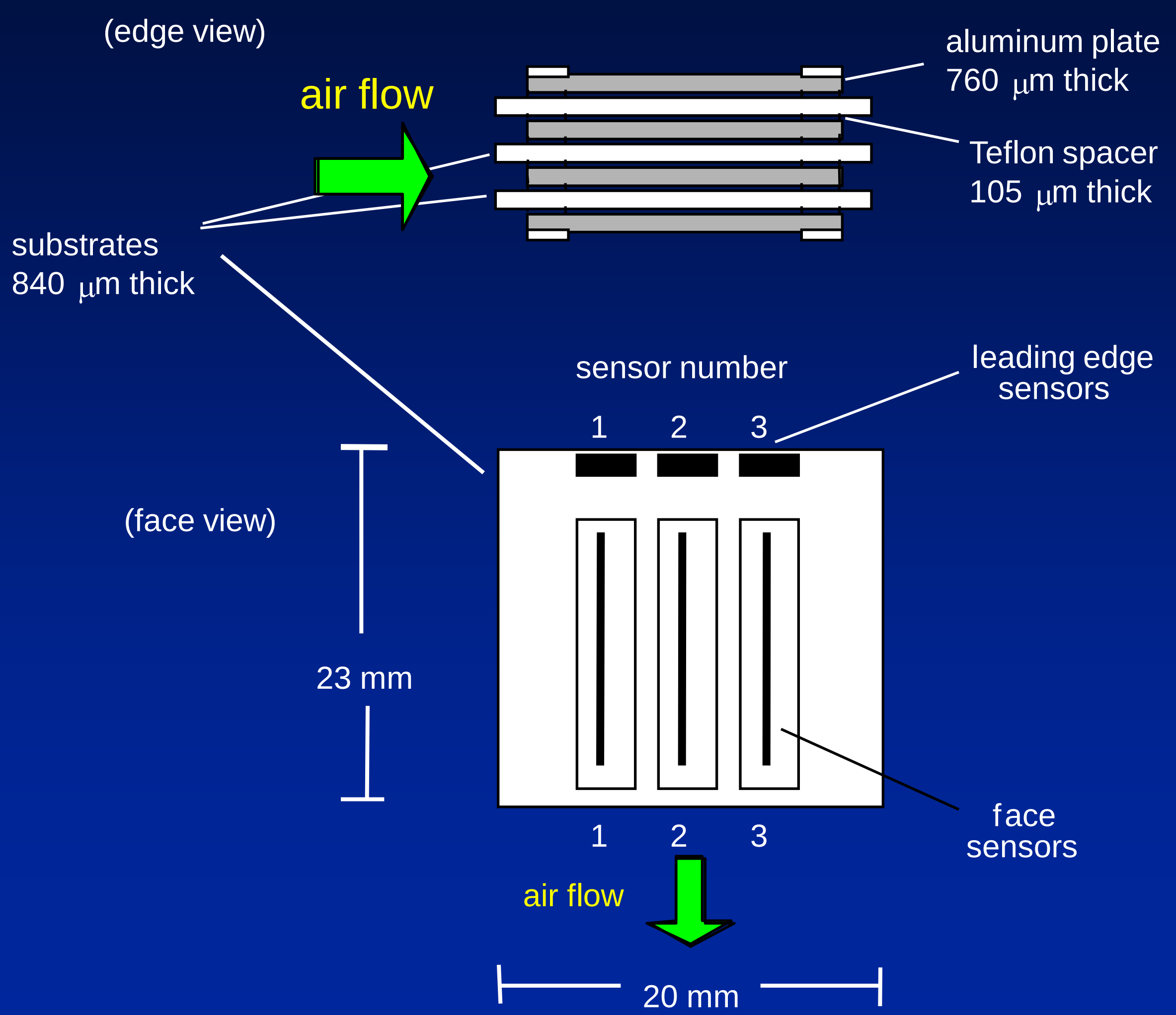
# DNT Sensor Heads







# Edge/Face Detector Array



# Response vs Time for Low and High Vapor Pressure Odorants

QuickTime™ and a
Microsoft Video 1 decompressor
are needed to see this picture.

# Response vs Time for Low and High Vapor Pressure Odorants

QuickTime™ and a
Microsoft Video 1 decompressor
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# S/N for Chemiresistors vs SAW Devices

Table 2: Limits of Detection for Carbon Black-Polymer Composite Vapor Detectors and for Polymer Film-Coated SAW Detectors

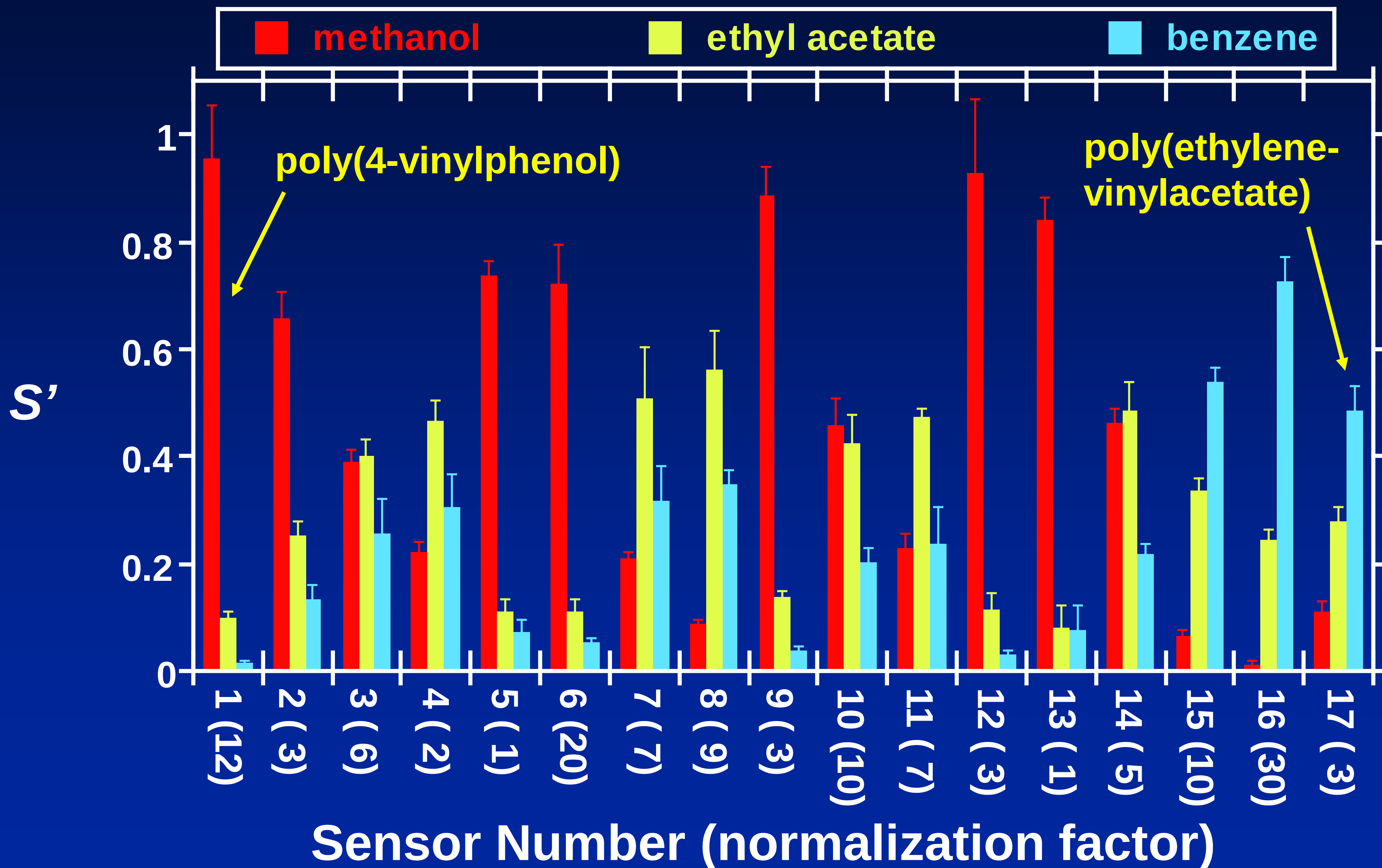
| | | LOD (μg/L) | | | |
|---|---|---|---|---|---|
| | polymer | benzene | cyclohexanone | hexane | nonane |
| Carbon Black Composite[a] | PEVA | 18 | 1.5 | 40 | 1.3 |
| | PCL | 525 | 45 | 1300 | 48 |
| SAW[b] | poly[bis(cyanoallyl)siloxane] | 401 | 15 | 5300 | 569 |
| | poly(methylphenylsiloxane) | 302 | 14 | 1520 | 111 |
| | poly(phenyl ether) | 216 | 13 | 991 | 79 |
| | poly(isobutylene) | 259 | 32 | 346 | 19 |

# Geometric Optimization of S/N Ratio

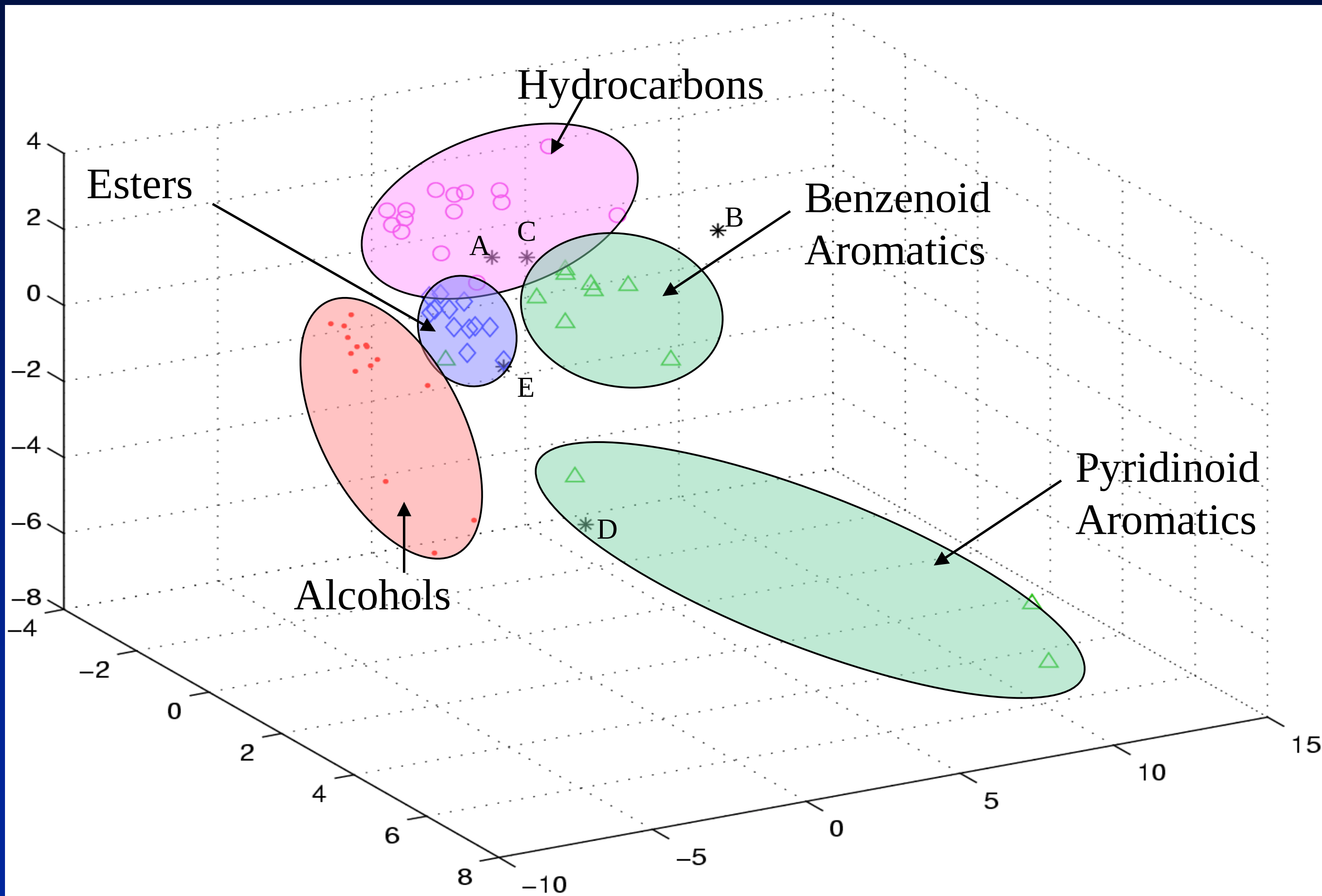
Table 1: Responses and S/N for two Types of Polymer-Carbon Black Composite Detectors in the Configuration of Scheme II.

| Analyte | Vapor Pressure of Pure Analyte | | $\Delta R/R_b$ x 100 | | | | S/N | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | PCL | | PEVA | | PCL | | PEVA | |
| | $P^o$ (Torr) | PPM [a] | le [b] | face | le | face | le | face | le | face |
| hexane | $1.28*10^{2}$ | $1.71*10^{5}$ | 1.5 | 1.2 | 5.7 | 4.2 | 17 | 28 | 150 | 400 |
| methanol | $1.02*10^{2}$ | $1.36*10^{5}$ | 1.7 | 2.1 | 1.2 | 0.8 | 18 | 60 | 55 | 64 |
| dodecane | $9.71*10^{-2}$ | $1.29*10^{2}$ | 1.1 | 0.0 | 2.9 | 0.0 | 11 | 1 | 130 | 0 |
| hexadecane | $9.11*10^{-4}$ | 1.21 | 0.3 | 0.0 | 0.5 | 0.0 | 3 | 1 | 22 | 0 |

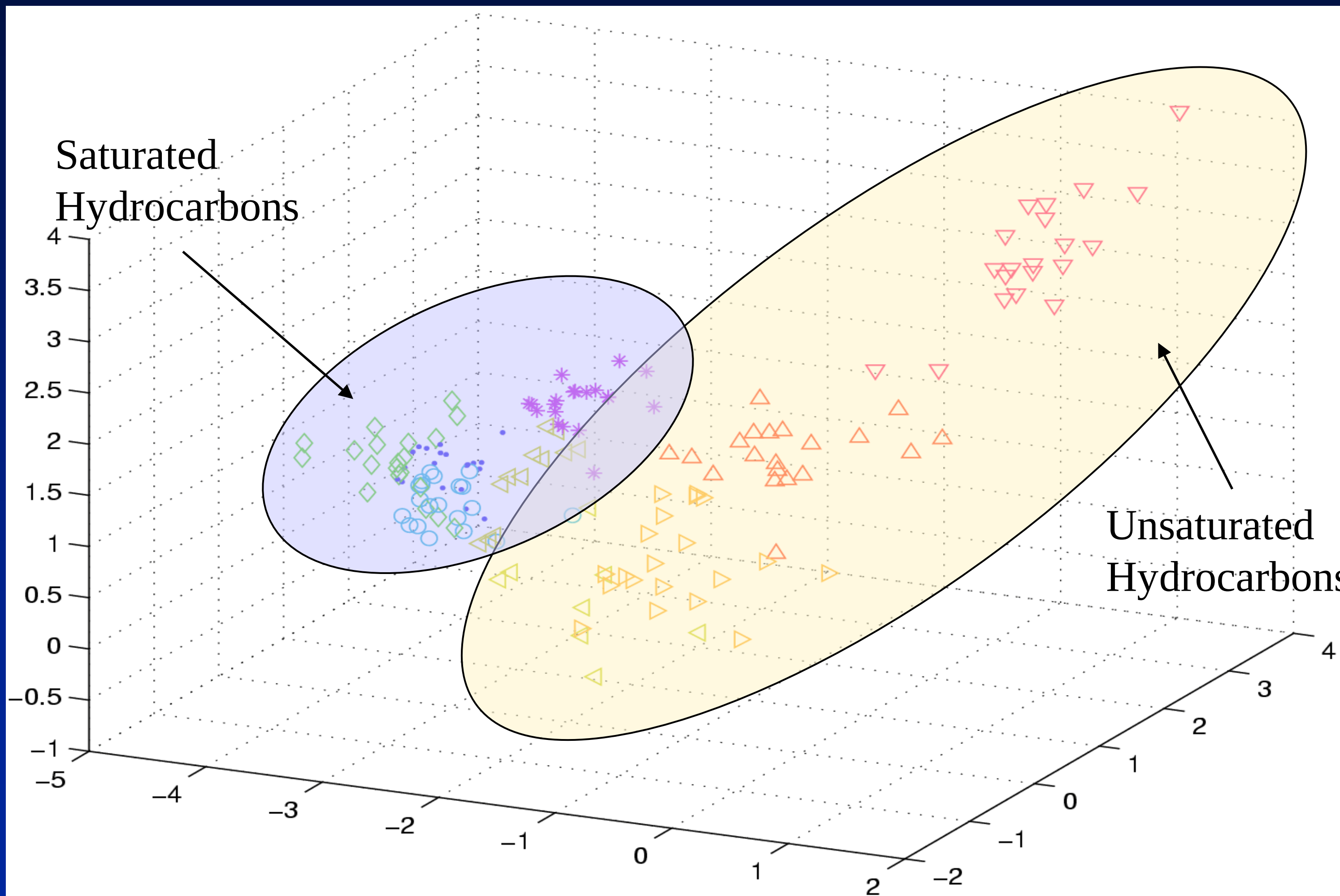
# Different Patterns for Different Vapors



