# THE MAN WHO MISTOOK HIS COMPUTER FOR A HAND

*Neural Control of Robotic Devices*

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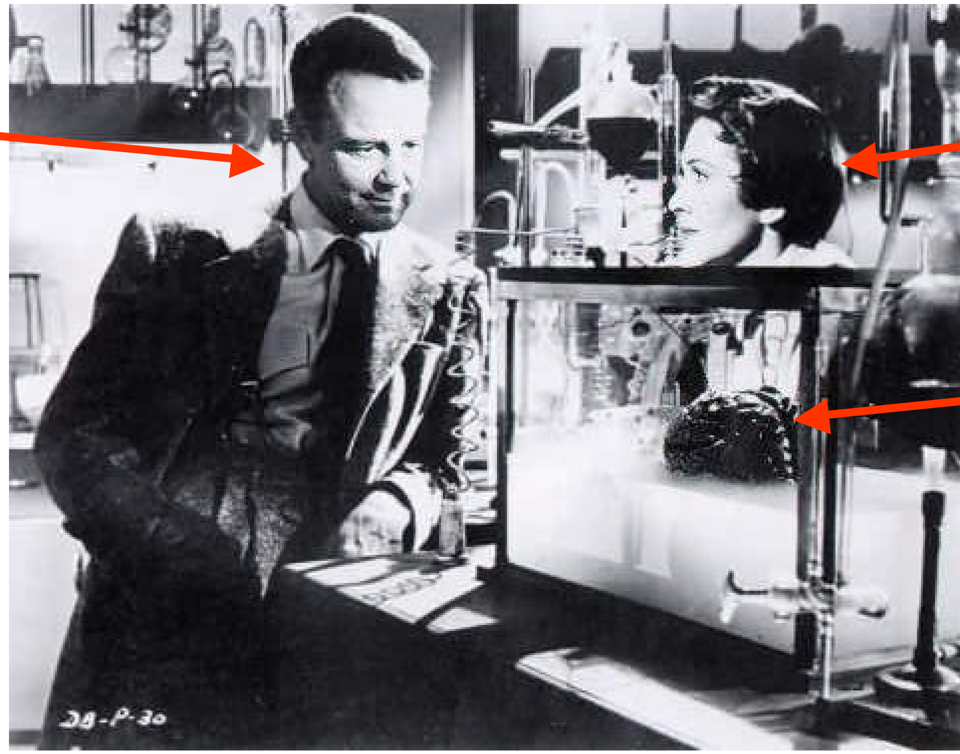
Applied Mathematics Computer Science Neuroscience

# XEROX ALTO 1973

Dell workstation, 2001

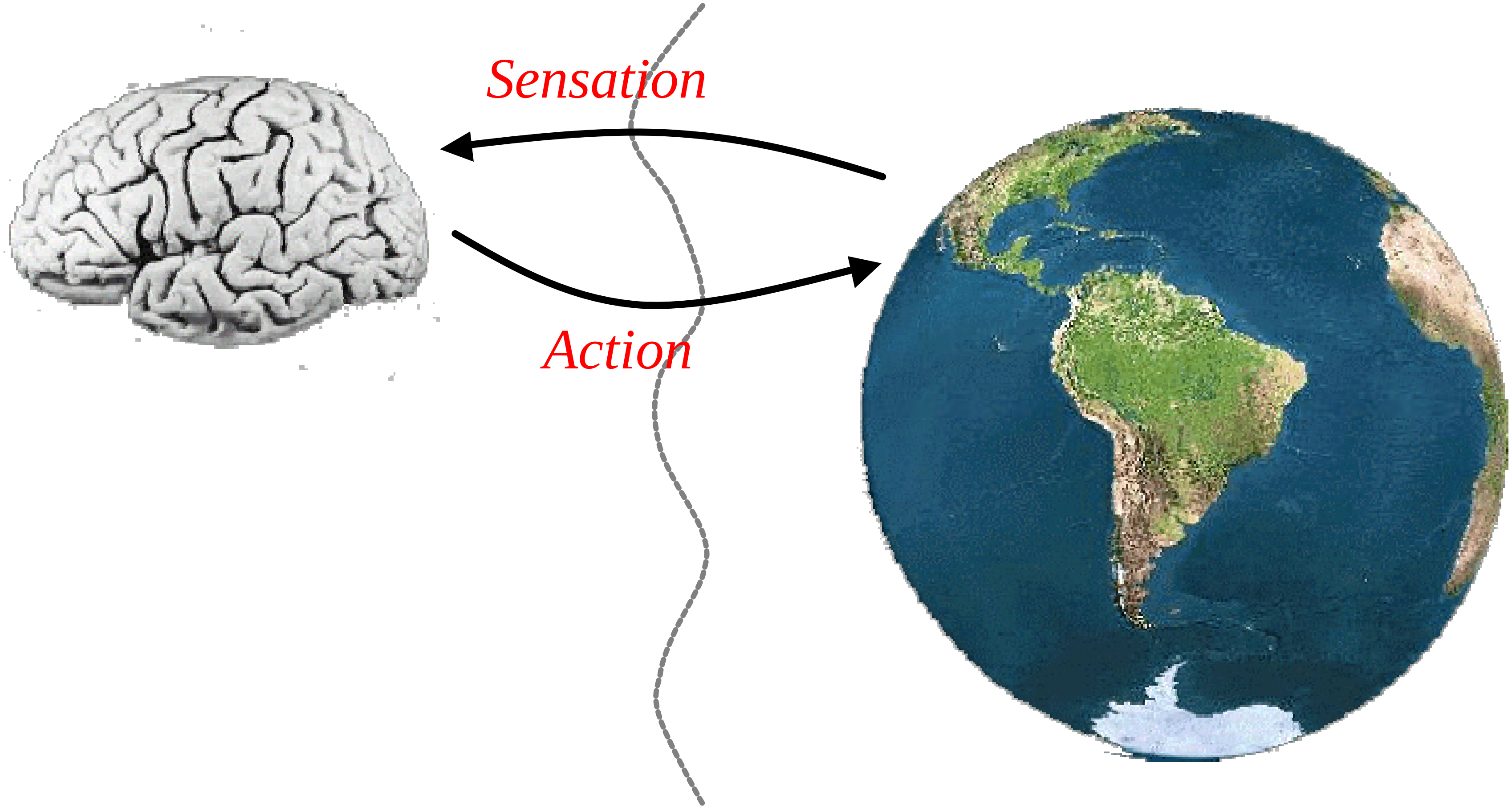
# BRAIN-COMPUTER INTERFACES



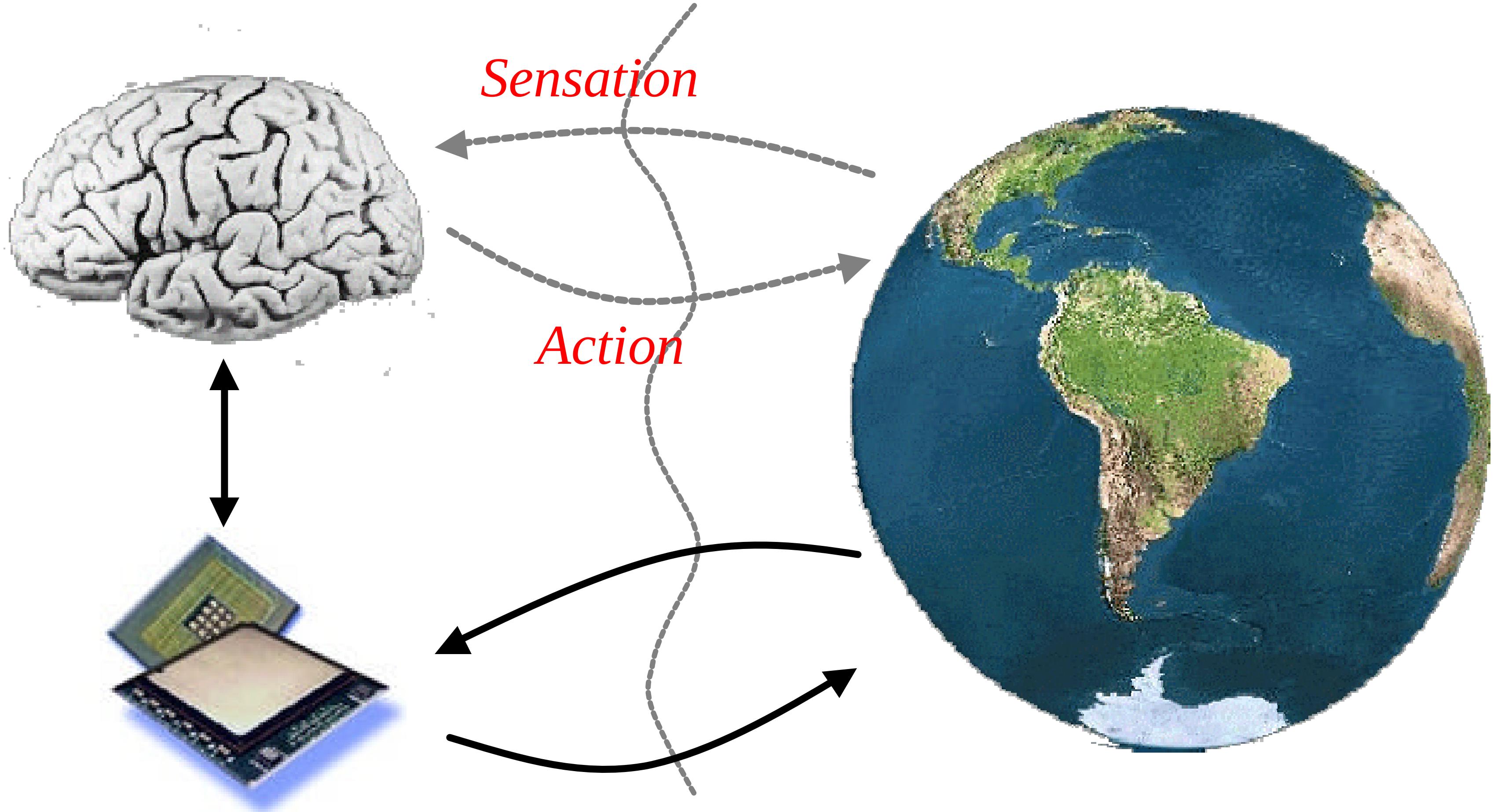

*"If I could find … a code which translates the relation between the reading of the encephalograph and the mental image …the brain could communicate with me."*

Curt Siodmak, 1942

# NEURAL PROSTHETICS

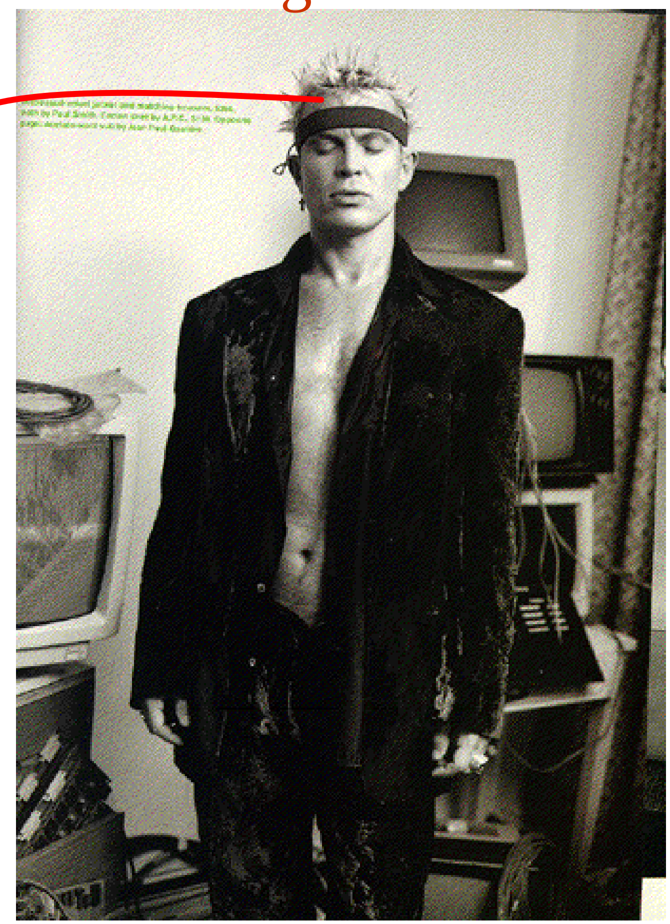


# NEURAL PROSTHETICS

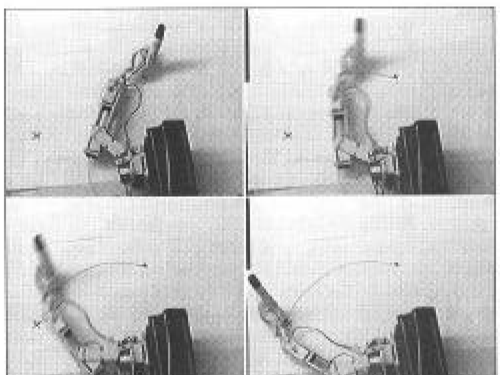


# NEURAL PROSTHETICS

Signals?



Representation, inference, and algorithms?