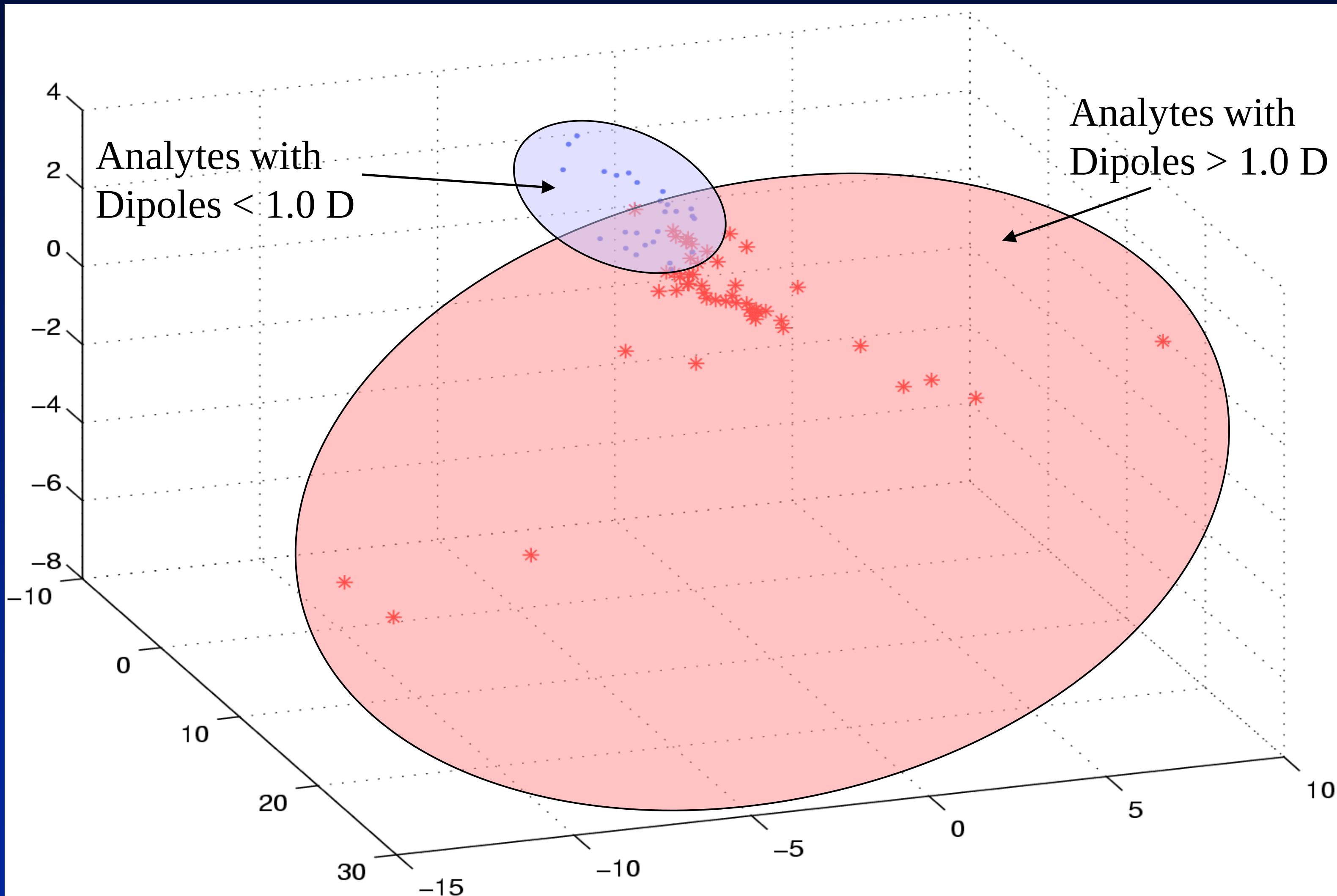
# Distribution of Analyte Classes in PCA Space



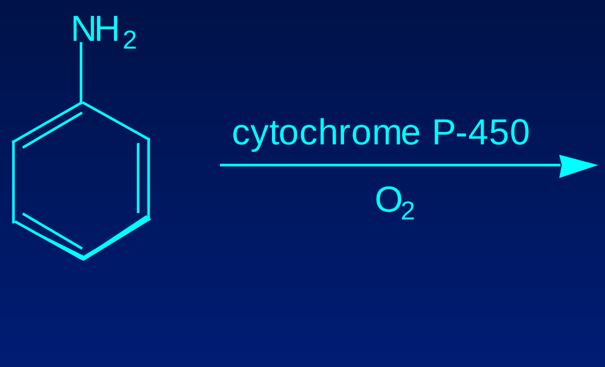
# Distribution of Analyte Classes in PCA Space



# Spatial Distribution as a Function of Dipole



# Biological Data



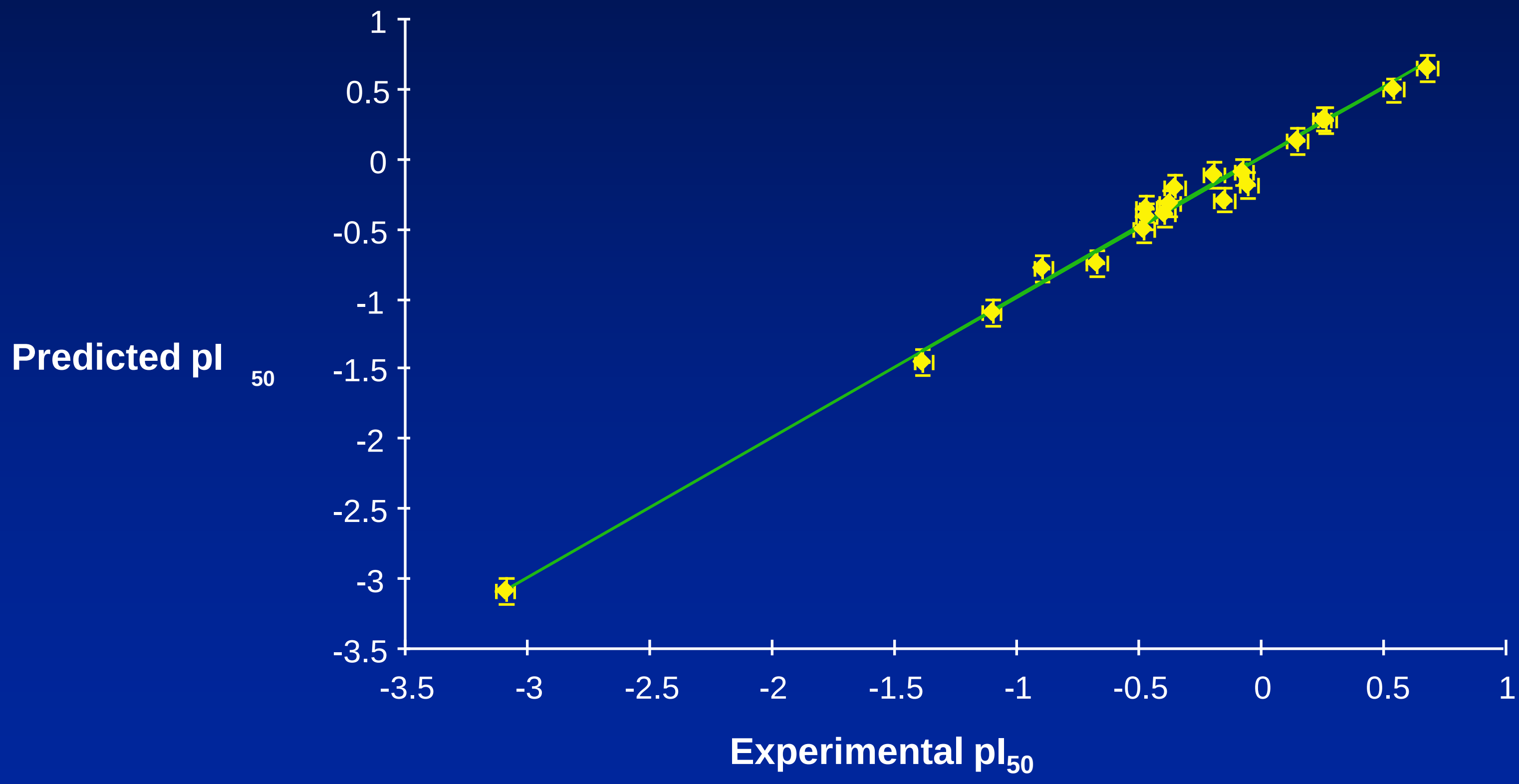

**$I_{50}$ = concentration (mM) of alcohol at which enzyme's activity is reduced by half**

**p $I_{50}$ = -log ($I_{50}$)**

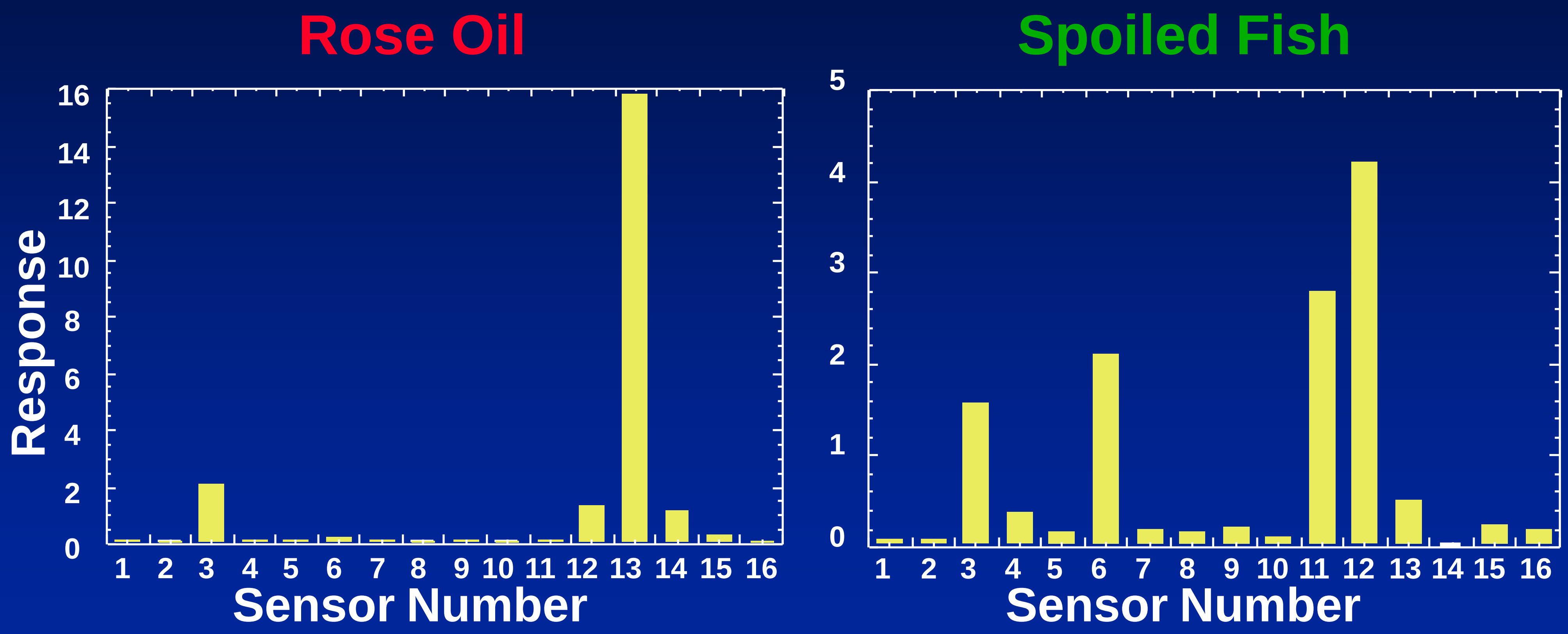
**higher p $I_{50}$ => stronger inhibitor**

| alcohol | experimental p$I_{50}$ |
|---|---|
| 1-butanol | -0.05 |
| 1-heptanol | 0.68 |
| 1-hexanol | 0.54 |
| 1-pentanol | 0.27 |
| 1-propanol | -0.48 |
| 2,4-dimethyl-3-pentanol | -1.38 |
| 2-butanol | -0.35 |
| 2-heptanol | 0.25 |
| 2-hexanol | 0.15 |
| 2-methyl-1-butanol | -0.15 |
| 2-methyl-1-propanol | -0.39 |
| 2-methyl-3-pentanol | -0.89 |
| 2-pentanol | -0.07 |
| 2-propanol | -0.47 |
| 3-hexanol | -0.47 |
| 3-methyl-1-butanol | -0.19 |
| 3-pentanol | -0.37 |
| ethanol | -1.1 |
| methanol | -3.09 |
| neopentanol (solid) | -0.67 |

# Predicted vs. Experimental $pI_{50}$



# Sensor Response



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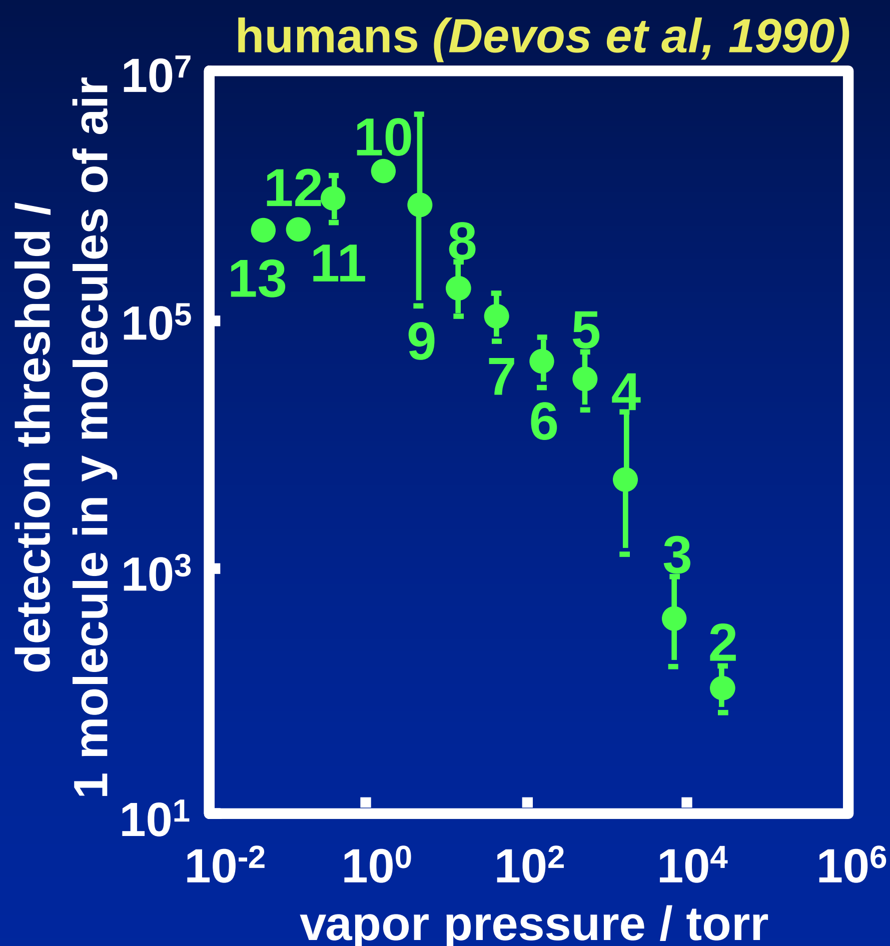
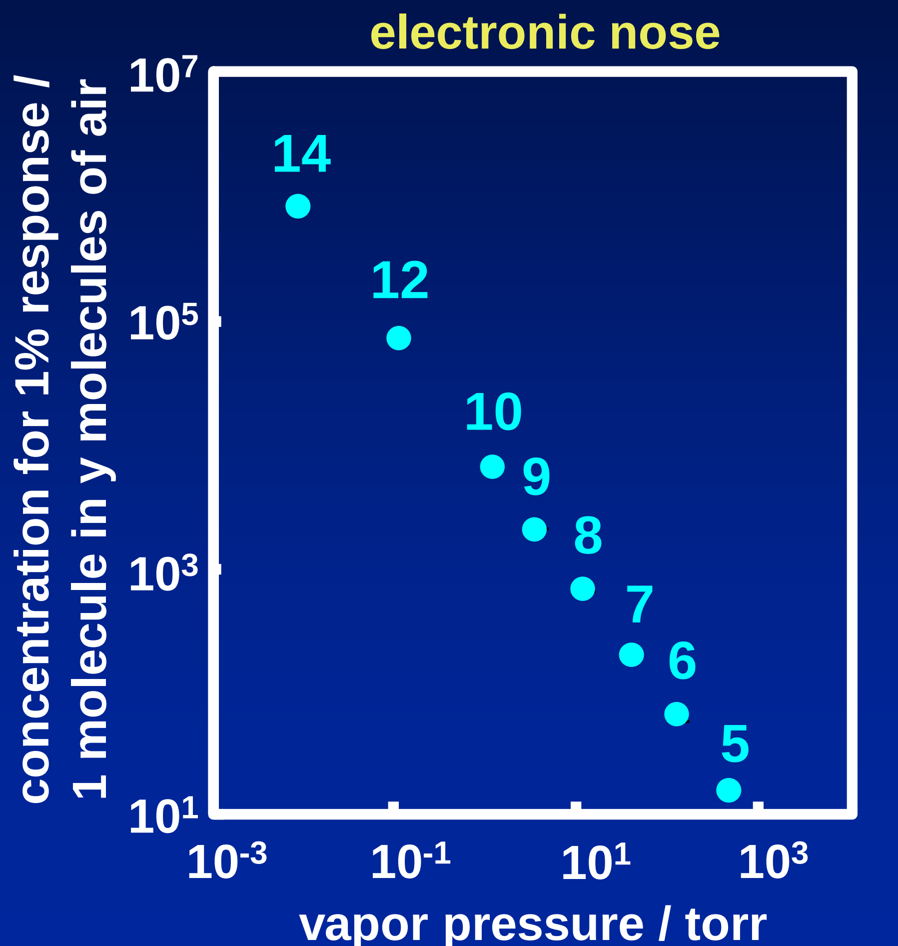
- **Semi-customizable Arrays**