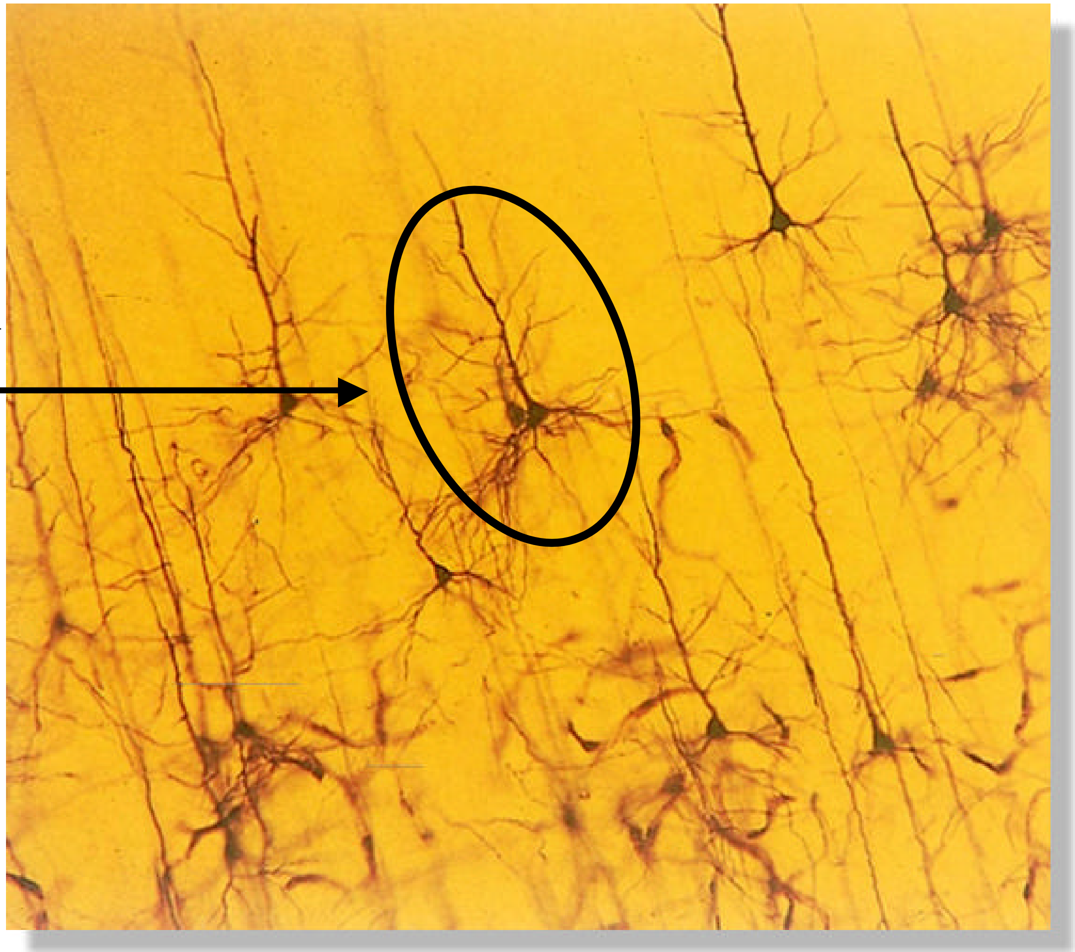
Robot control?

< 200 ms

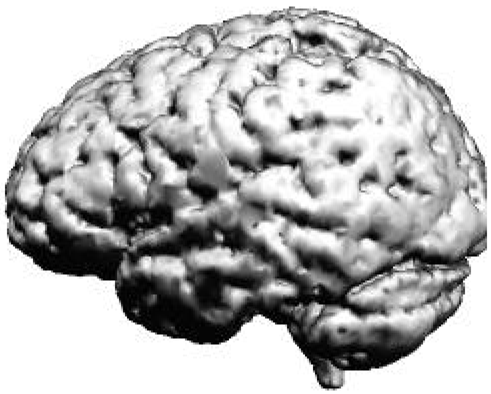
# VISUALIZING THE PLAYERS

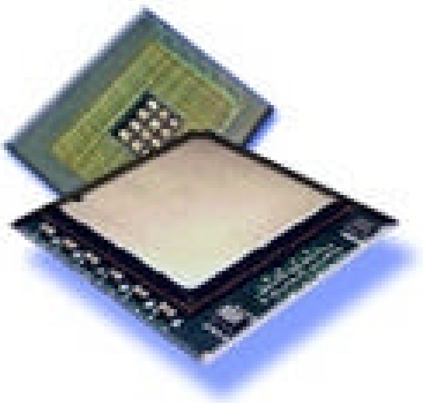
Single cells of
the nervous system

NEURON



# BRAIN VERSUS COMPUTER





Computational Elements

100,000,000,000 Neurons

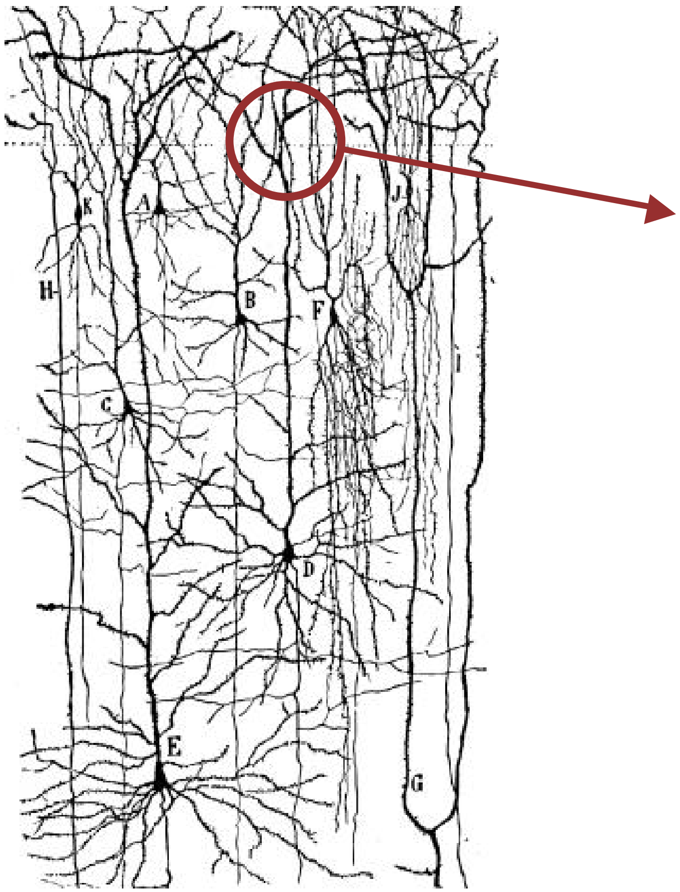
50,000,000 Transistors (P IV)

Speed (operations/second/element)

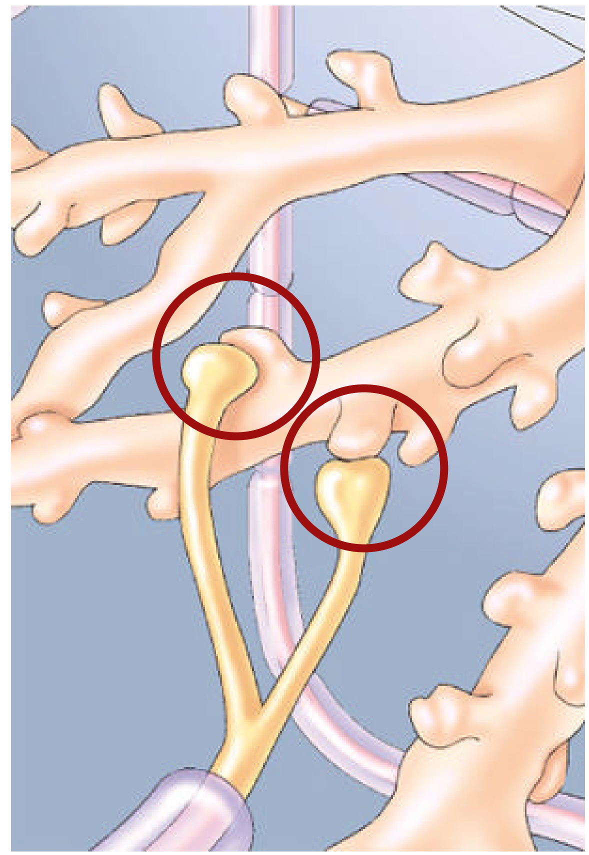
30-300

$1.5 * 10^9$

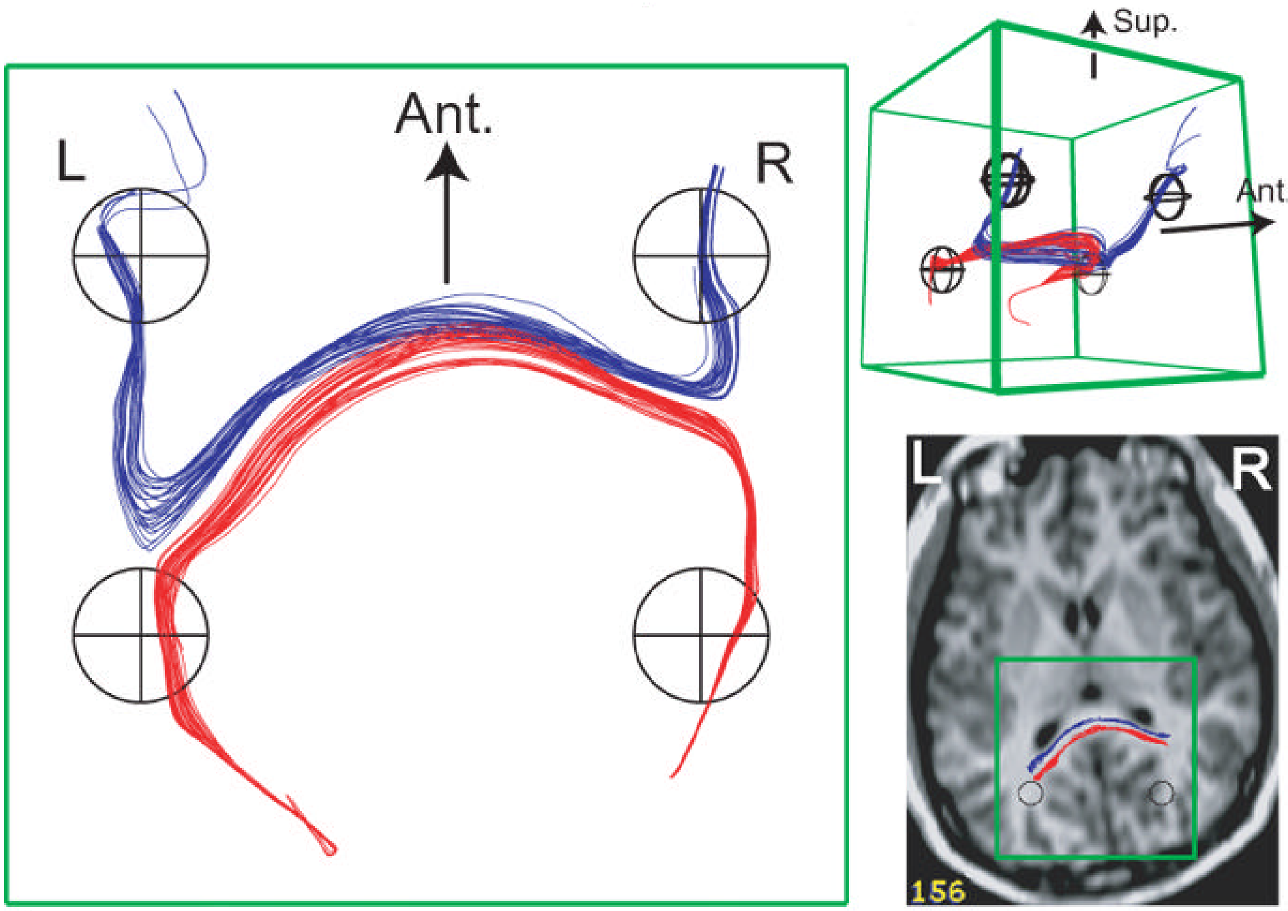
# Massive Connectivity



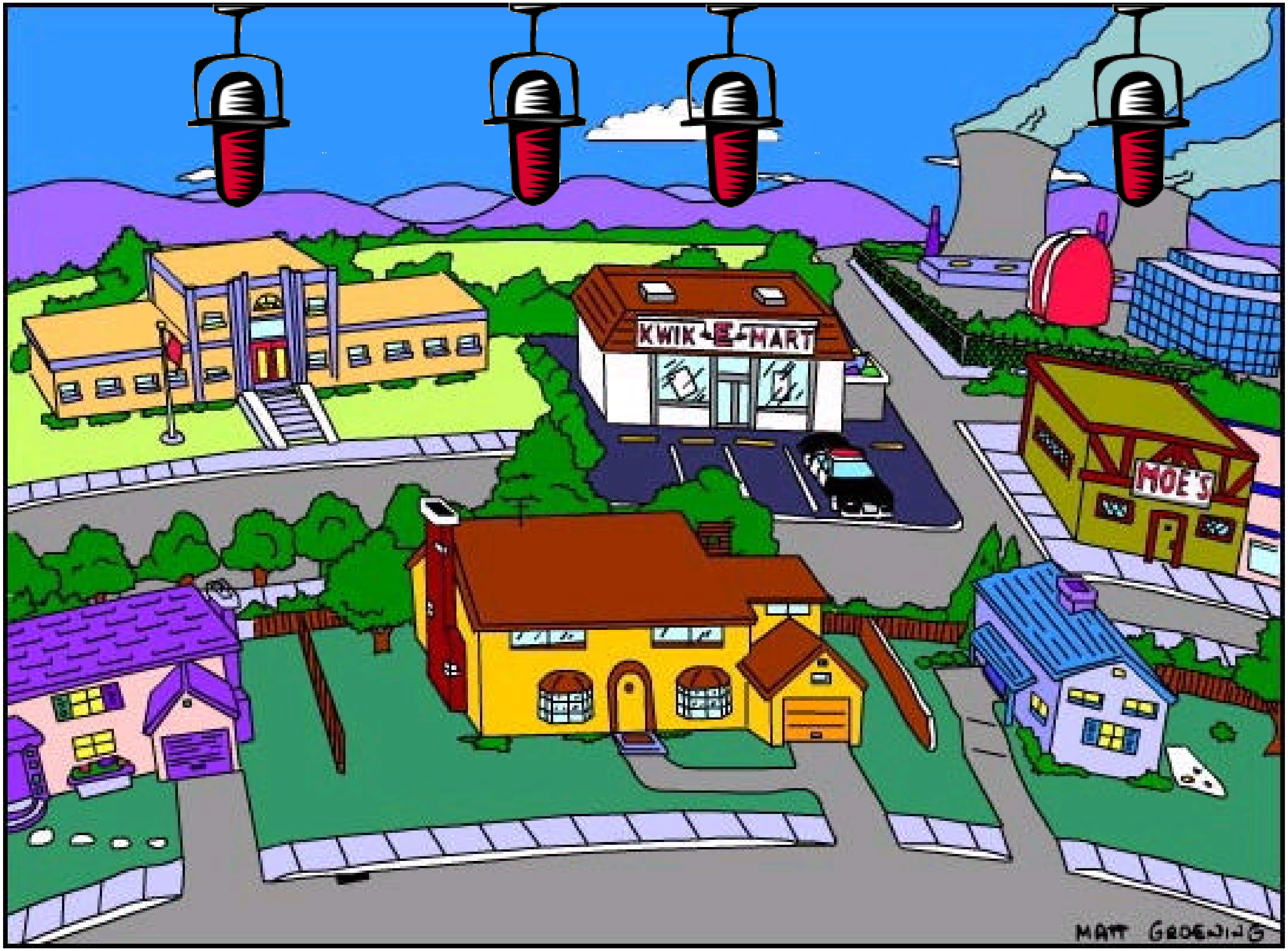

Synapses

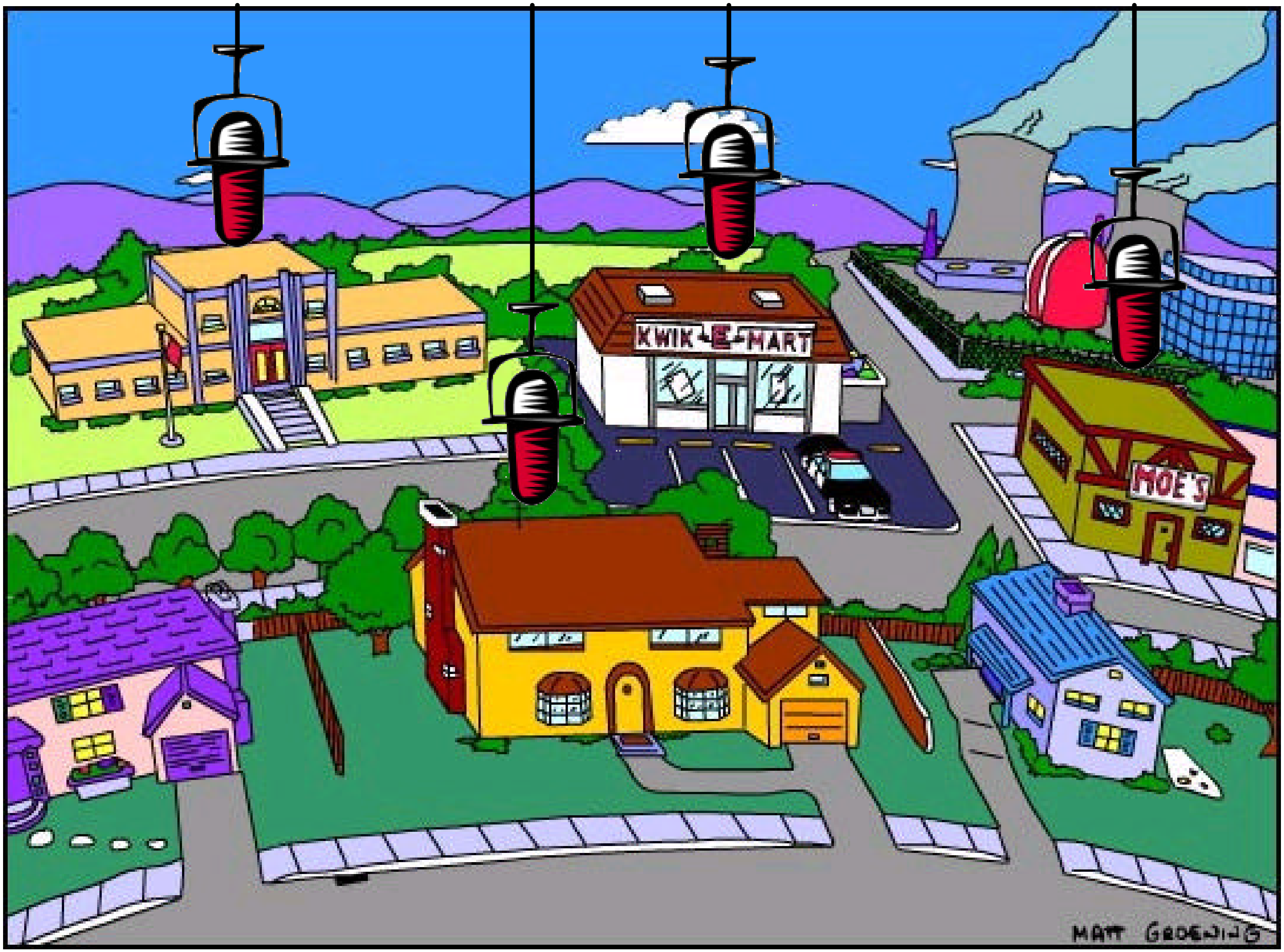


# LONG DISTANCE CALLS




*Conturo et al., 1999*


KWIK-E-MART
MOE'S
MATT GROENING


KWIK-E-MART
MOE'S
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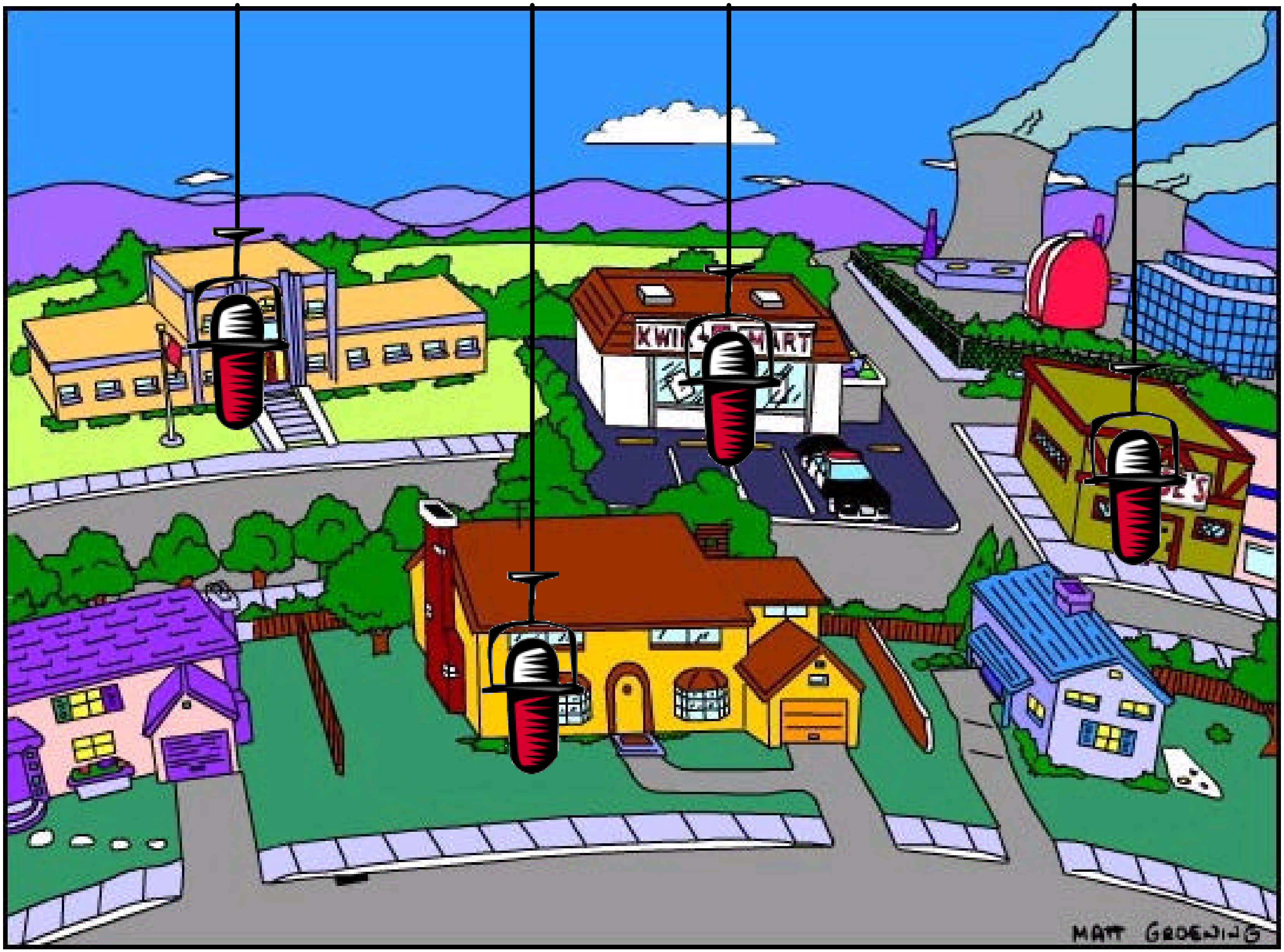
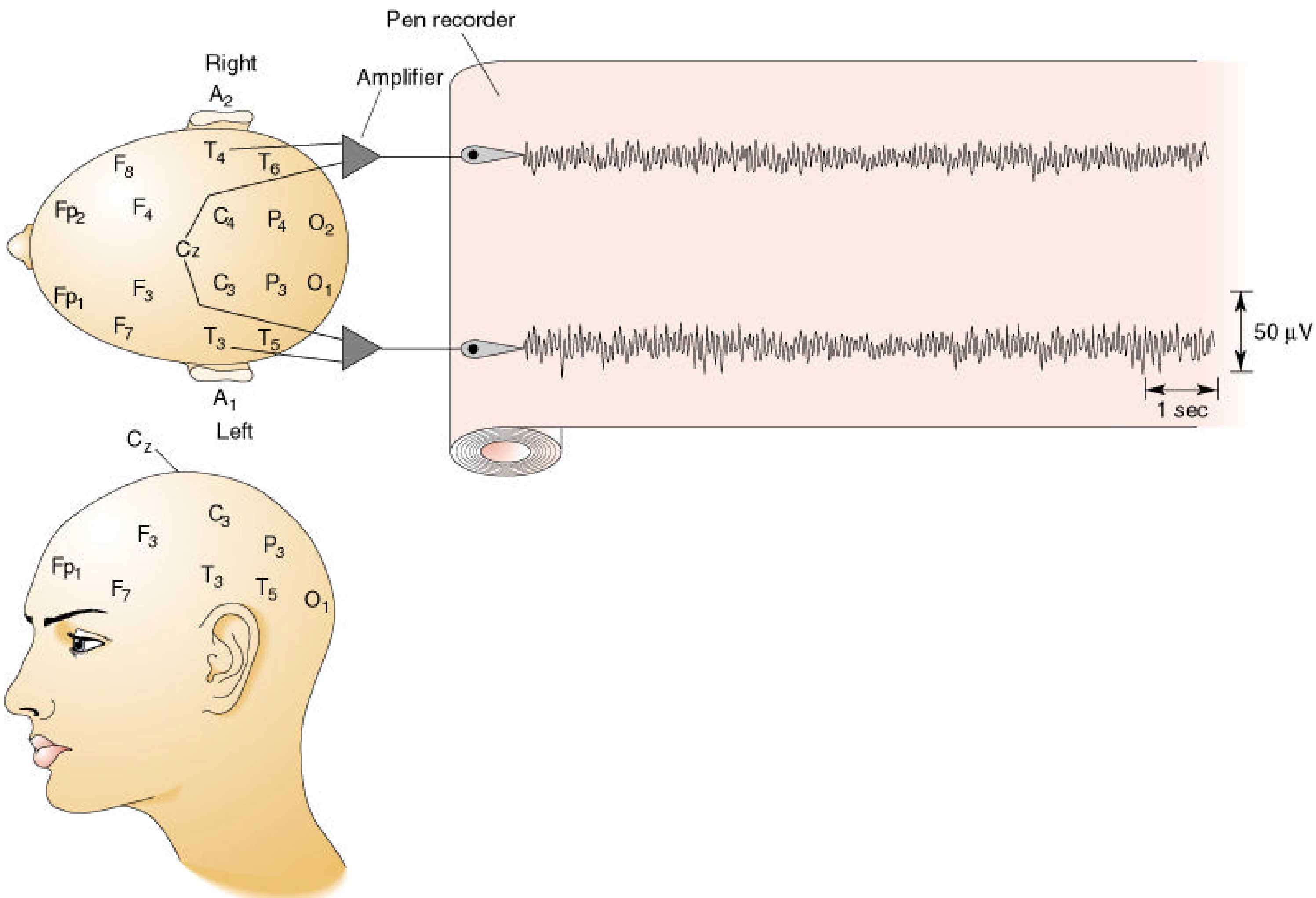
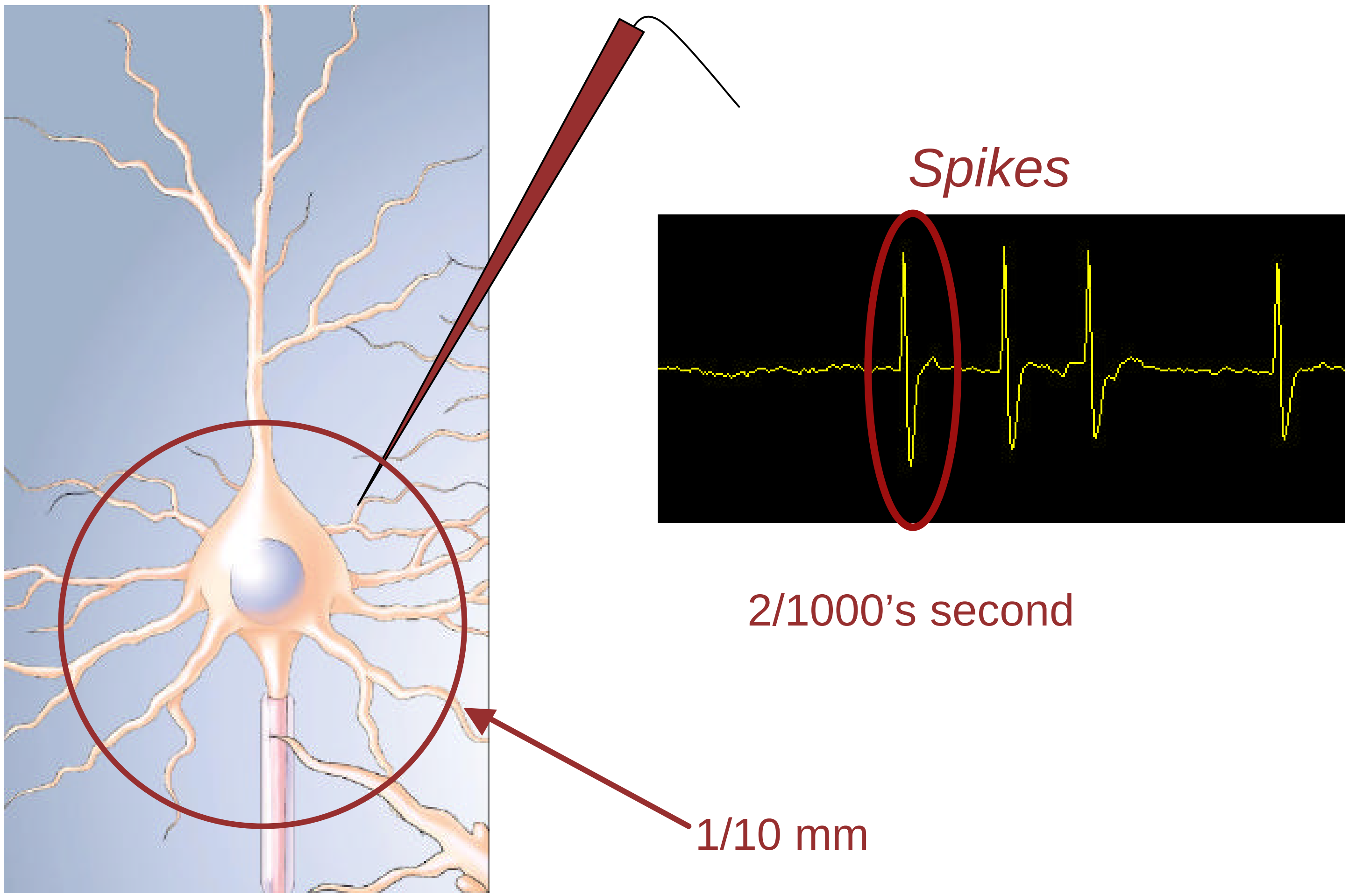