# Disease Diagnosis

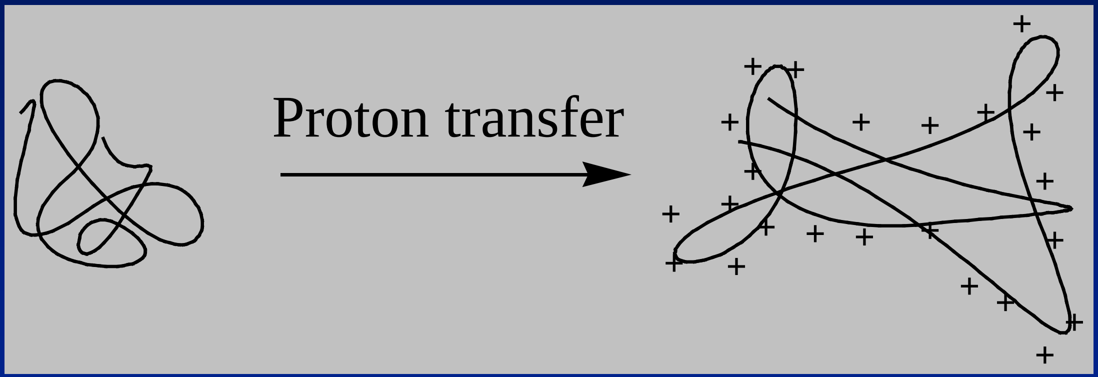
| Disease | Targets |
| --- | --- |
| **Uremia** | dimethyl amine, trimethylamine |
| **Trimethylaminuria** | trimethylamine |
| **Lung Cancer** | aniline, o-toliduine |
| **Cystinuria** | cadaverine, putrescine, piperidine |
| **Halitosis** | cadaverine, putrescine |
| **Bacterial Vaginosis** | various amines |

# Sensitivity Trends for Humans vs. the Electronic Nose (n-Alkanes)



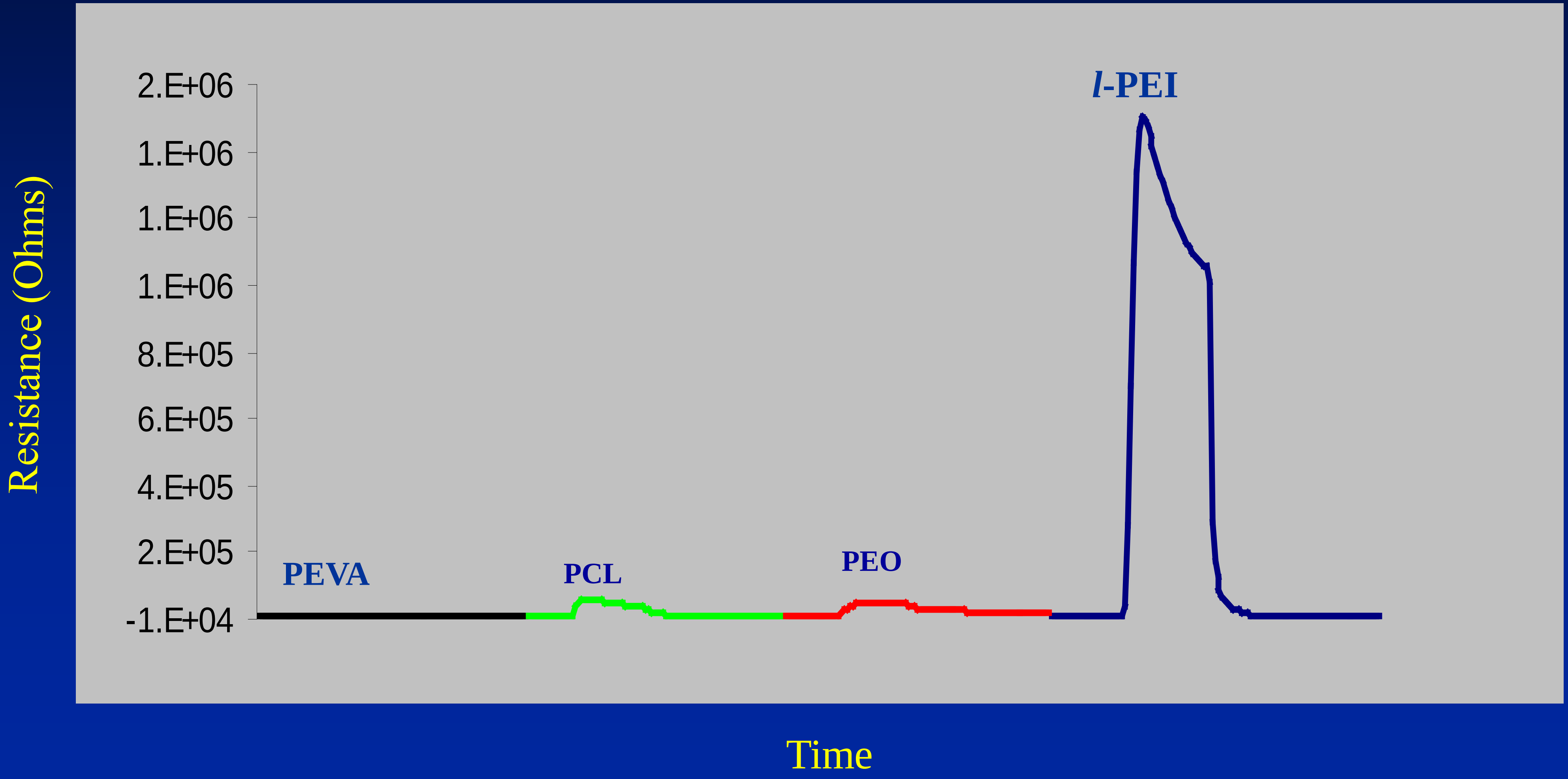
# Exploiting Chemical Interactions to Enhance Sensitivity




**Uncharged polymer** **Charged polymer**

Charge-induced swelling will result in larger volume expansion than mass-induced swelling alone.

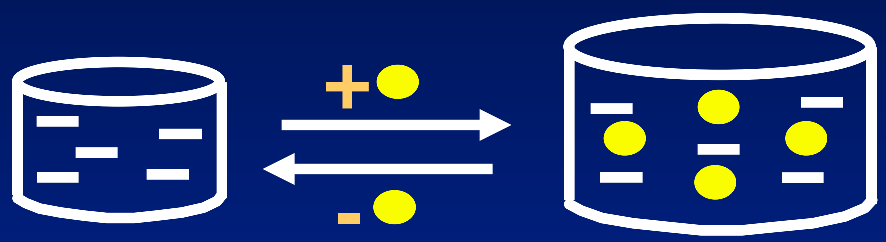
# 160 ppm Acetic Acid (P/P$^0$=0.010)

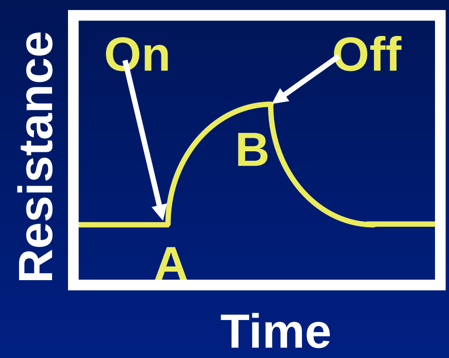


# Resistance Changes in Conducting Polymers

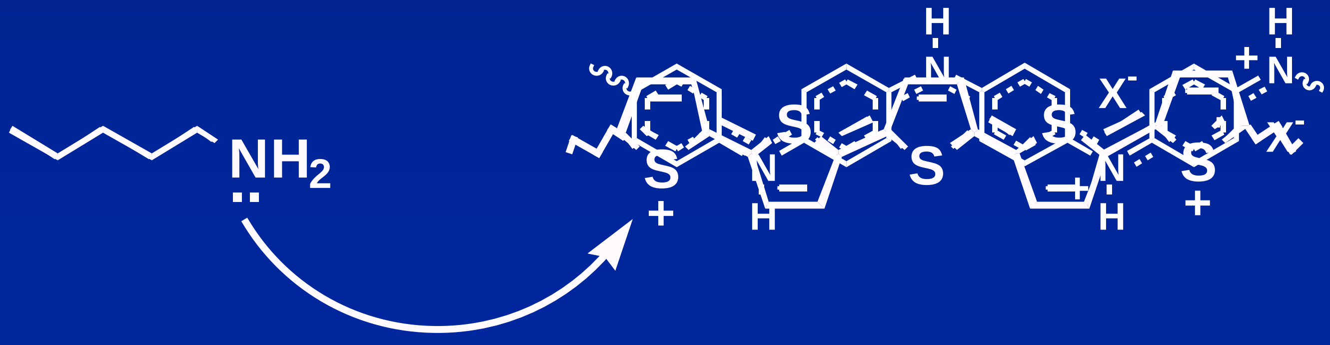
- **Change in the extrinsic conductivity**