MATT GROENING

# THE EEG

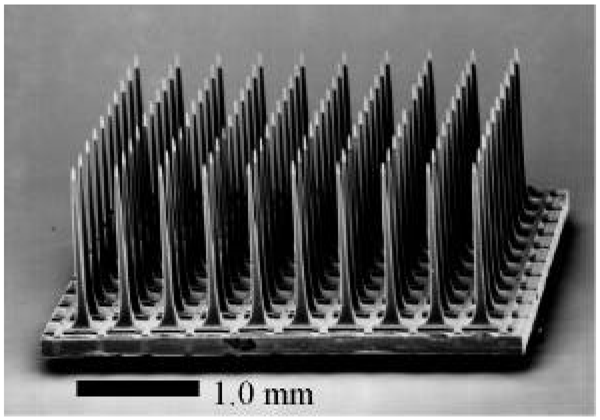


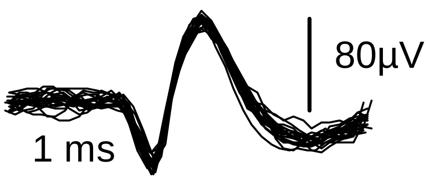
Pen recorder
Right
A2
Amplifier
T4
T6
F8
Fp2
F4
C4
P4
O2
Cz
Fp1
F3
C3
P3
O1
F7
T3
T5
A1
Left
50 µV
1 sec
Cz
C3
F3
P3
Fp1
T3
F7
T5
O1

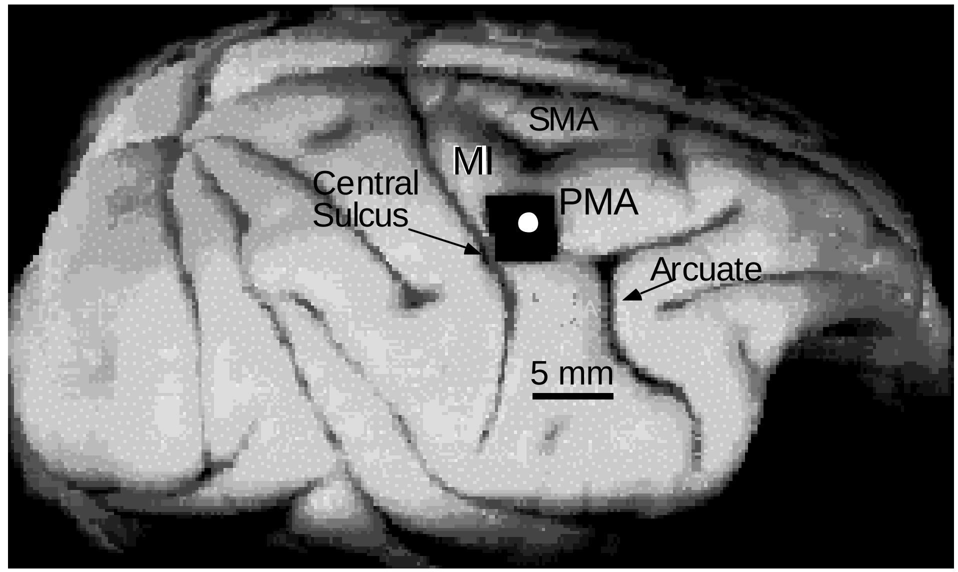
# SINGLE UNIT ACTIVITY



# Cell Ensebles



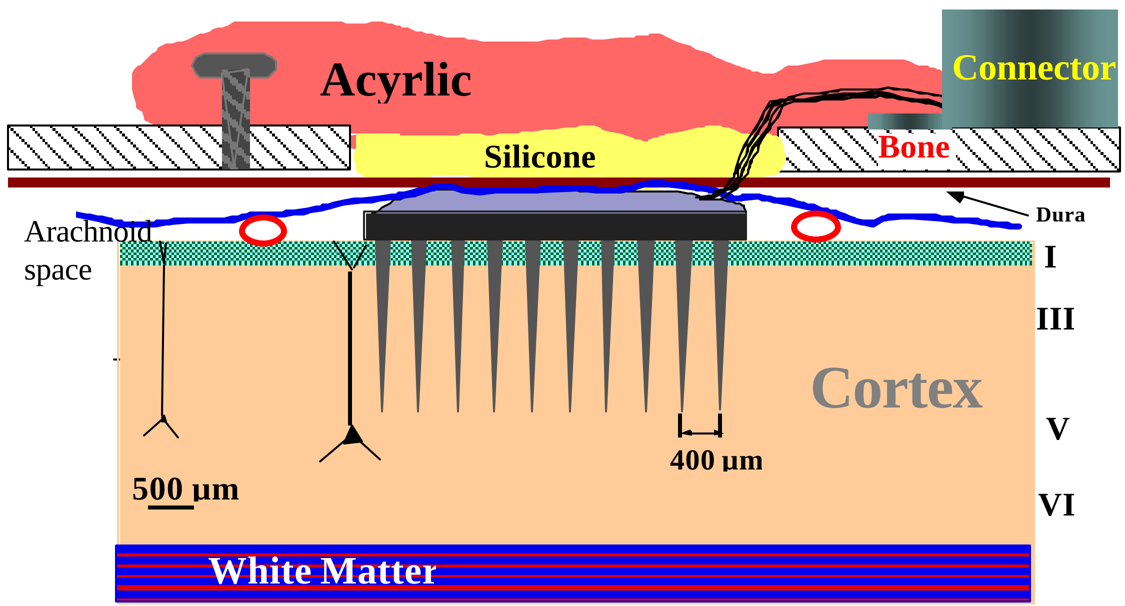

100 electrodes, 400µm separation

4x4 mm

Implanted in the MI arm area of motor cortex

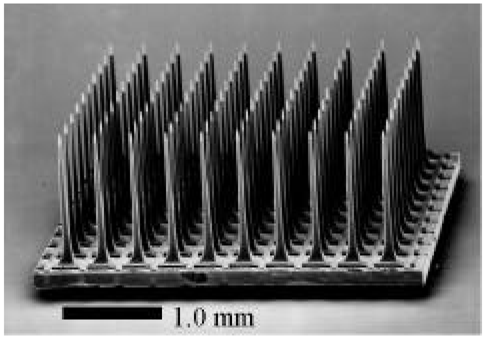
- lacks strict somatopy

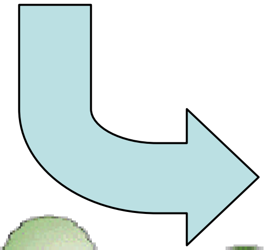
# Neural Implant

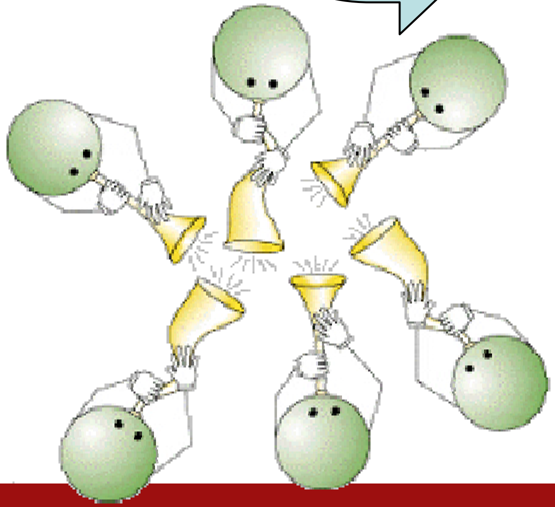


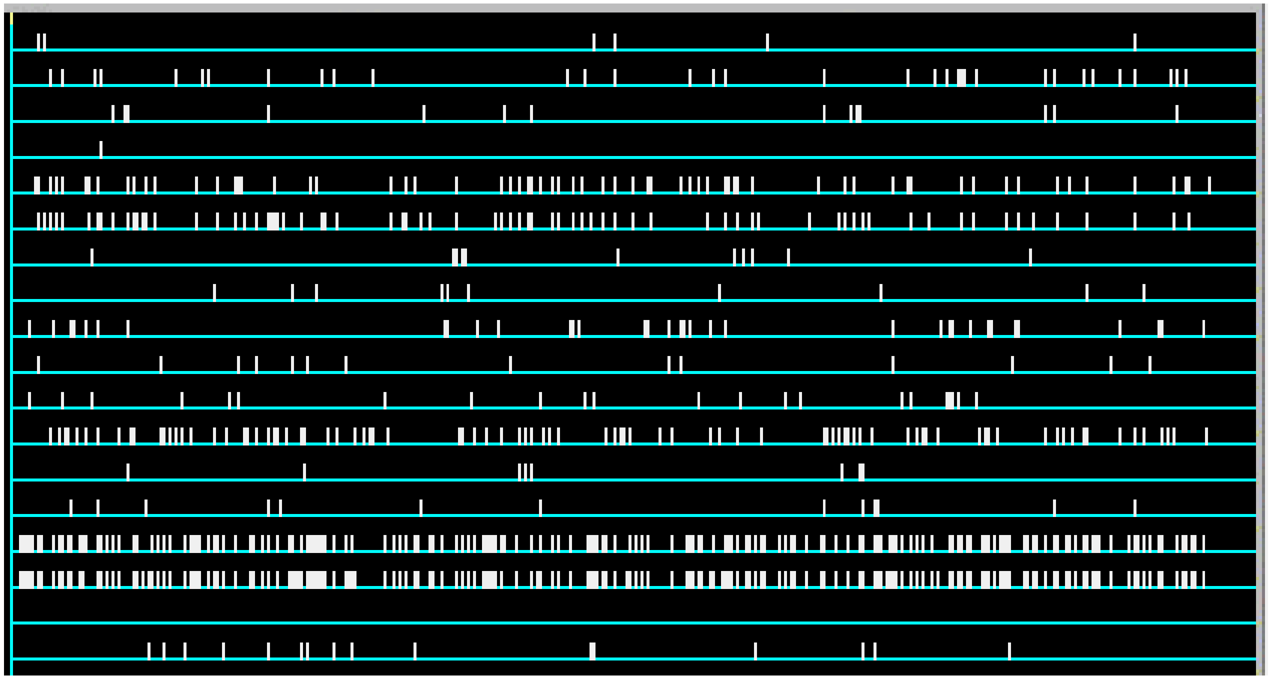

Chronically implanted.
Stable recording for 2-3 years
(but not necessarily the same cells every day)