  **swelling effects**

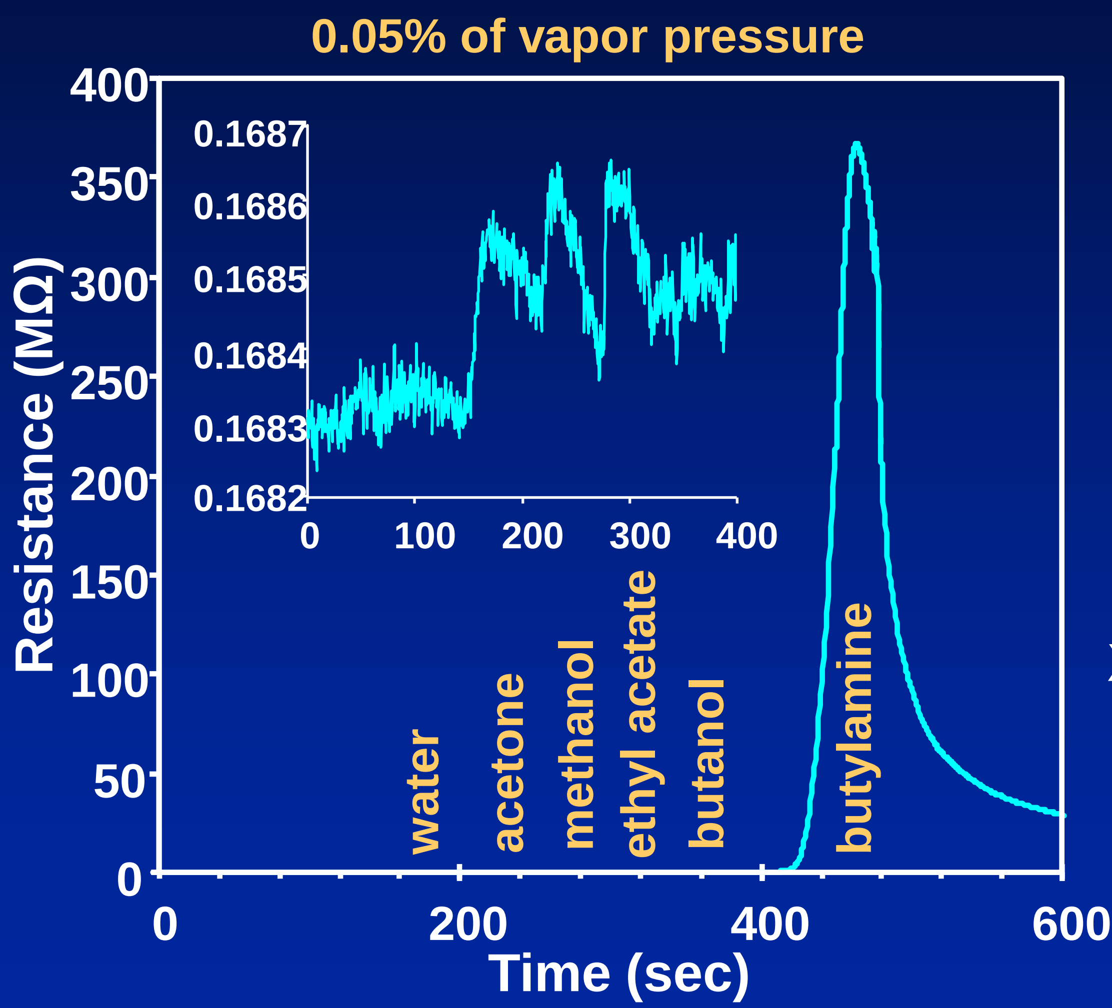




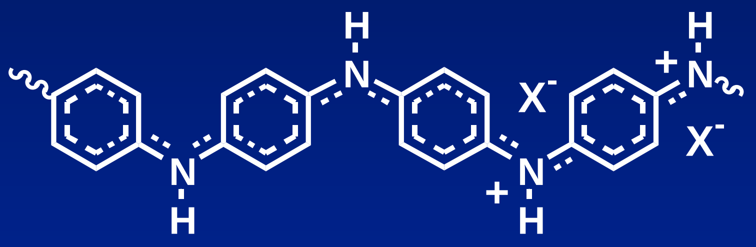

- **Change in the intrinsic conductivity**



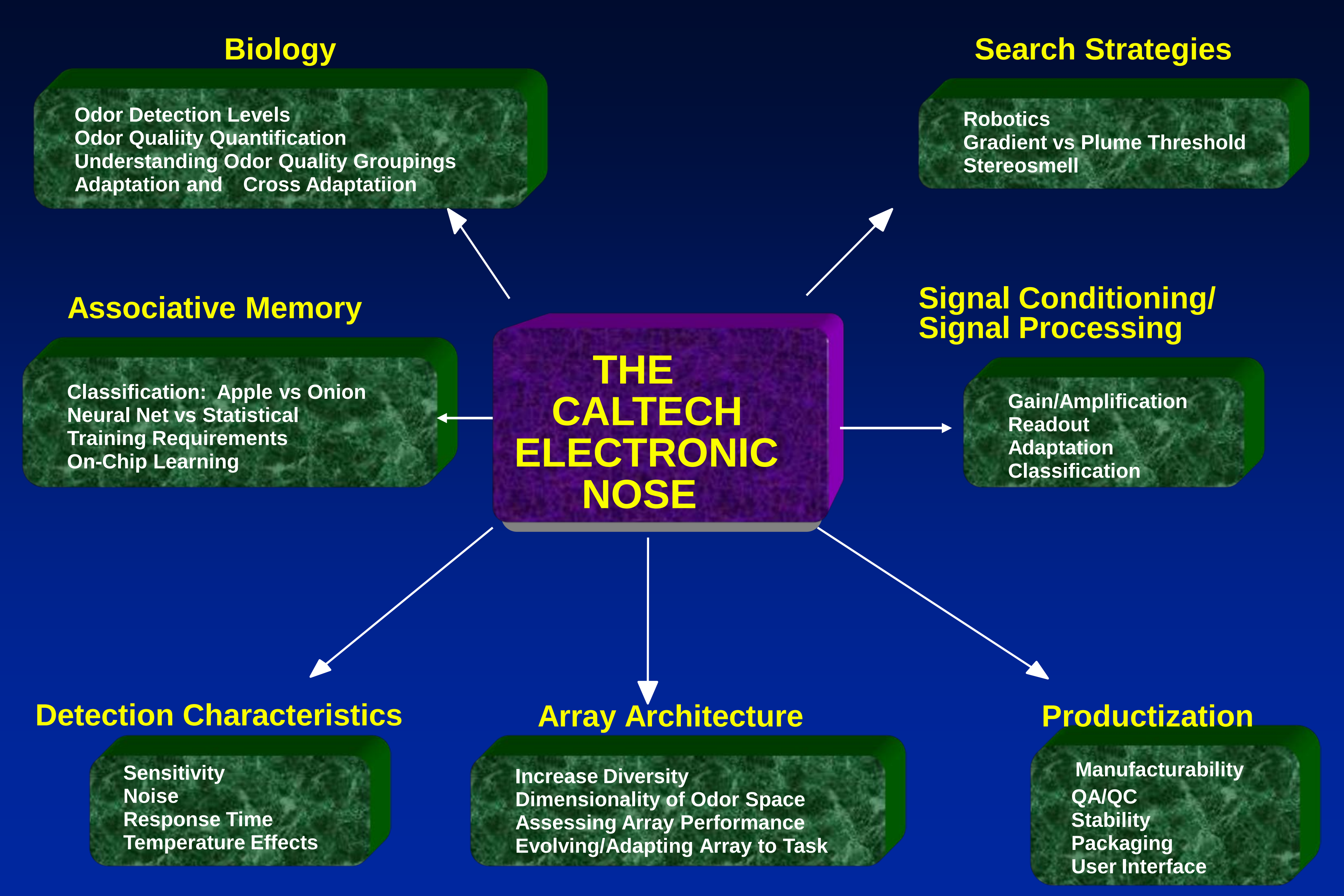
# Static Headspace Exposures




## Sensing material




$X^-$ = dodecylbenzene sulfonate

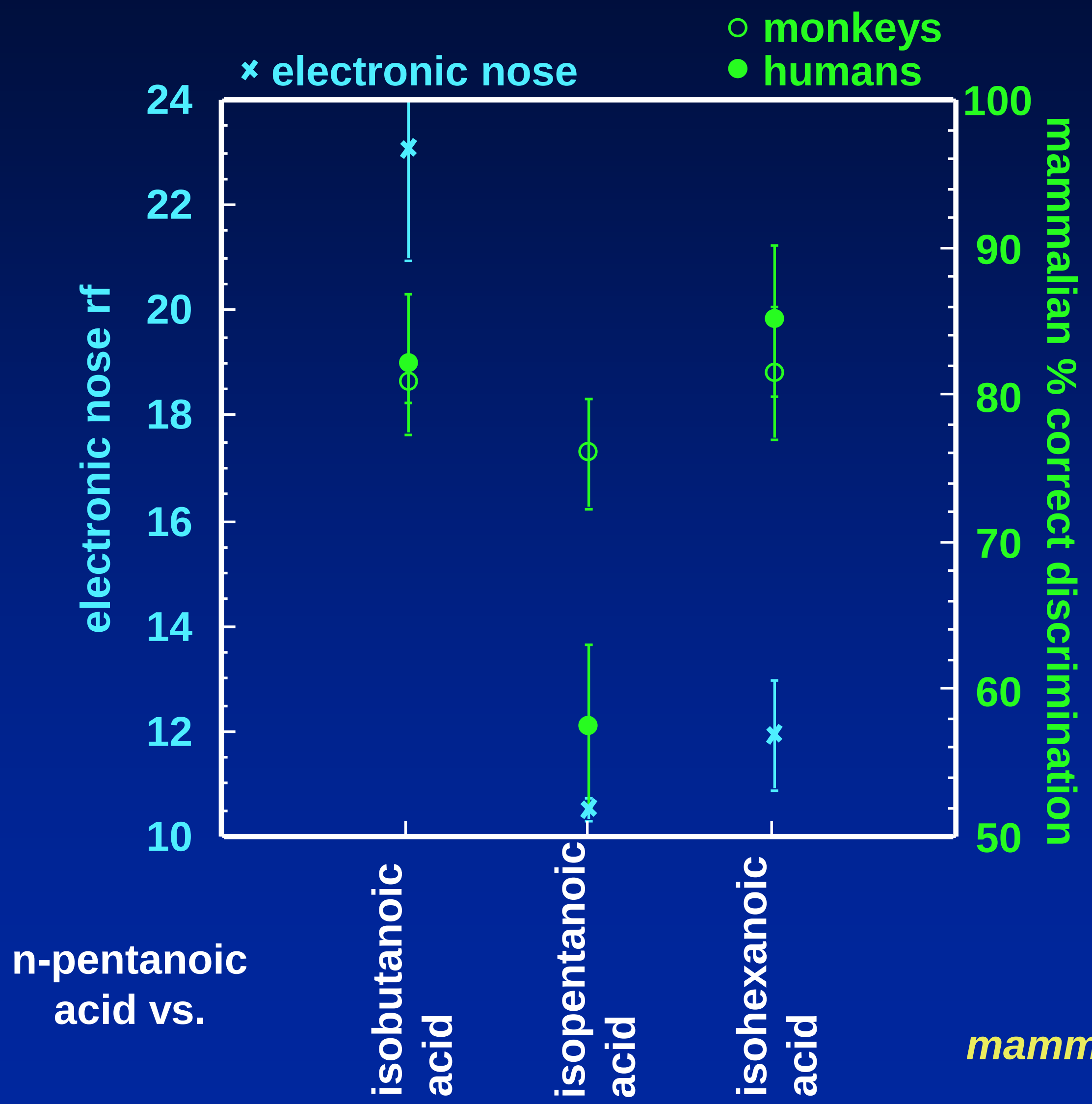

THE CALTECH ELECTRONIC NOSE
Biology
Odor Detection Levels
Odor Qualiity Quantification
Understanding Odor Quality Groupings
Adaptation and Cross Adaptatiion
Search Strategies
Robotics
Gradient vs Plume Threshold
Stereosmell
Associative Memory
Classification: Apple vs Onion
Neural Net vs Statistical
Training Requirements
On-Chip Learning
Signal Conditioning/
Signal Processing
Gain/Amplification
Readout
Adaptation
Classification
Detection Characteristics
Sensitivity
Noise
Response Time
Temperature Effects
Array Architecture
Increase Diversity
Dimensionality of Odor Space
Assessing Array Performance
Evolving/Adapting Array to Task
Productization
Manufacturability
QA/QC
Stability
Packaging
User Interface

# Polymer Composite Sensor Arrays for Demining

- Characterized Sensors
- Miniaturized Sensors
- Improved Sensitivity, Response Time, Manufacturability
- Developed Discrete Electronic Circuitry
- Transitioned to NASA, DOE, Commercial Sector
- Developed Sampler
- Developed System Fluidics Design
- Developed Ultrathin Skins for Improved FlowDynamics
- Demonstrated On-Chip Capability
- Developed Read-Out, On-Chip Gain, and Adaptation Circuitry
- Developed Microheaters
- Field Tested Prototypes

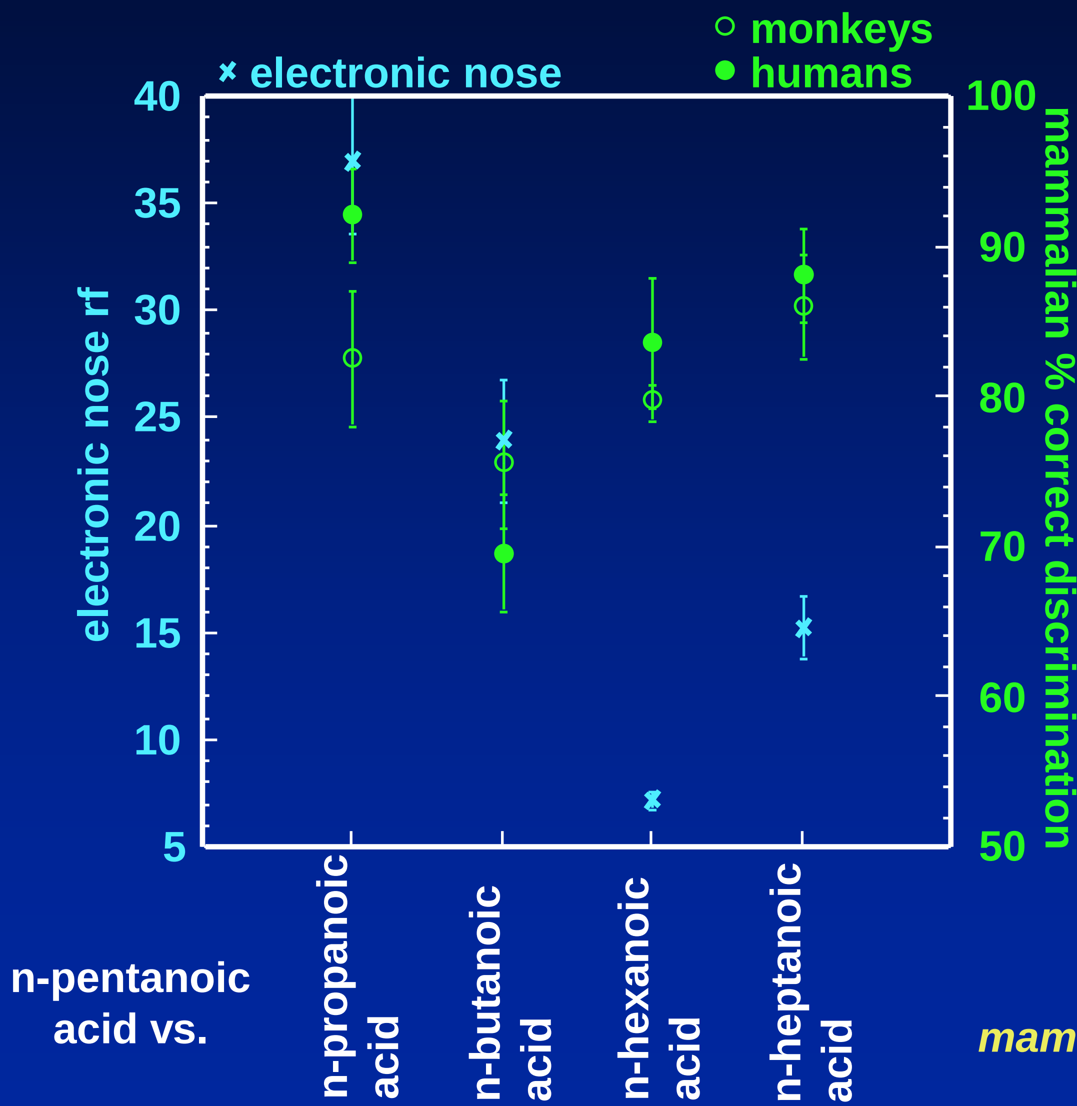
ARO/MURI

# Odorant Discrimination Trends for Mammals and the Electronic Nose (Carboxylic Acids)



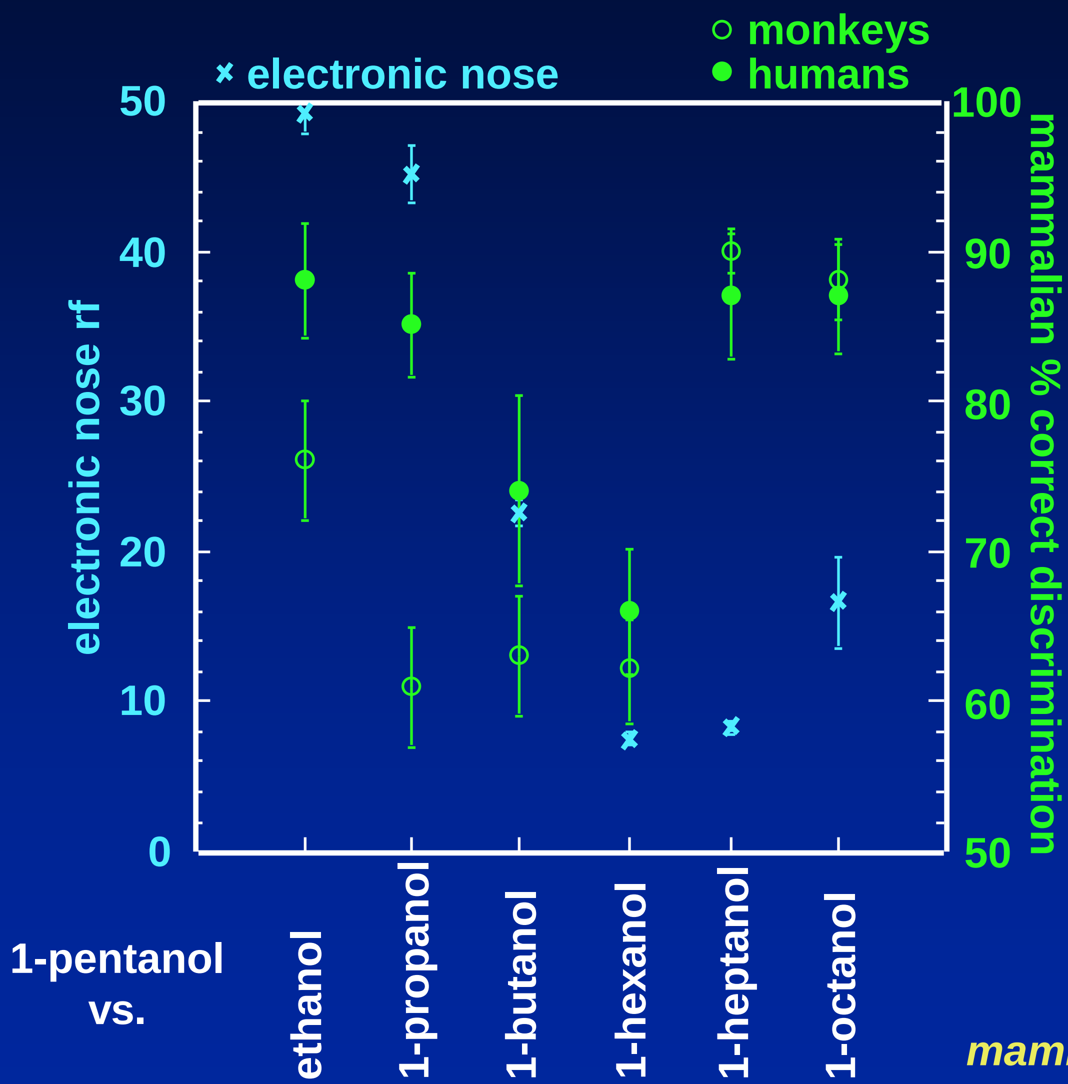

*mammalian data courtesy of Laska et al, 1998*

# Odorant Discrimination Trends for Mammals and the Electronic Nose (Carboxylic Acids)



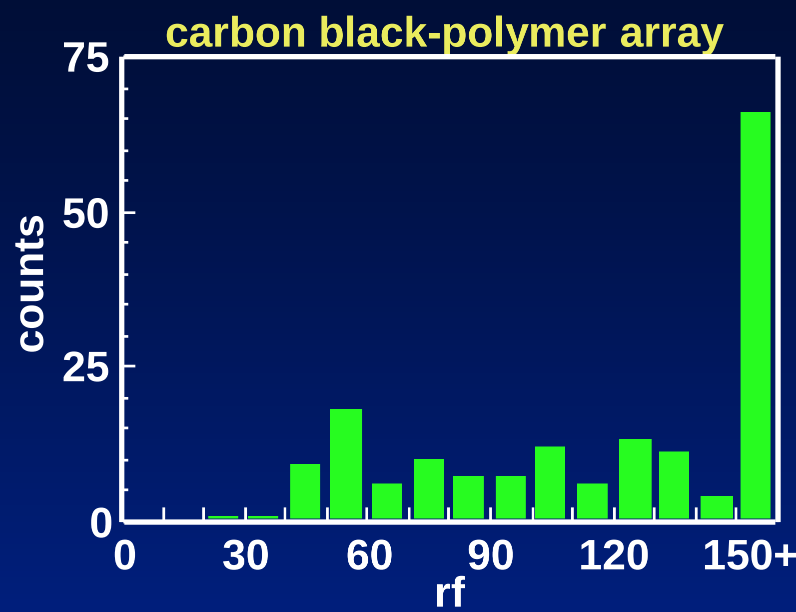

*mammalian data courtesy of Laska et al, 1998*

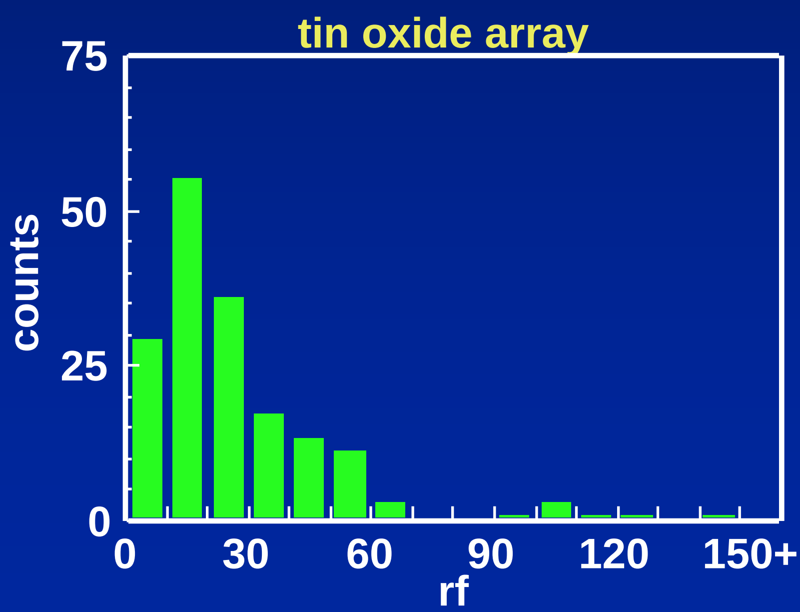
# Odorant Discrimination Trends for Mammals and the Electronic Nose (Alcohols)