# PATTERNS IN NEURAL ACTIVITY

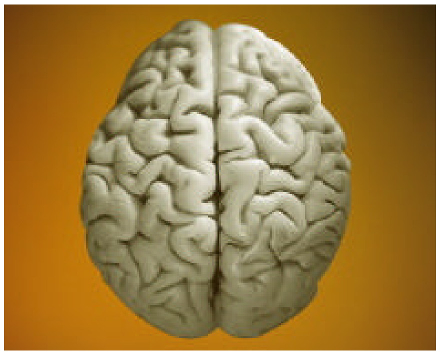


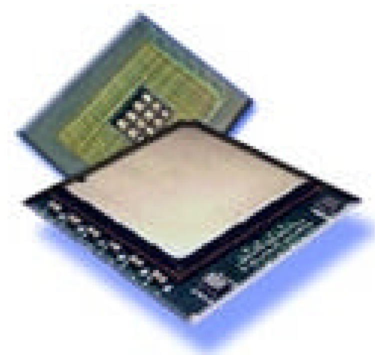





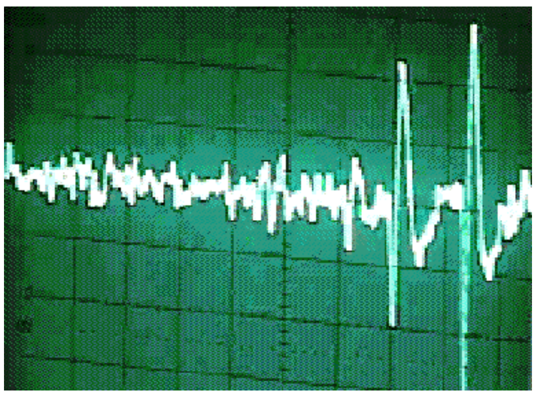


# LANGUAGE OF THE BRAIN

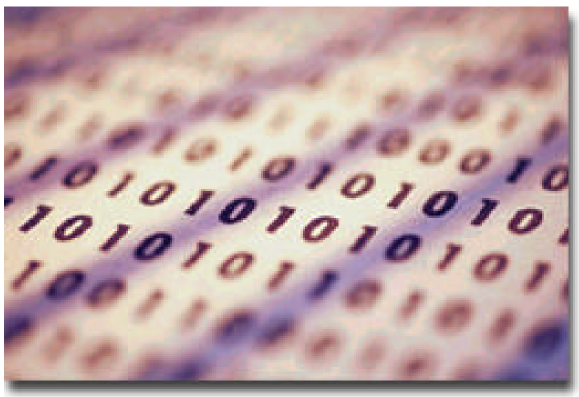




Language of the brain.



Language of the computer.

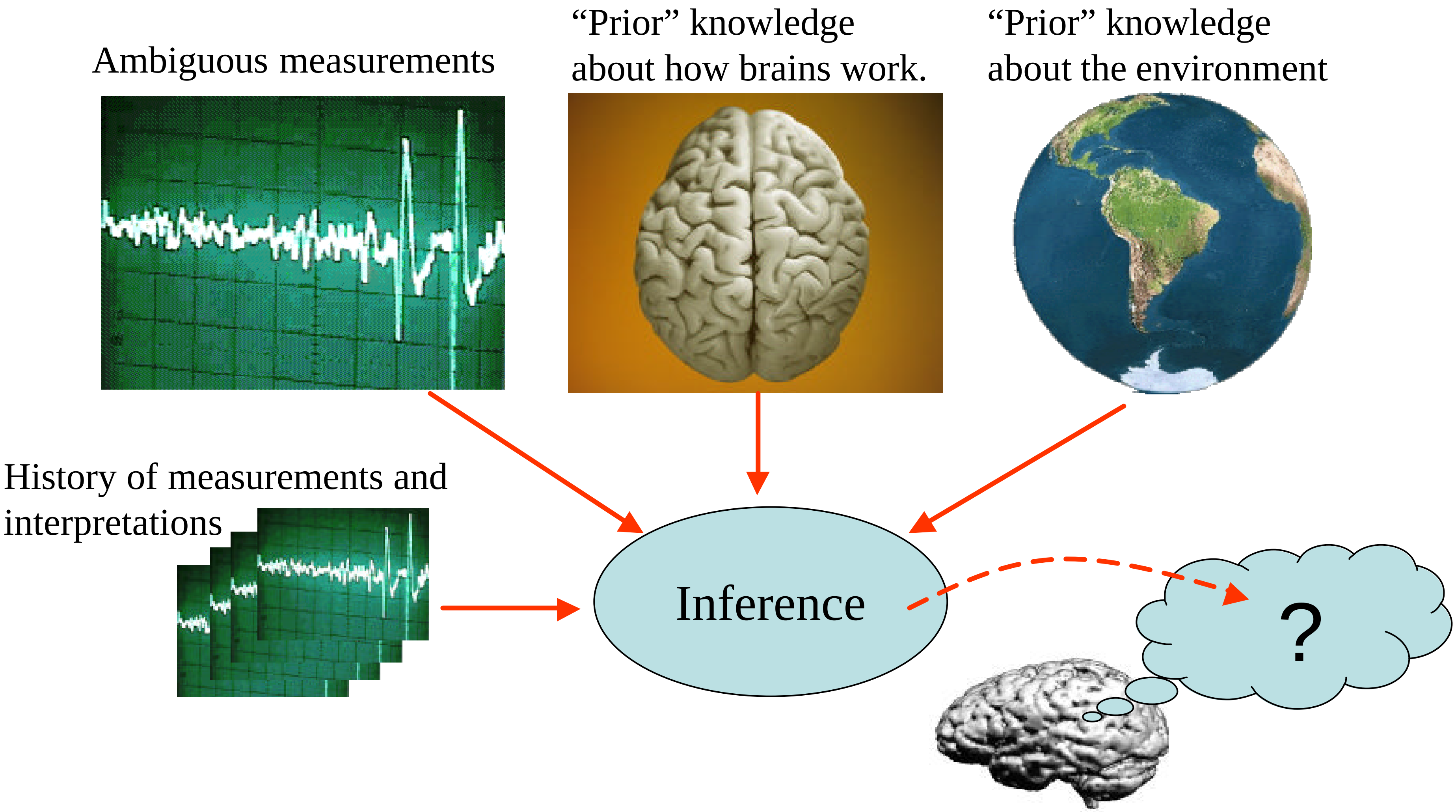


Interpretation

“Translation”

# AMBIGUOUS SIGNALS

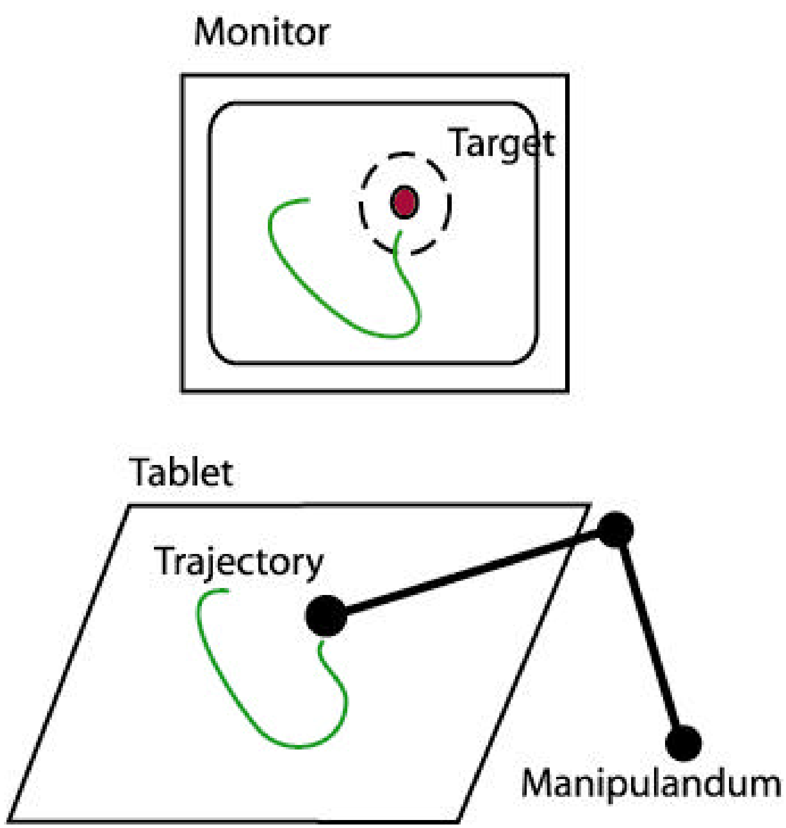
# INFERENCE


Ambiguous measurements
"Prior" knowledge about how brains work.
"Prior" knowledge about the environment
History of measurements and interpretations
Inference
?

# GOALS

* Model neural activity in motor cortex.
* Explore how the brain codes information.
* Model the statistical relationship between neural activity and action.
* Develop new statistical methods for analyzing neural codes.
* Build prosthetic devices to assist the severely disabled.
* Explore new output devices that can be controlled by brains.

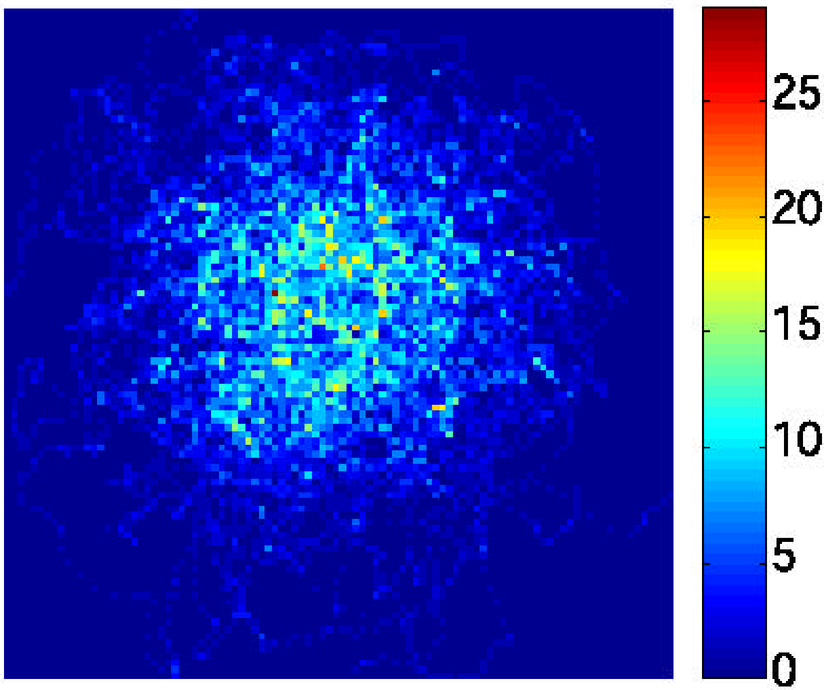
# MODELING NEURAL FUNCTION



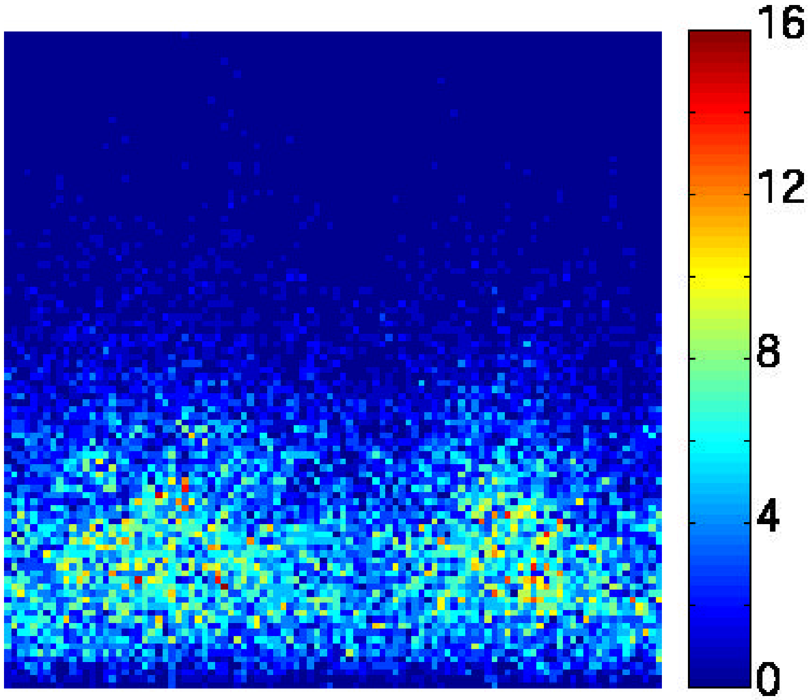

Simultaneously record hand position, velocity, and neural activity in motor cortex.

# Arm Motion

Distribution of training motions:

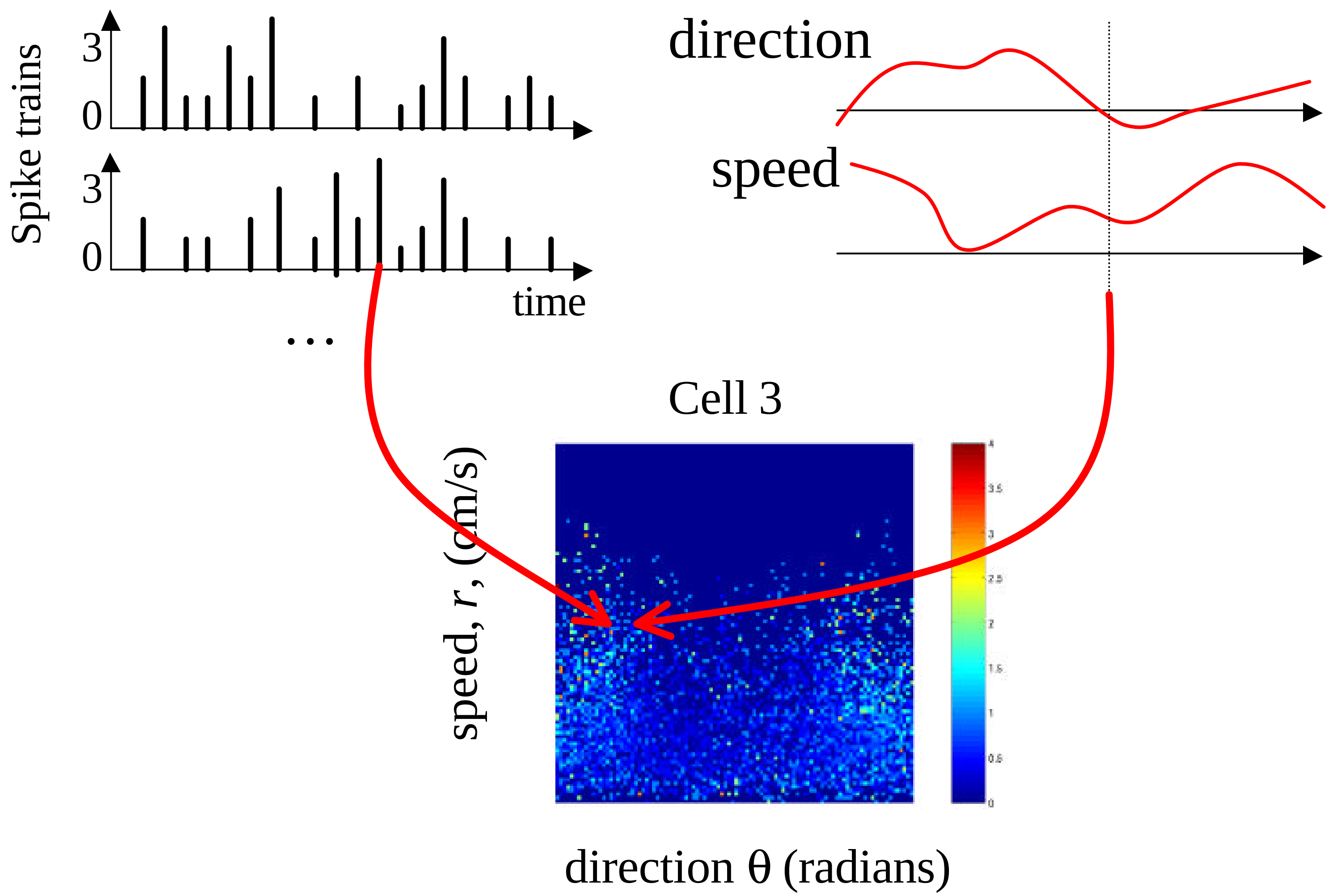



Position

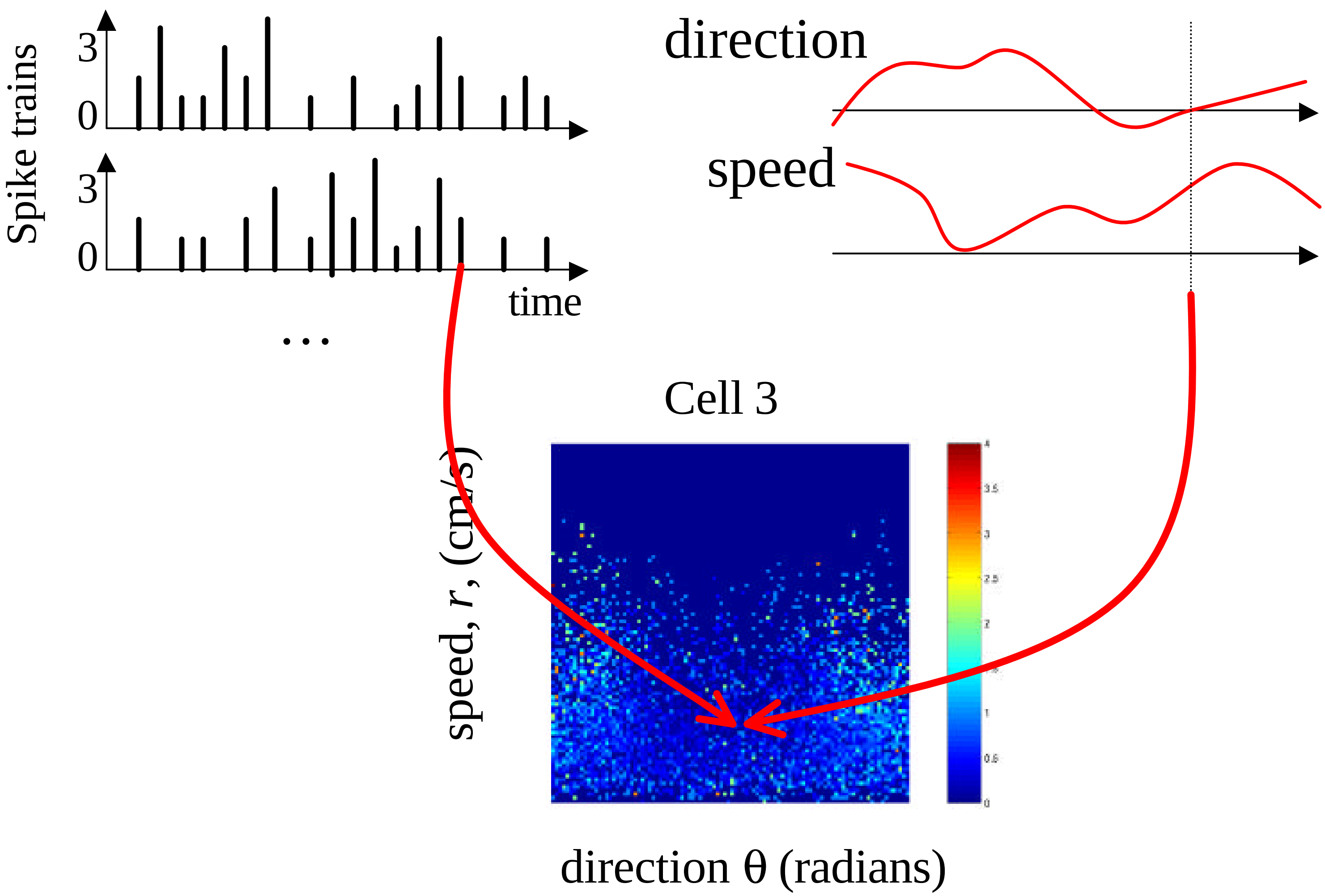



Velocity

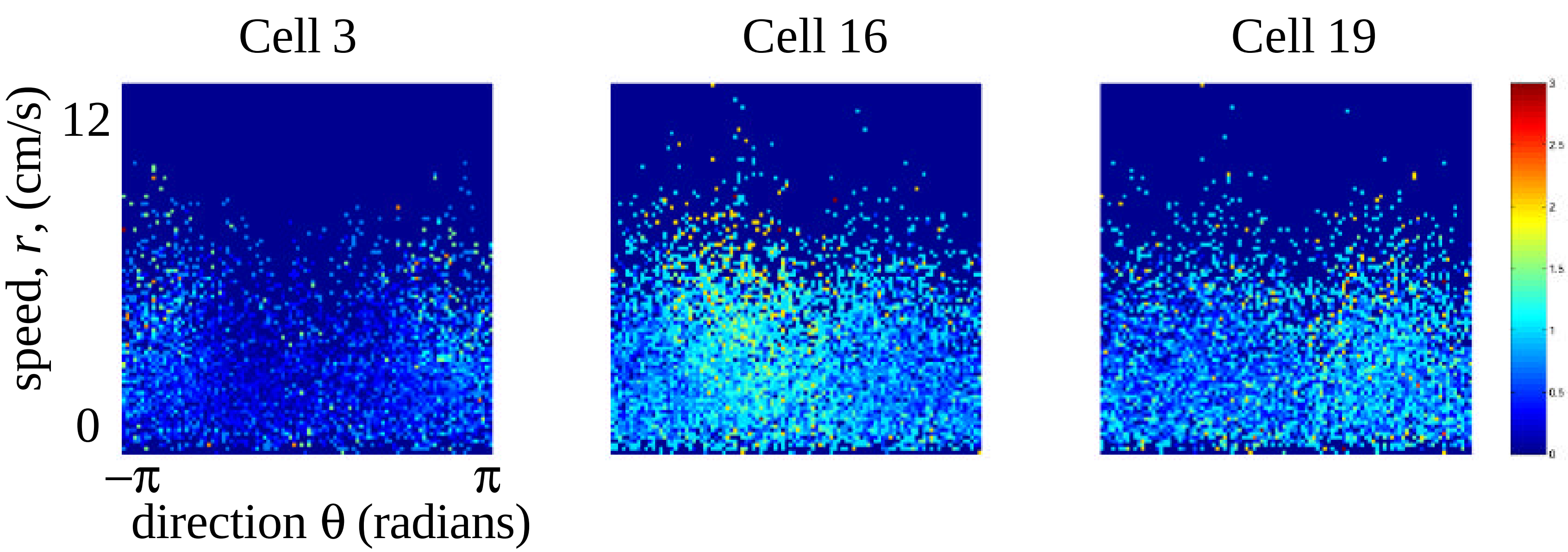
# MODELING NEURAL FUNCTION



# MODELING NEURAL FUNCTION



# NEURAL ACTIVITY




Is there some "true" underlying response function?

# NON-PARAMETRIC MODEL

$f_{\mathbf{v}}$ : Observed mean firing rate for velocity $v$

$g_{\mathbf{v}}$ : True mean firing rate for velocity $v$

$$\mathbf{v} = [r, q]^T$$

$f_{\mathbf{v}}$ is a noisy realization of the model $g_{\mathbf{v}}$

Infer $g_{\mathbf{v}}$ from $f_{\mathbf{v}}$ using Bayesian inference.

$$p(\mathbf{g} \mid \mathbf{f}) = \prod_{\mathbf{v}} \left(k\, p(f_v \mid g_v) \prod_{i=1}^{h} p(g_v \mid g_{v_i})\right)$$

*likelihood* *spatial prior*

# LIKELIHOOD

Observed firing rate modeled a sample from

*Poisson:*

$$p_P(f \mid g) = \frac{1}{f!} g^f e^{-g}$$

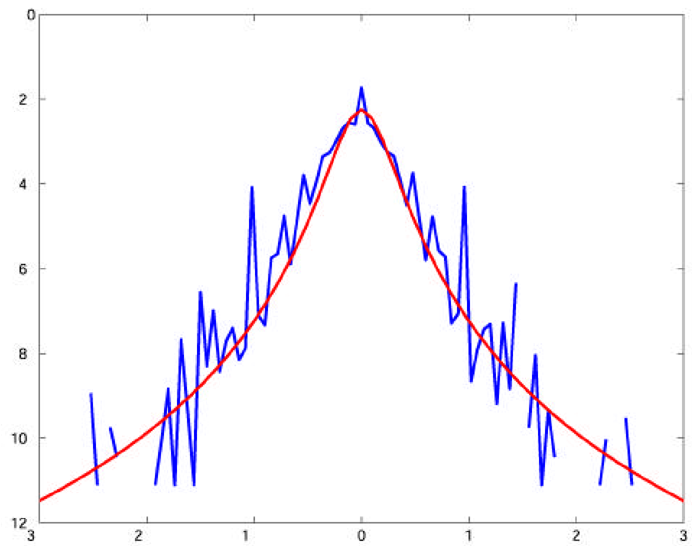
# SPATIAL PRIOR

Markov Random Field assumption

$$p(g_v \mid \mathbf{g}) = \prod_{i=1}^{h} p(g_v \mid g_{v_i})$$

T-distribution.