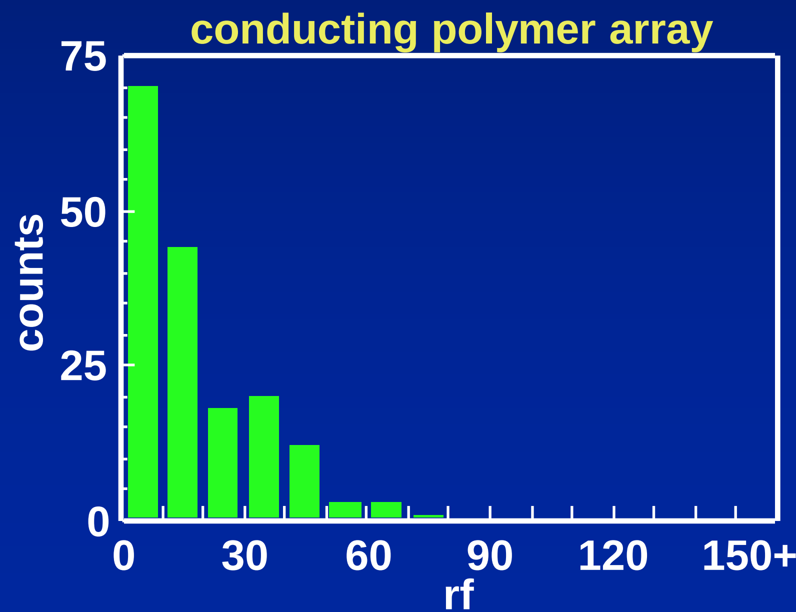



*mammalian data courtesy of Laska et al, in press*

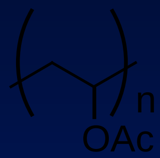
# Resolving Power of Different Sensor Types



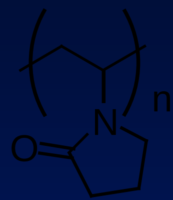



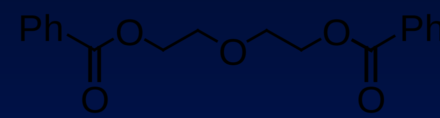
# Plasticization of PVA with DGD



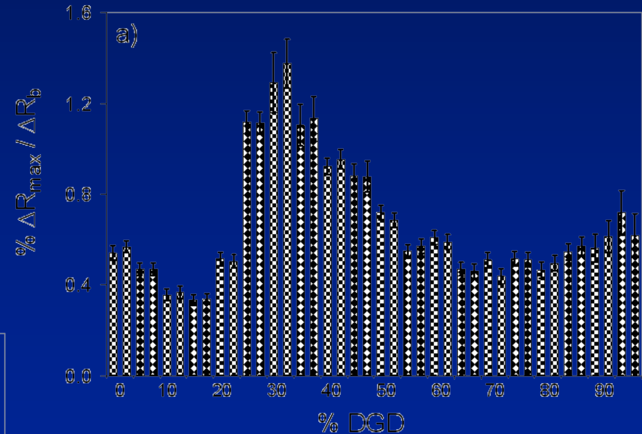

poly(vinyl acetate)
(PVAc)




poly(N-vinyl pyrrolidone)
(PVPd)

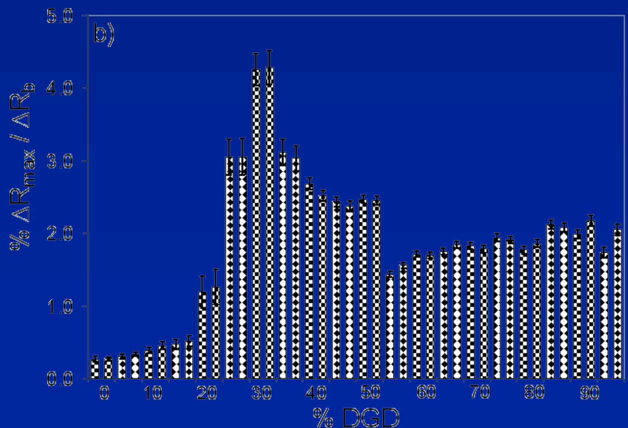



Diethylene glycol dibenzoate
(DGD)