$$p(\Delta g) = \frac{2s^3}{p(s^2 + \Delta g^2)^2}$$



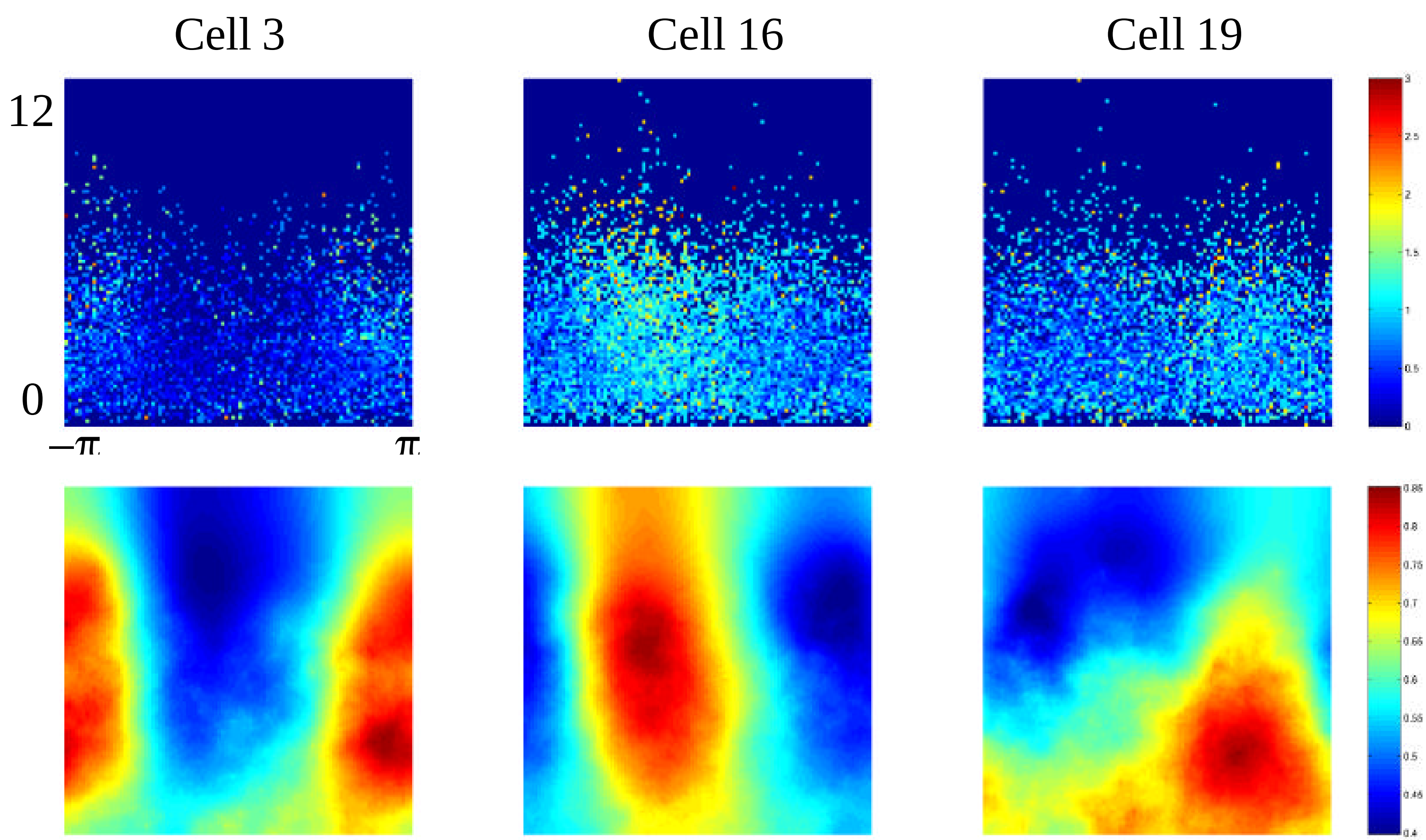
# OPTIMIZATION

Many ways to maximize over $g_v$

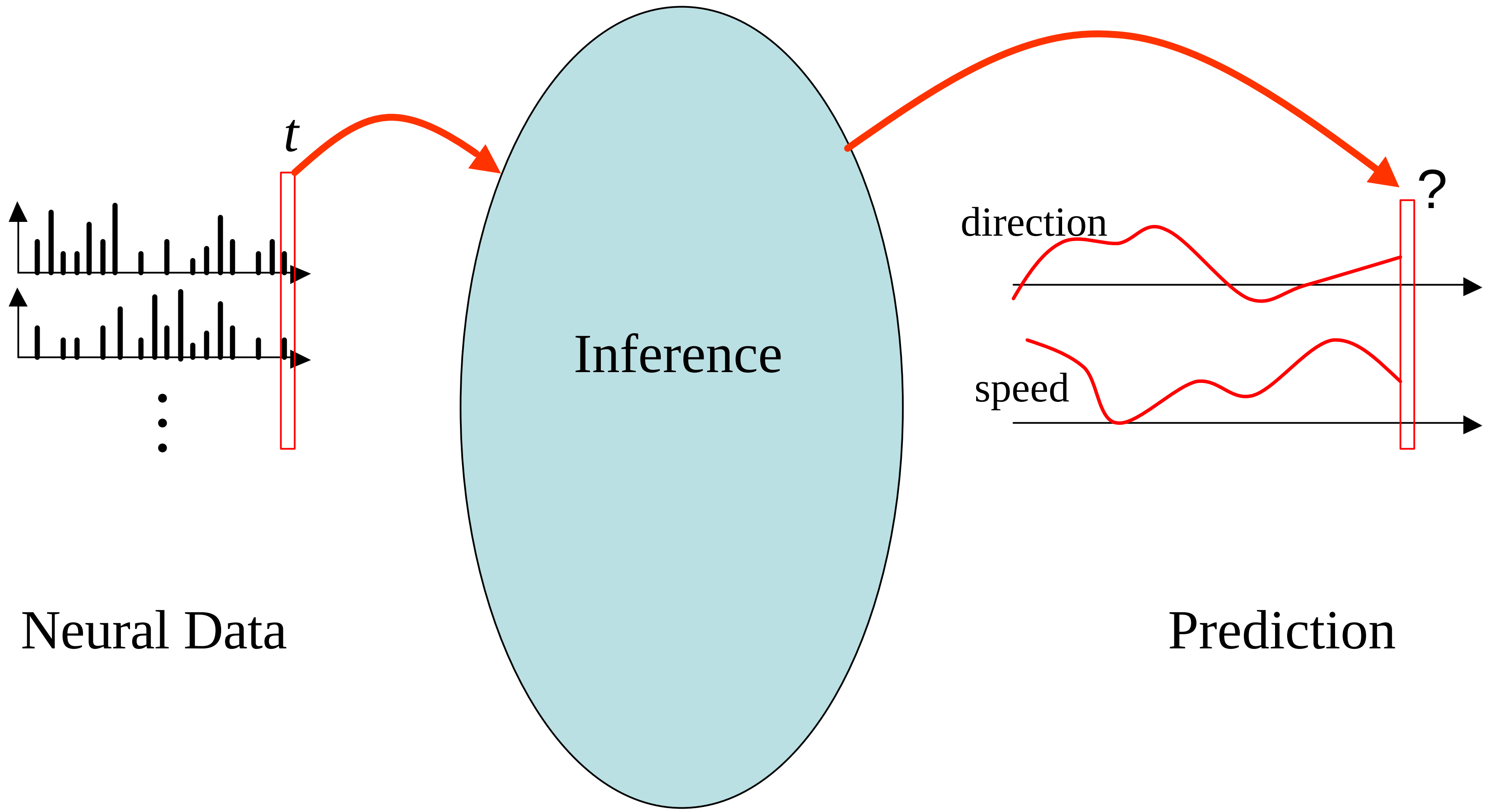
$$p(\mathbf{g} \mid \mathbf{f}) = k \prod_v p(f_v \mid g_v) p(g_v \mid \mathbf{g})$$

- Simulated annealing, etc.
- We exploit an approximate deterministic regularization method.
  - Take the negative log of $p(\mathbf{g} \mid \mathbf{f})$
  - Minimize using gradient descent
  - Not ideal (loopy propagation, see Yedidia, Freeman, & Weiss, NIPS'00).

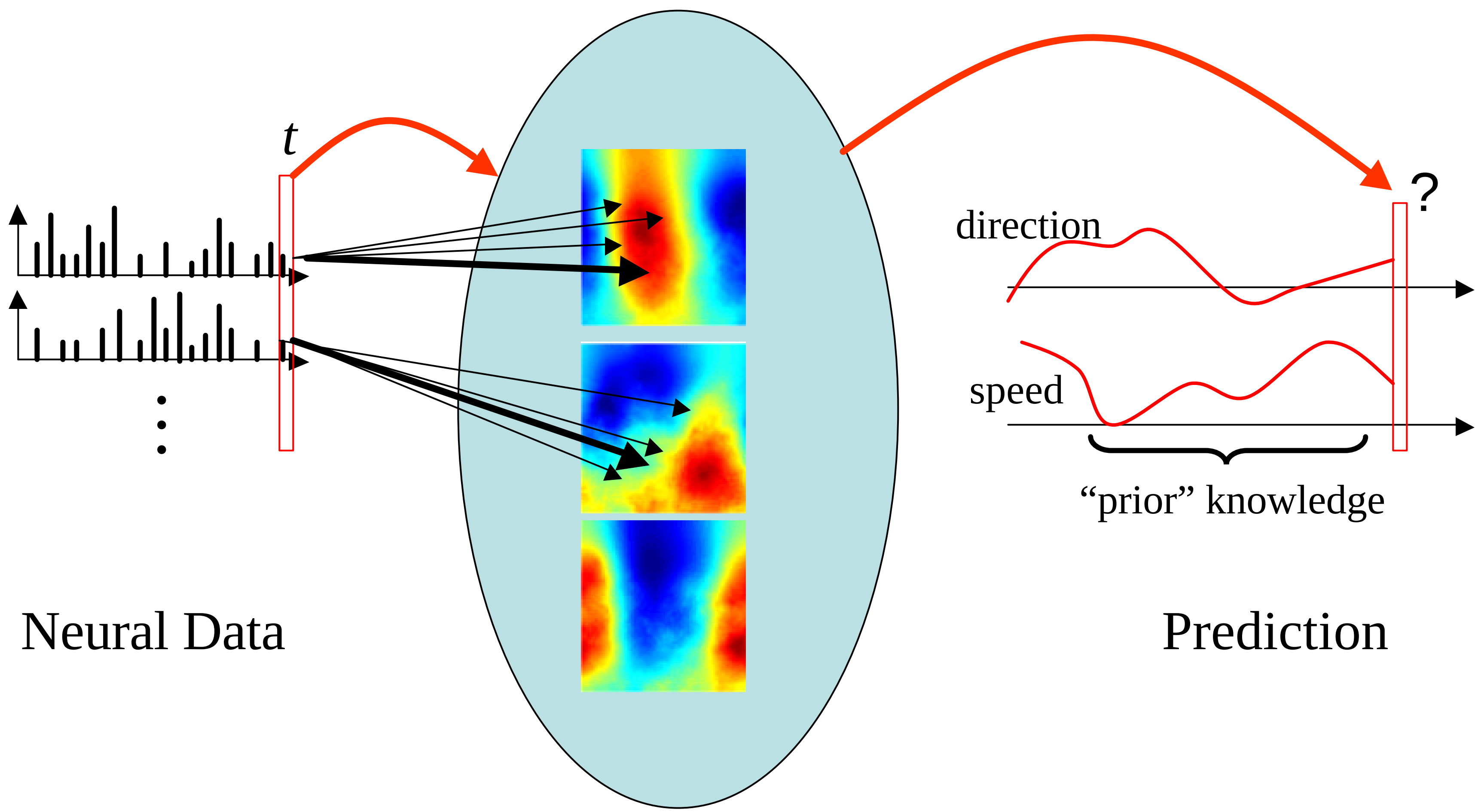
# Poisson+Robust



# INFERENCE FROM ACTIVITY



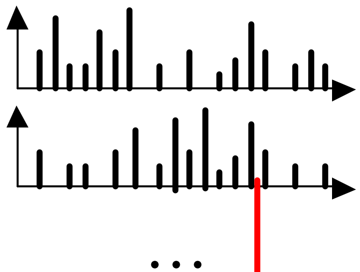
# INFERENCE FROM ACTIVITY



# GOALS

- sound probabilistic inference
- causal
- estimate over short time intervals to reduce lag
- cope with non-linear dynamics of hand motion
- cope with ambiguities (multi-modal distributions)
- more realistic firing models (Poisson or Poisson+refractory period [Kass&Venture, Neural Comp. '01])
- support higher level analysis of activities

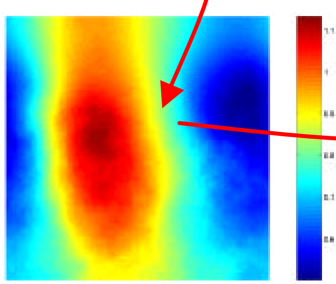
# Bayesian Inference



$$p(\mathbf{s}_t \mid \mathbf{C}_t) = k_2\, p(\mathbf{c}_t \mid \mathbf{s}_t)\, p(\mathbf{s}_t \mid \mathbf{C}_{t-1})$$

*likelihood*

$$p(\mathbf{c}_t \mid \mathbf{s}_t) = \prod_{i=cells} \frac{1}{c_{i,t}!}\, g_{\mathbf{s}_t}^{\;c_{i,t}}\, e^{-g_{\mathbf{s}_t}}$$



Want to infer state of hand $\mathbf{s}_t = [r, q]$ given the activity, $\mathbf{C}_t$, of (~25 cells) up to time *t*.

# BAYESIAN INFERENCE

$$p(\mathbf{s}_t \mid \mathbf{C}_t) = k_2\, p(\mathbf{c}_t \mid \mathbf{s}_t)\, p(\mathbf{s}_t \mid \mathbf{C}_{t-1})$$

*prior*

$$p(\mathbf{s}_t \mid \mathbf{C}_{t-1}) = \int p(\mathbf{s}_t \mid \mathbf{s}_{t-1})\, p(\mathbf{s}_{t-1} \mid \mathbf{C}_{t-1})\, d\mathbf{s}_{t-1}$$

Temporal dynamics
(constant velocity)

# PARTICLE FILTER

Represent posterior with a discrete set of N states and their normalized likelihood.

Posterior

$$p(\mathbf{s}_{t-1} | \mathbf{C}_{t-1})$$

sample →

Temporal dynamics

$$p(\mathbf{s}_t | \mathbf{s}_{t-1})$$

↓ sample

$$p(\mathbf{c}_t | \mathbf{s}_t)$$

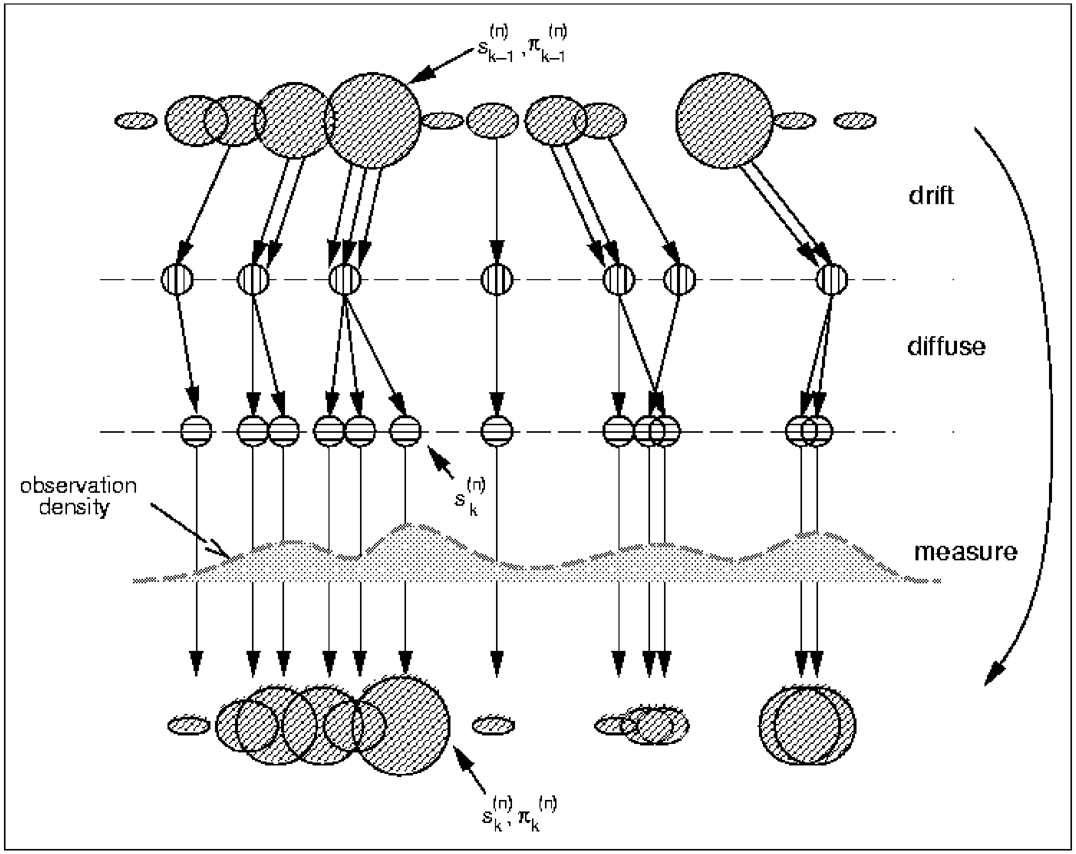
Likelihood

← normalize

$$p(\mathbf{s}_t | \mathbf{C}_t)$$

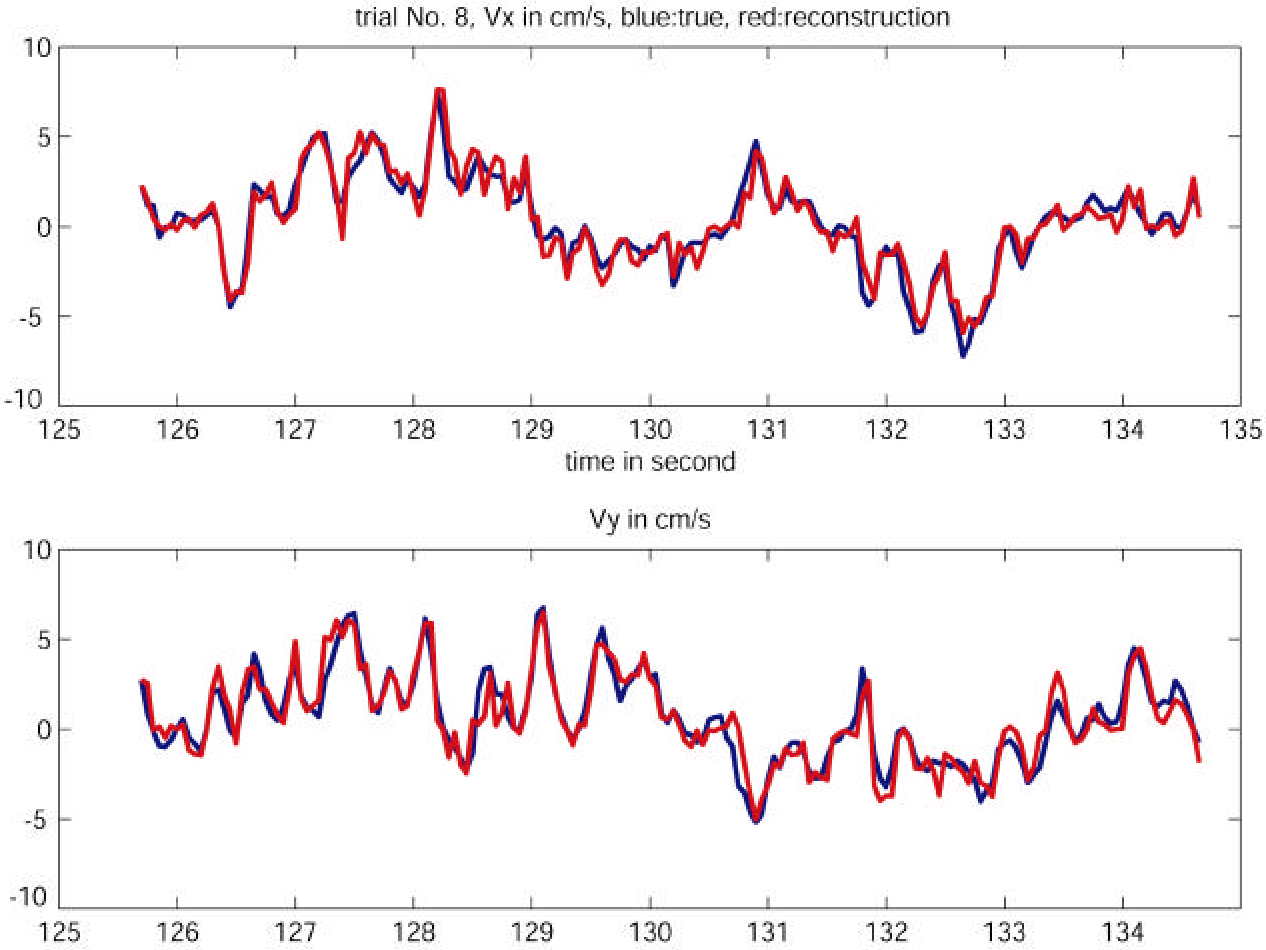
Posterior

# PARTICLE FILTER




Isard & Blake '96

# 1000 "SYNTHETIC" CELLS

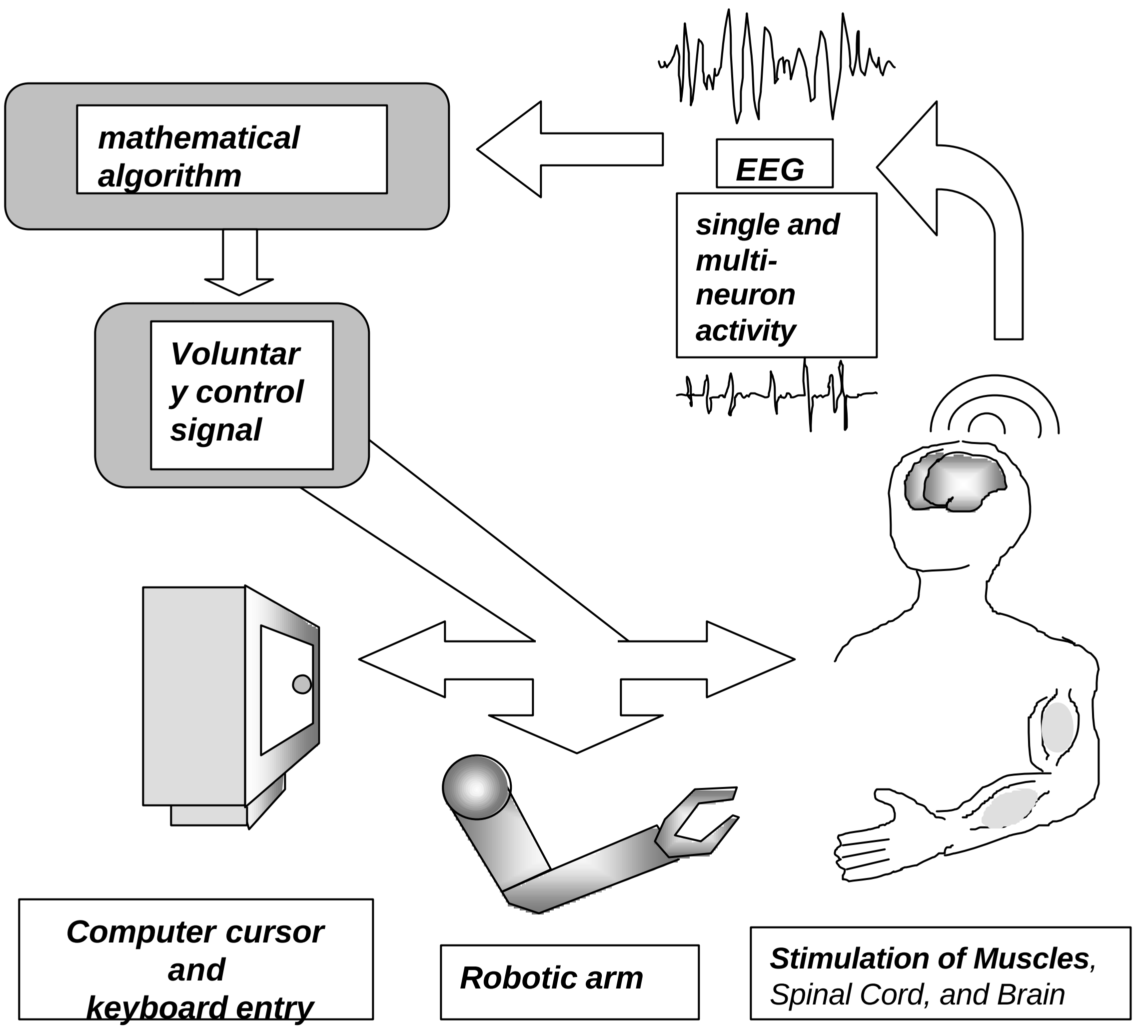



Particle filtering in 50 ms:

$v_x$: $r^2 = 0.8746$

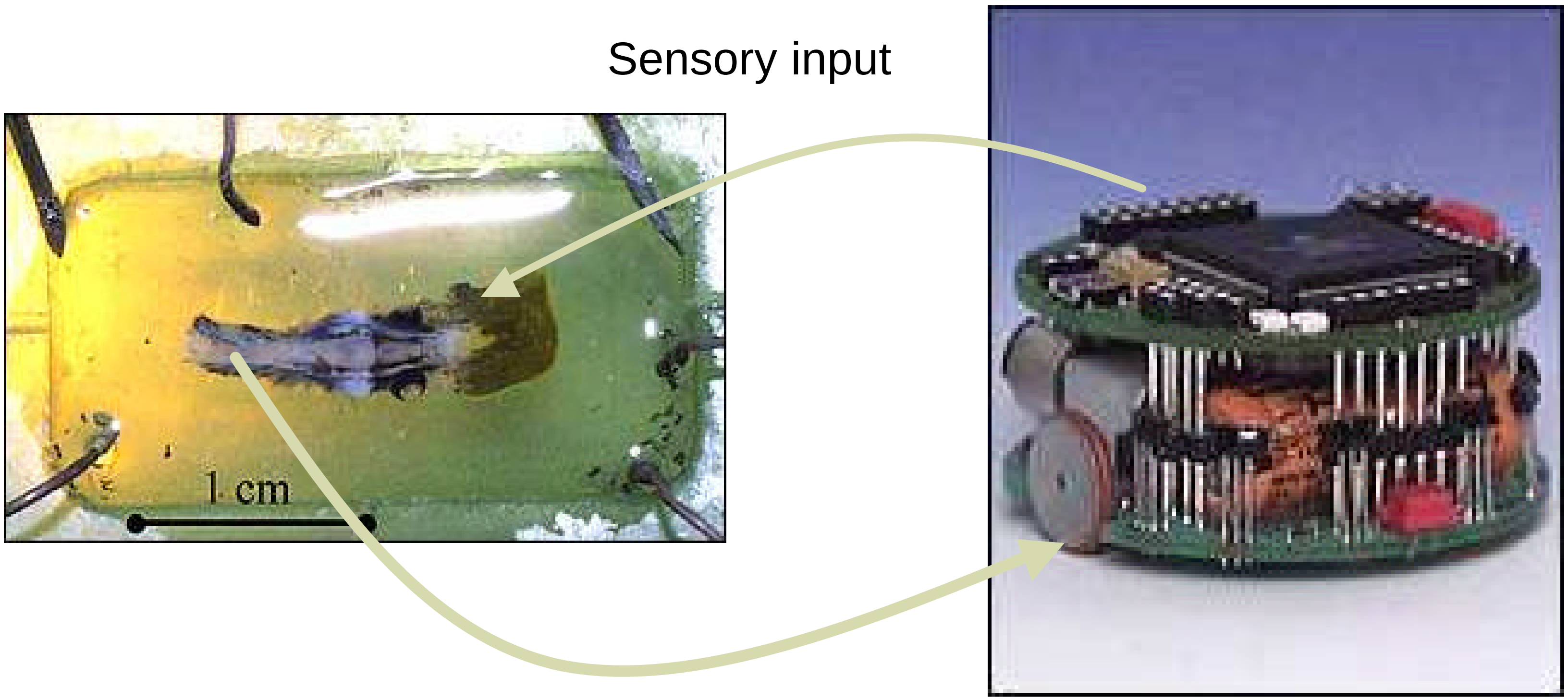
$v_y$: $r^2 = 0.9033$

# A Neural Prosthetic



# Neural-Prosthetic Limbs

# HYBRID SYSTEMS




Connecting Brains to Robots, Reger et al, Artificial Life, 2000.

# BRAIN/MACHINE HYBRIDS

- Explore biological sensory/control systems with artificial systems.
- Develop computational models of biological control.
- Re-map input modalities.
- Opportunity for robotic prostheses.
- Augment limited neural control with autonomy (eg. obstacle avoidance).

# Our Bodies Ourselves?

- Service robots under neural control.
- Sensation and action at a distance.
- Stimulating the brain.

Probotics/Jim Judkis

Ethics, liminality, fear, and the “uncanny”.

Honda robot

# THANKS

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