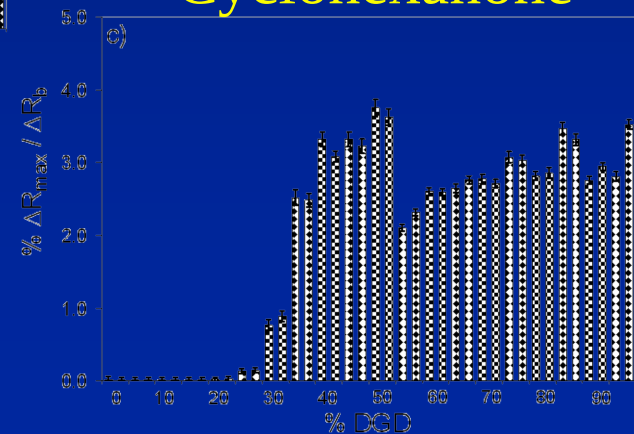



Acetone

Methanol



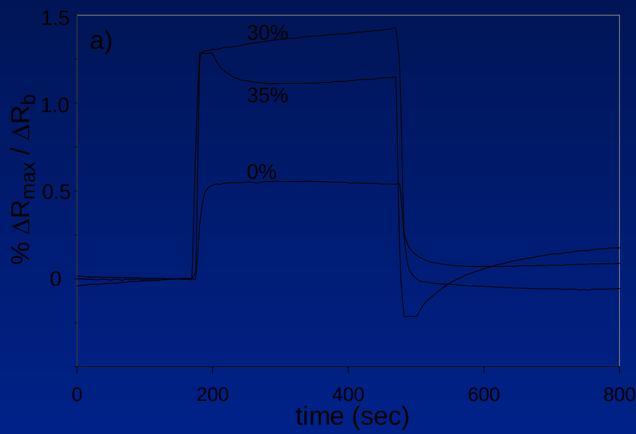

Cyclohexanone



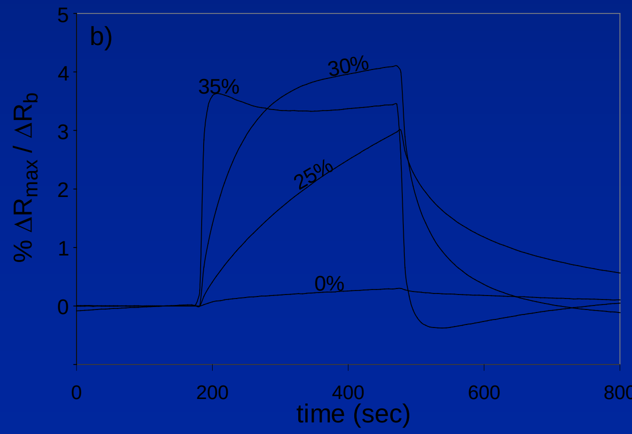

$P/P^o = 0.050$

# Plasticization of PVA with DGD

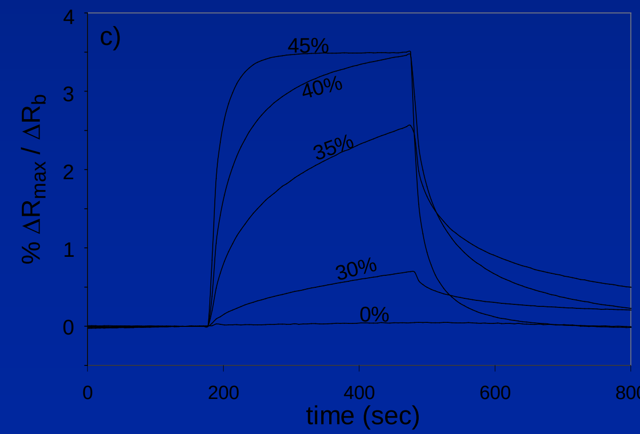
Methanol




Acetone



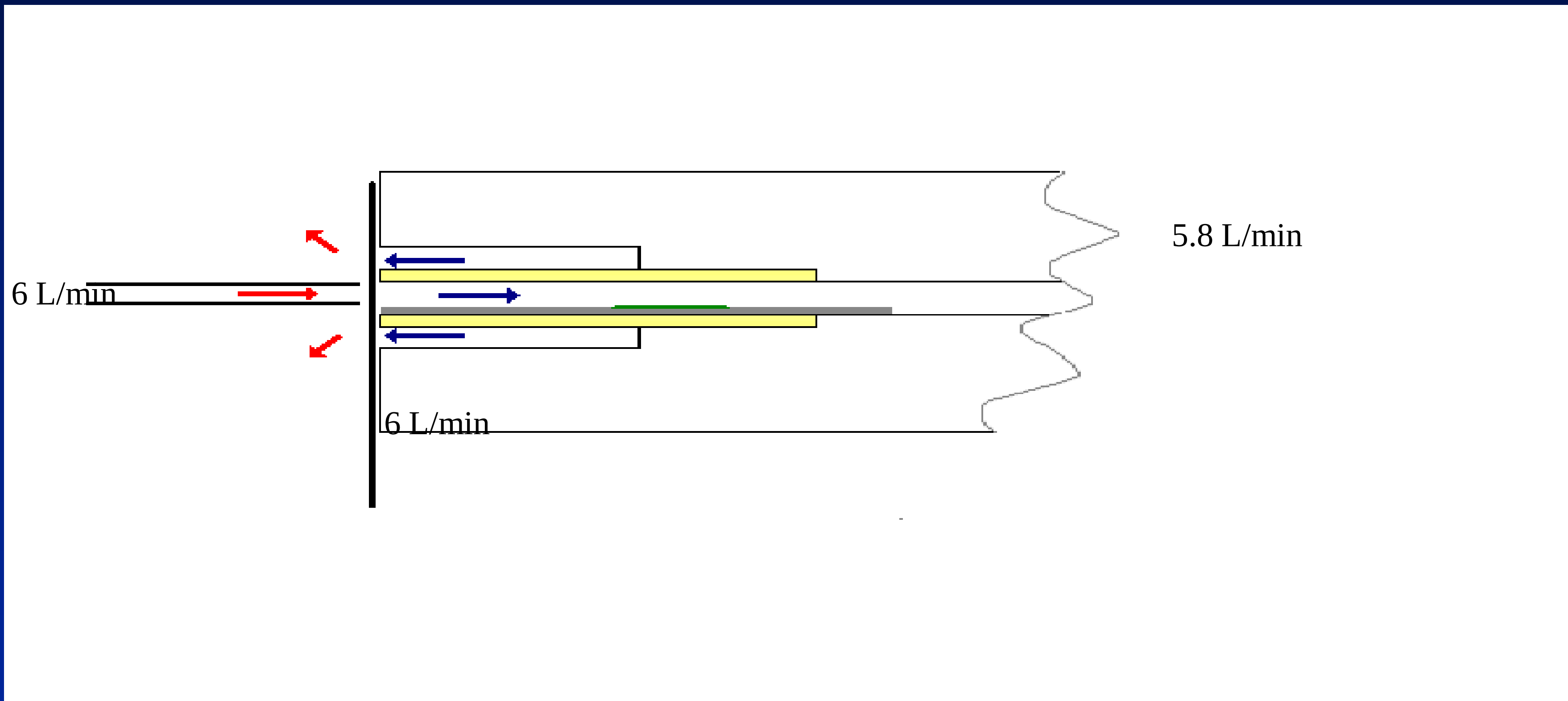

Cyclohexanone



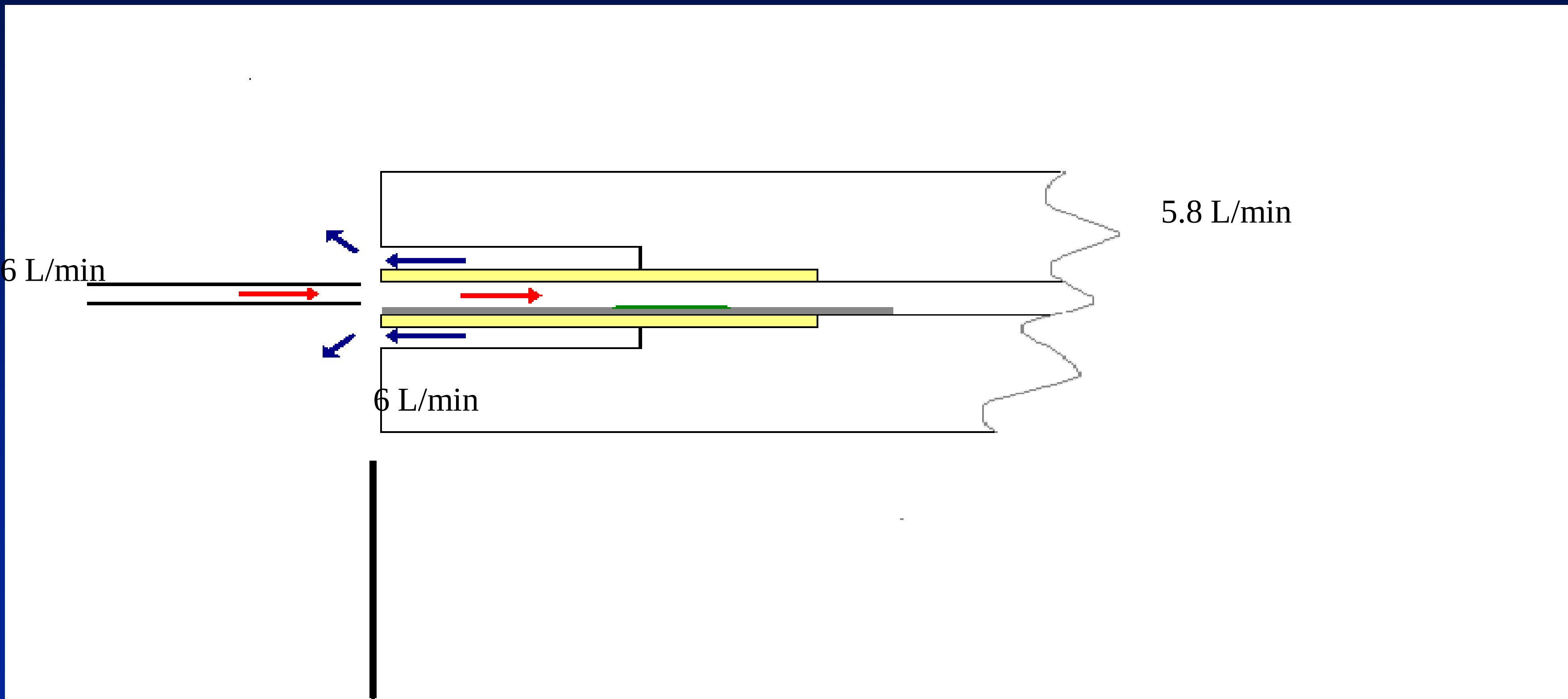

$P/P^o=0.050$

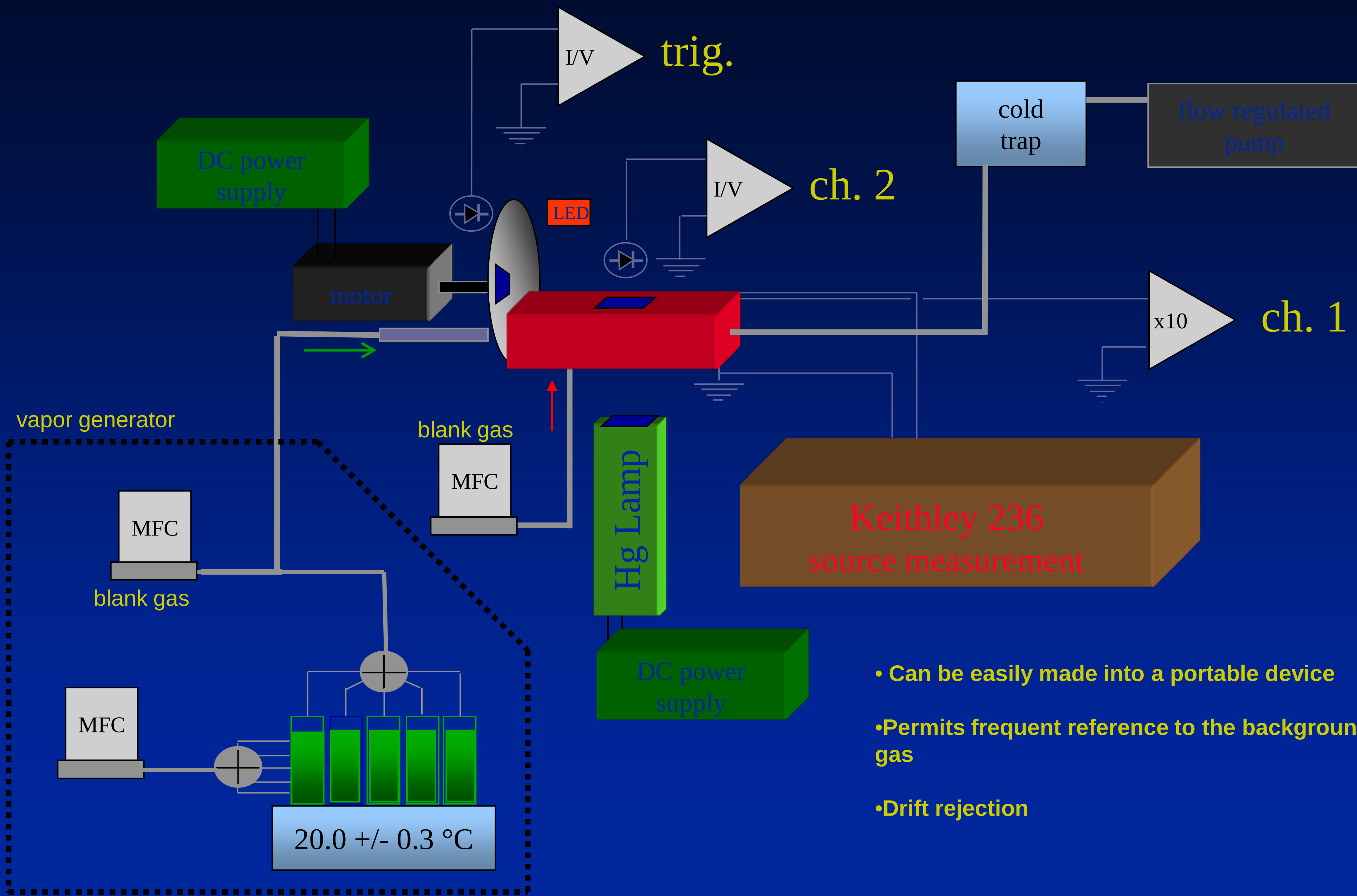

Chopper Wheel

# Closed - Analyte Vapor Off



# Open - Analyte Vapor On

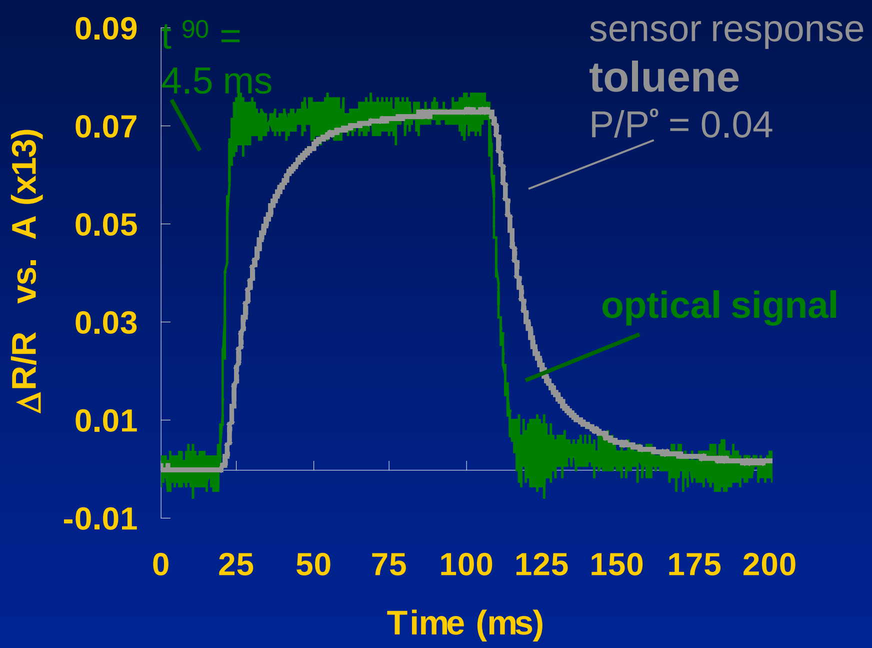




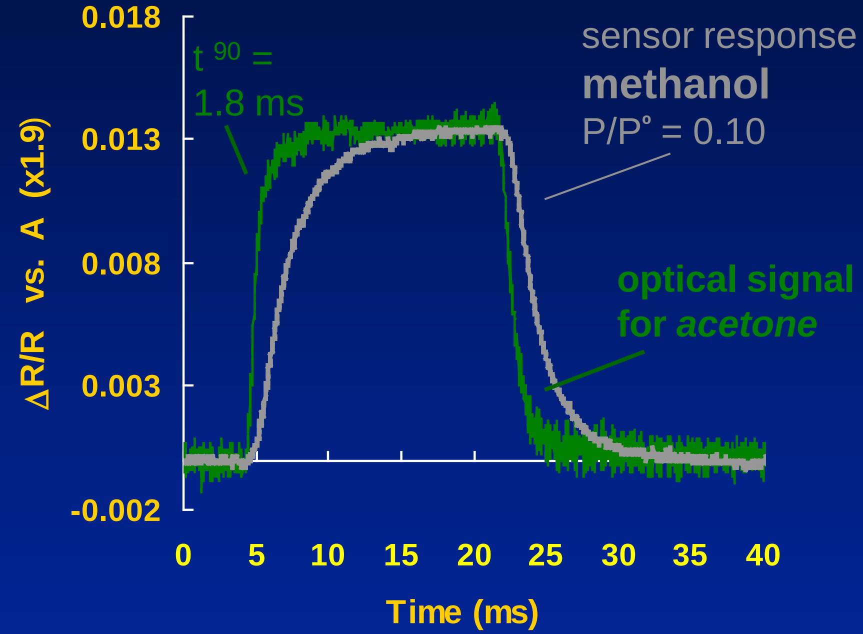

- **Can be easily made into a portable device**
- **Permits frequent reference to the background gas**
- **Drift rejection**

# Response of a PEVA Detector to Pulses of Two Different Analyte

**92 ms pulse**




**18 ms pulse**



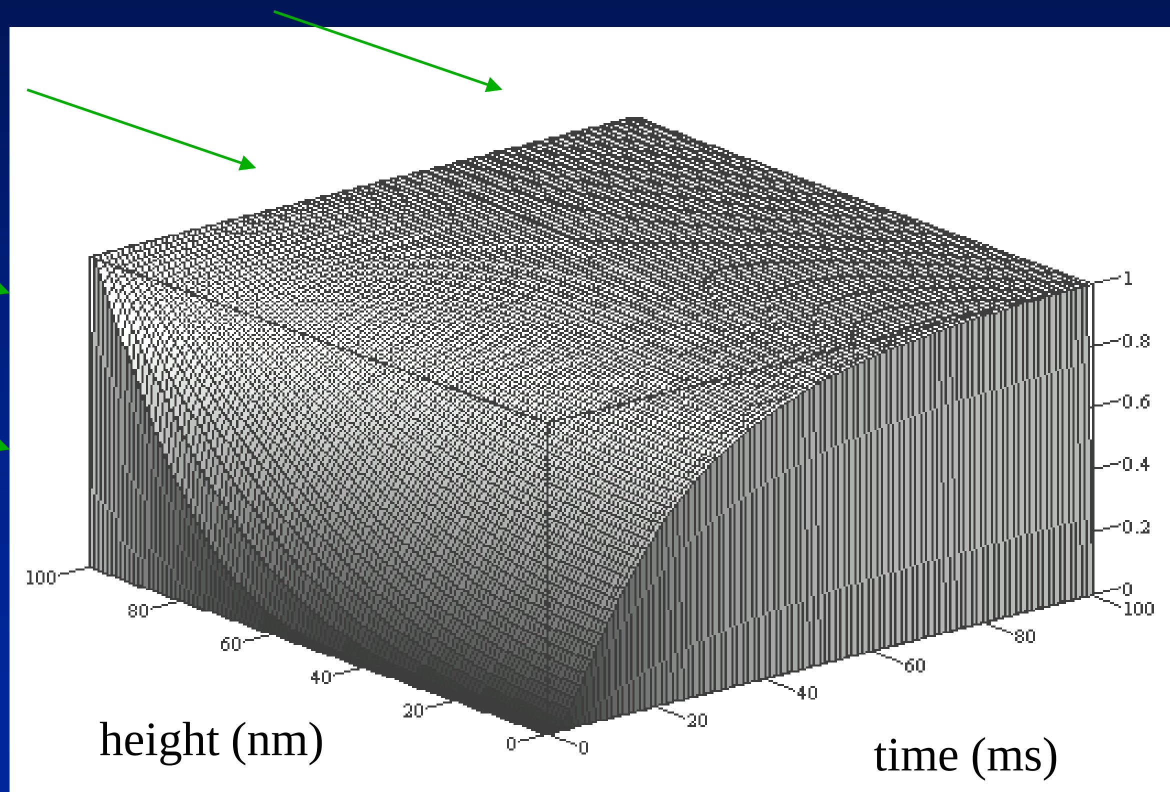

•The ability to quickly step analyte concentration provides a useful tool for characterizing the sensor time response

•Fast response for some polymer/analyte combinations

**rough 180 nm PEVA film**

# Simulated Detector Response

Analyte
$C_{vap}$




$C = K\ C_{vap}$

$D = 2x10^{-6}\ cm^2\ s^{-1}$

# Crank's Numerical Solutions for Diffusion in a Plane Sheet

$$S_{t,i} := 1 - \frac{4}{\pi} \cdot \sum_{n=0}^{20} \frac{(-1)^n}{2 \cdot n + 1} \cdot e^{\left[\frac{-D \cdot (2 \cdot n + 1)^2 \cdot \pi^2 \cdot time_t}{4 \cdot L^2}\right]} \cdot \cos\left[\frac{(2 \cdot n + 1) \cdot \pi \cdot x_i}{2 \cdot L}\right]$$

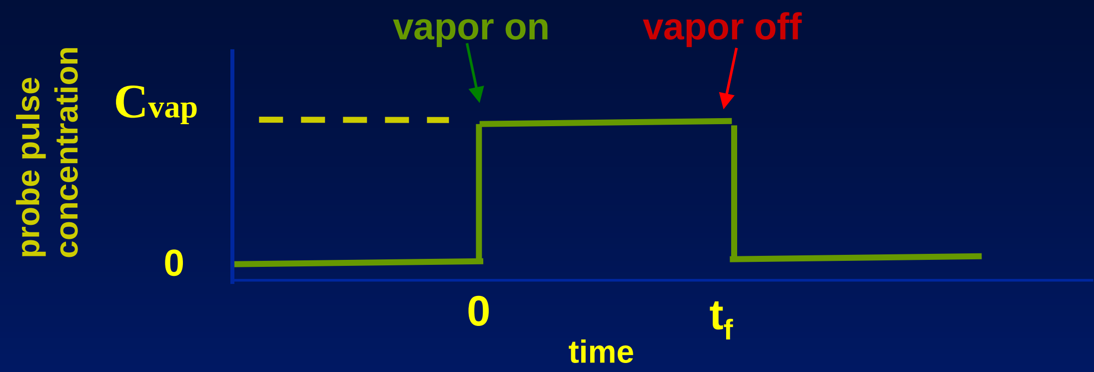
$$SS_{t,i} := \sum_{n=0}^{20} (-1)^n \cdot \left[1 - \mathrm{erf}\left[\frac{(2 \cdot n + 1) \cdot L - x_i}{2 \cdot \left(D \cdot time_t\right)^{\frac{1}{2}}}\right]\right] + \sum_{n=0}^{20} (-1)^n \cdot \left[1 - \mathrm{erf}\left[\frac{(2 \cdot n + 1) \cdot L + x_i}{2 \cdot \left(D \cdot time_t\right)^{\frac{1}{2}}}\right]\right]$$

# Sensor Response

**Fick's 2[nd] Law of Diffusion**

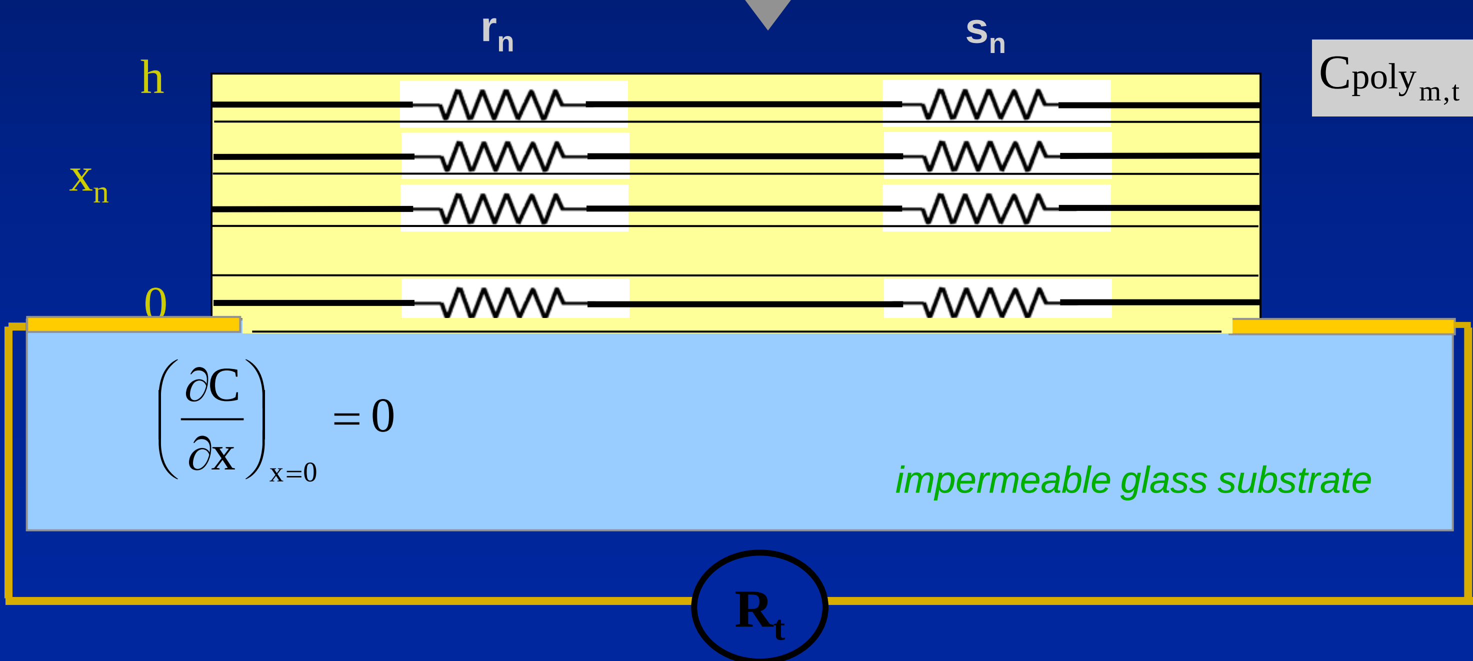
$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}$$

$$Cpoly_{n,t} =$$




$$r_{n,t} = m \cdot R_i$$

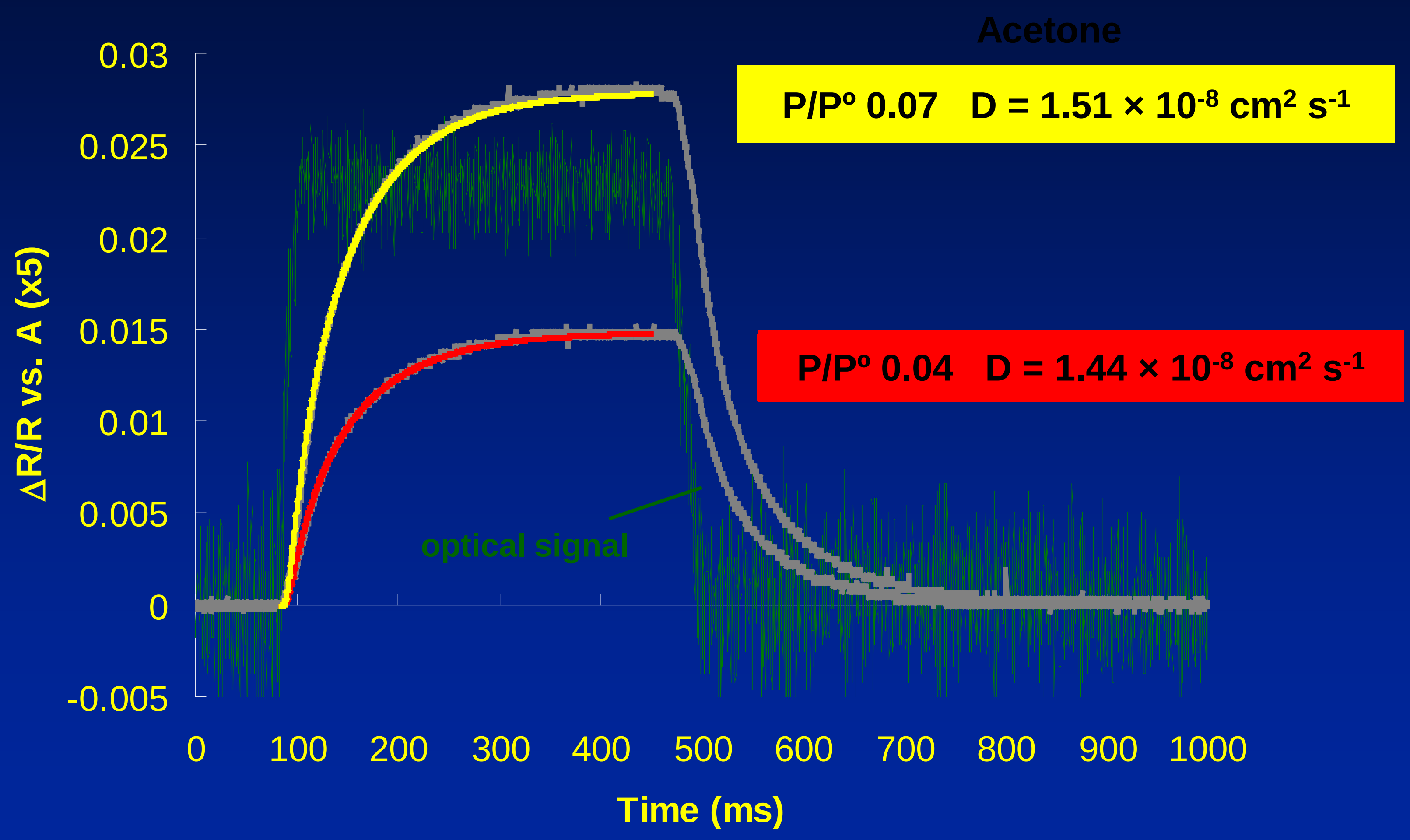
$$s_{n,t} = A \cdot Cpoly_{n,t}$$




$$Cpoly_{m,t} = K \cdot Cvap_t$$

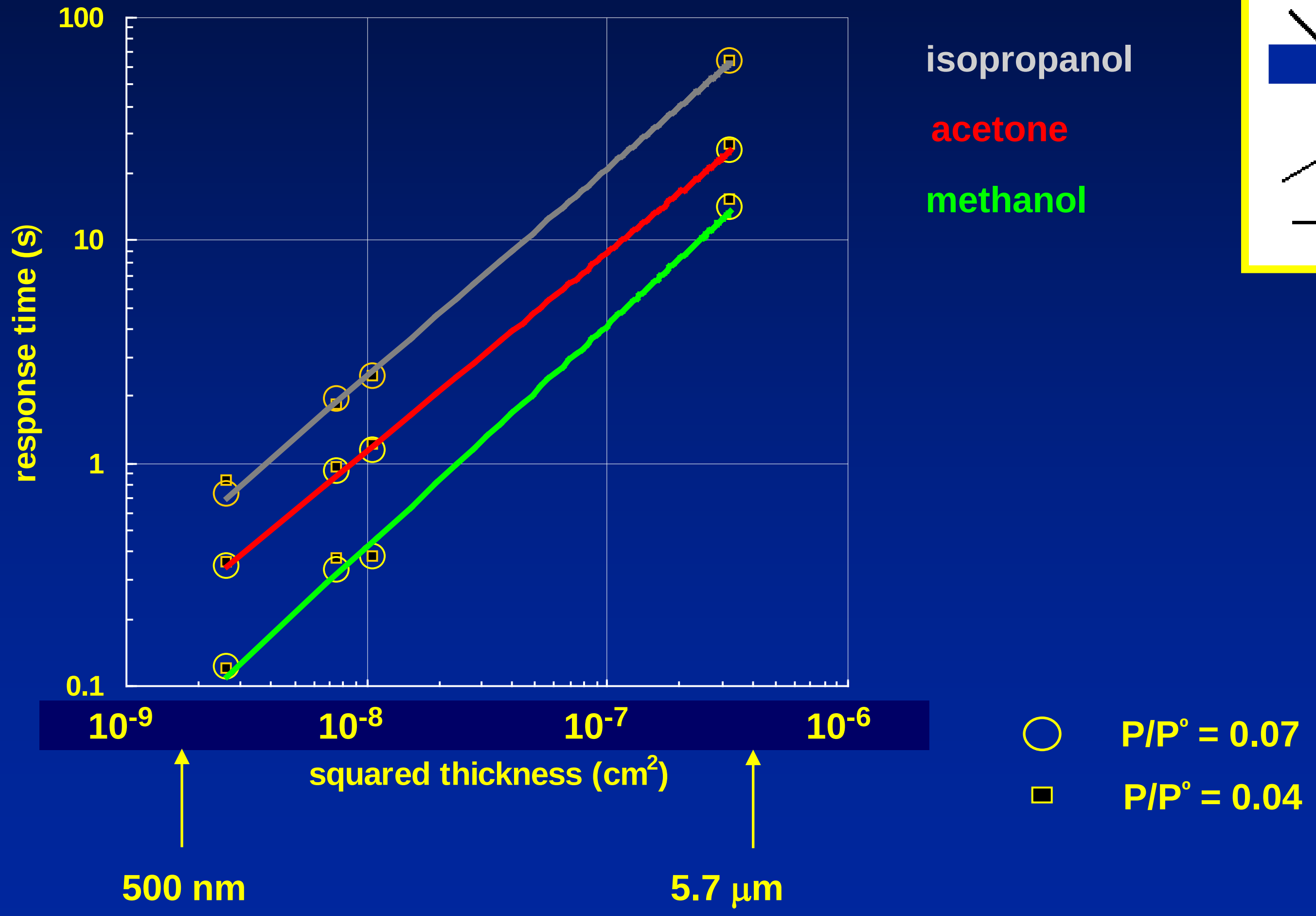
$$R_t = \frac{1}{\sum_{n=1}^{m} \frac{1}{m \cdot R_i + s_{n,t}}}$$

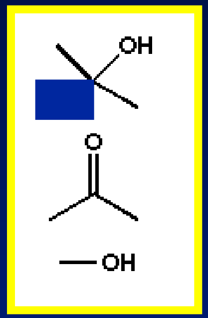
# Detector/Analyte Pair Exhibiting Fickian Diffusion for two Concentrations of an Analyte



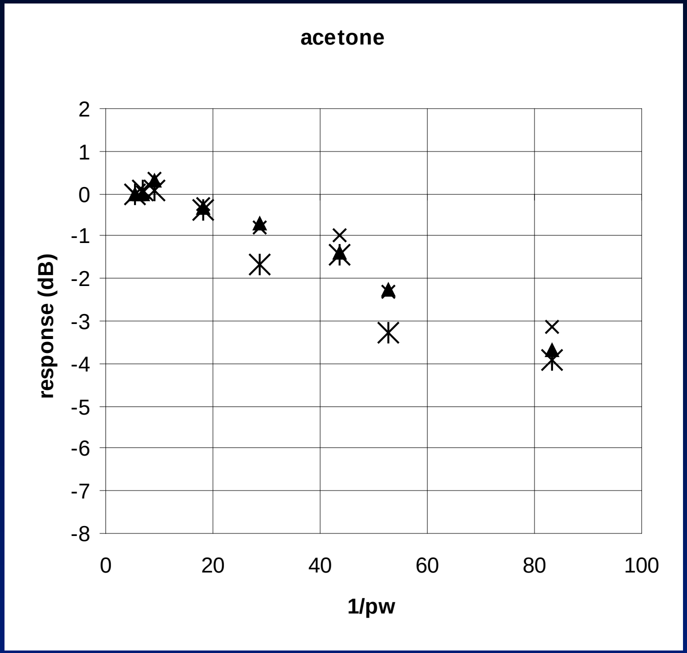

**500 nm PEVA film     400 ms pulse**

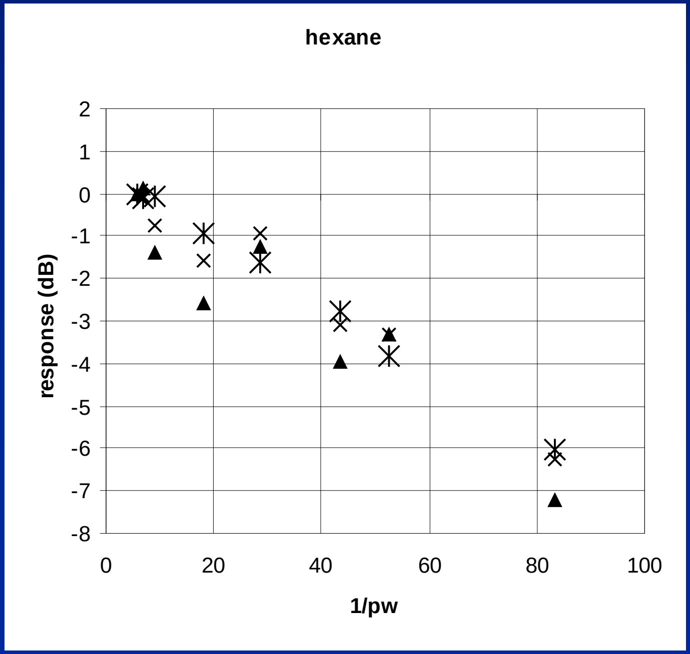
# Response Time Demonstrates Expected Dependence on Film Thickness

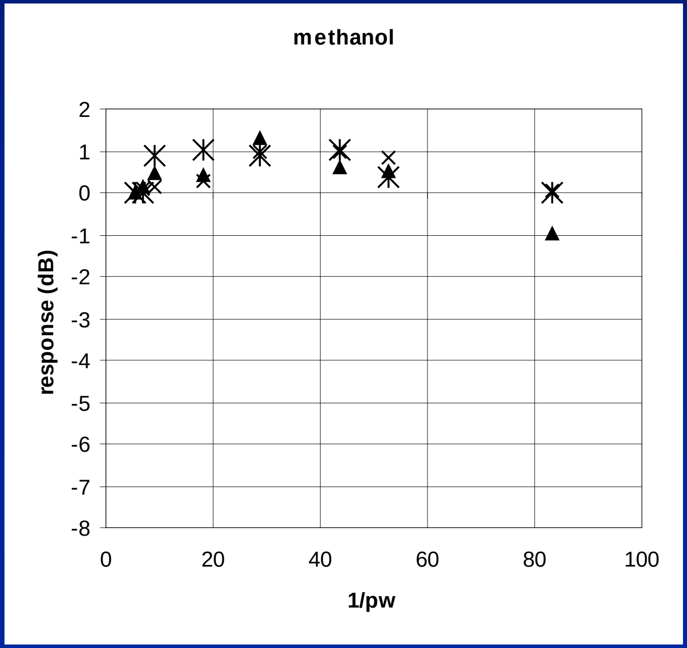


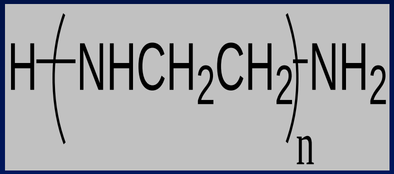
# Frequency Response



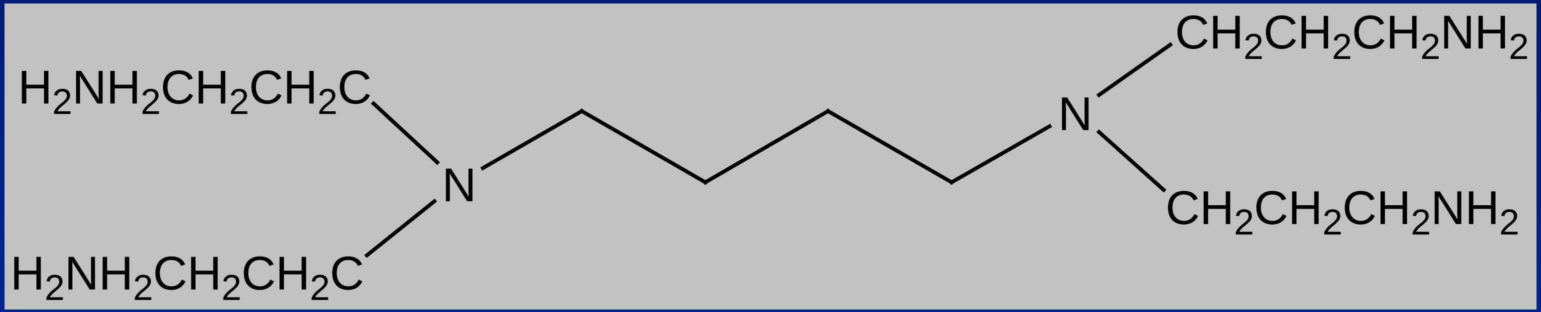



# Amine Containing Polymeric Component of Composites for Enhanced Detection of Volatile Fatty Acids



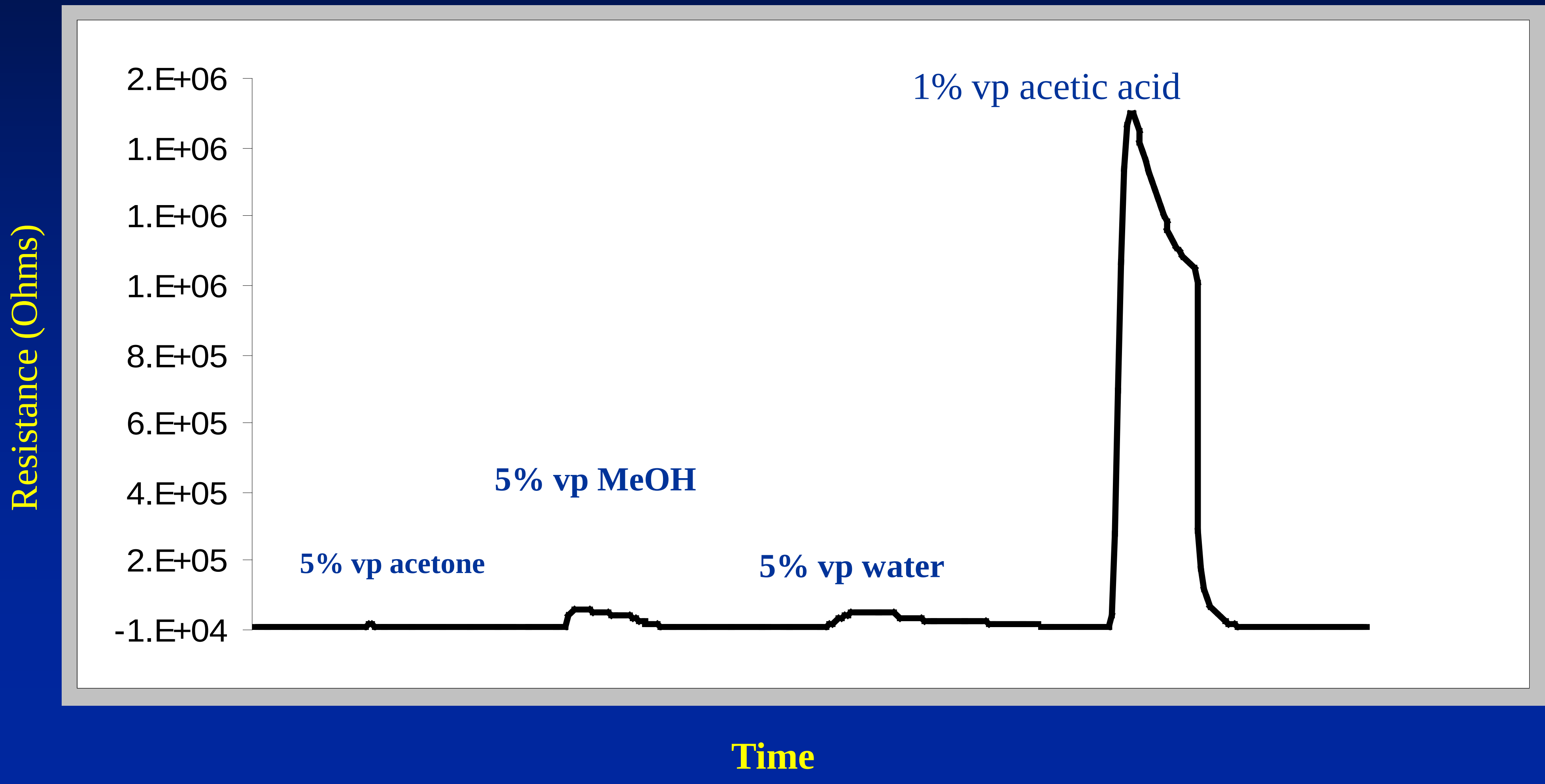

*l*-PEI Poly(ethylene imine)



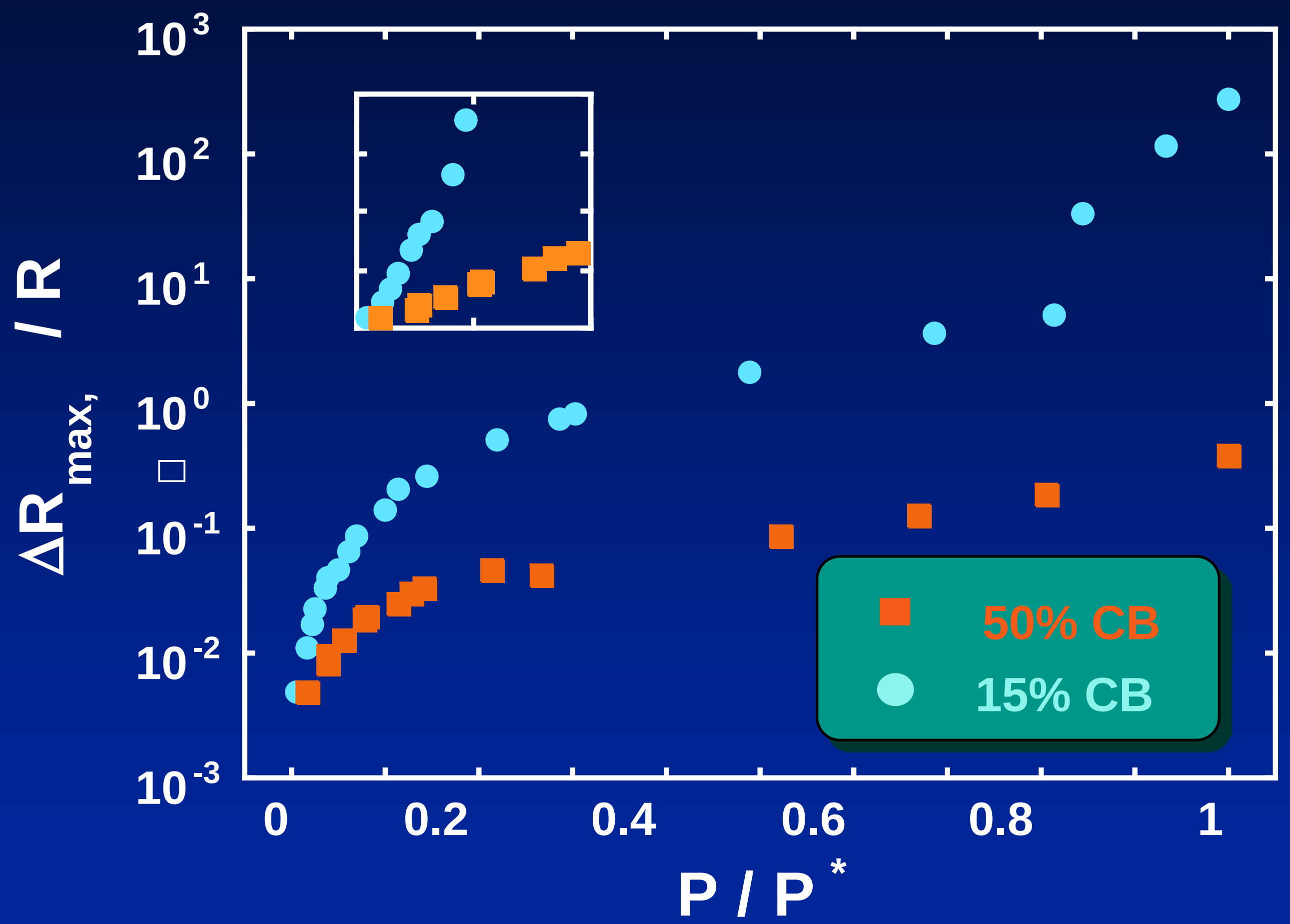

DAB-Am-4

Polypropylenimine tetraamine Dendrimer, Gen 1.0

# *l*-PEI- 20% Carbon Black Composite



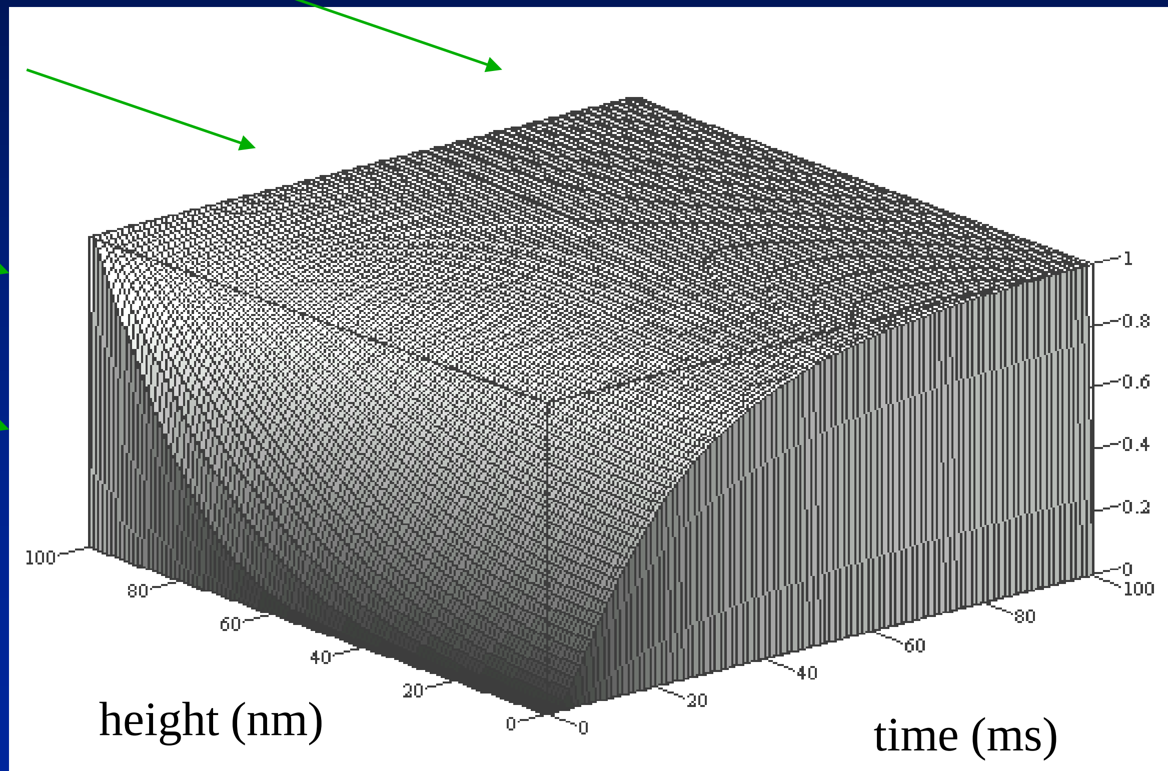
# Percolation Behavior




*Poly(ethylene-co-vinylacetate)-Carbon Black*
*Exposed to Benzene*

# Simulated Detector Response

Analyte
$C_{vap}$




$C = K\ C_{vap}$

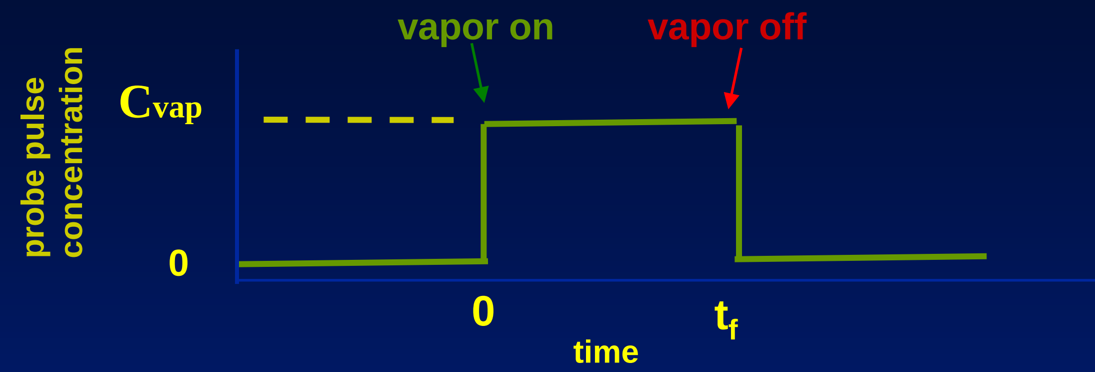
$D = 2x10^{-6}\ cm^2\ s^{-1}$

# Sensor Response

**Fick's 2[nd] Law of Diffusion**

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}$$

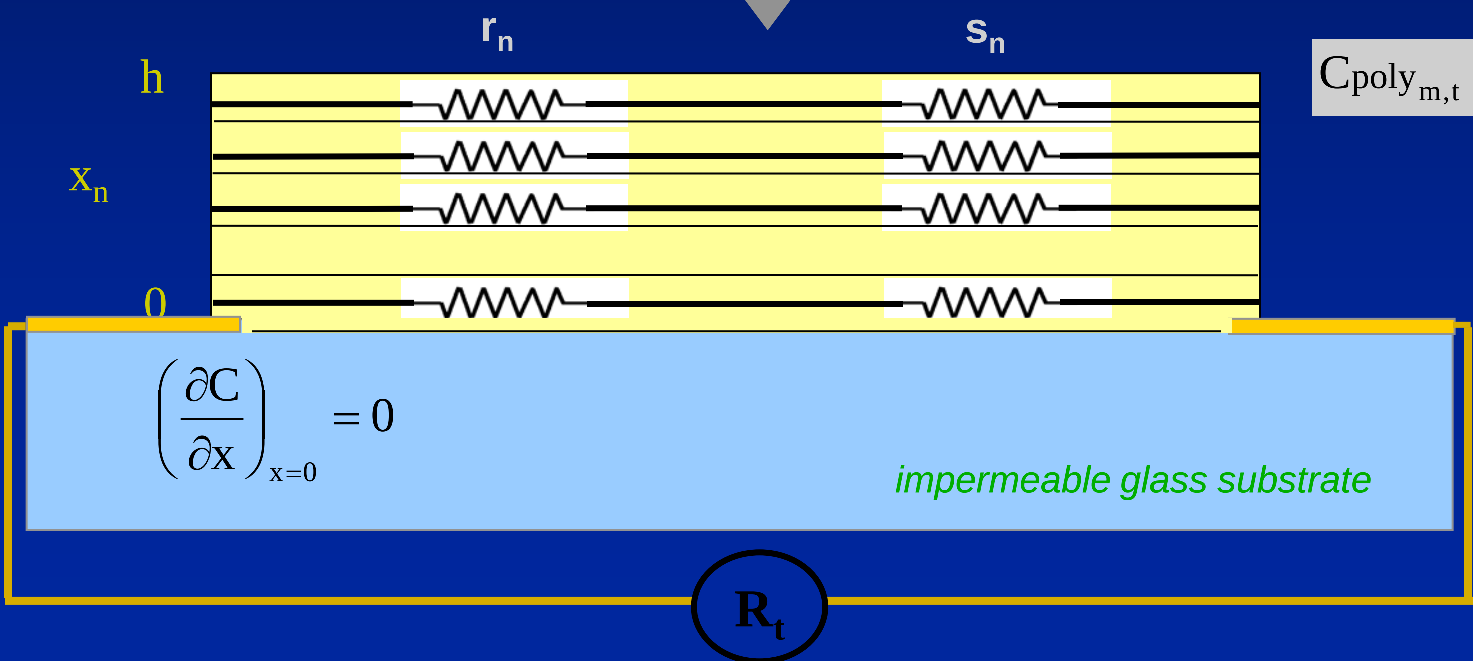
$$Cpoly_{n,t} =$$




$$r_{n,t} = m \cdot R_i$$

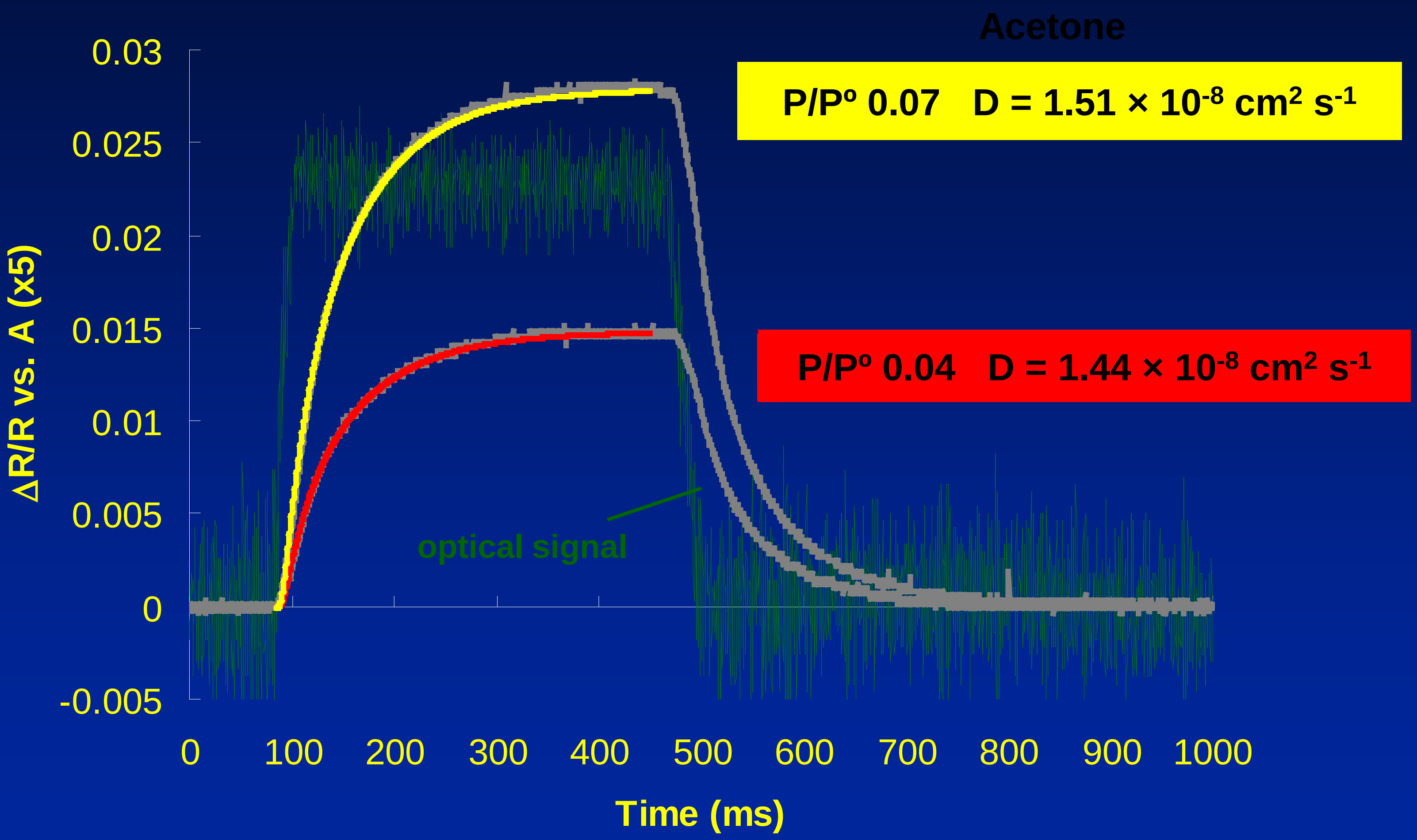
$$s_{n,t} = A \cdot Cpoly_{n,t}$$

$$Cpoly_{m,t} = K \cdot Cvap_t$$




$$R_t = \frac{1}{\sum_{n=1}^{m} \frac{1}{m \cdot R_i + s_{n,t}}}$$

# Detector/Analyte Pair Exhibiting Fickian Diffusion for two Concentrations of an Analyte




**500 nm PEVA film 400 ms pulse**