Prof. Kay Tye
9.17

Roach Week

(Section 4)

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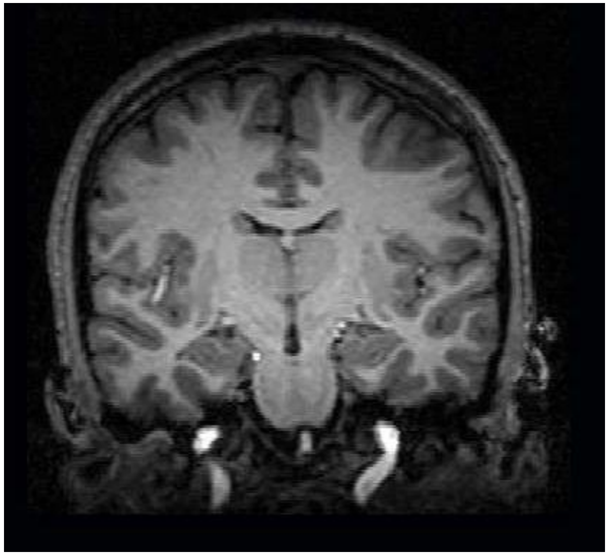
Neuroanatomy: Who talks to whom?



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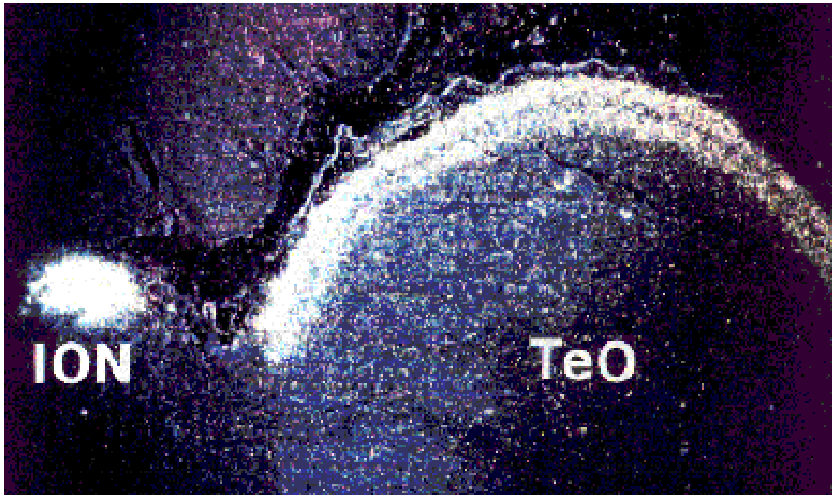

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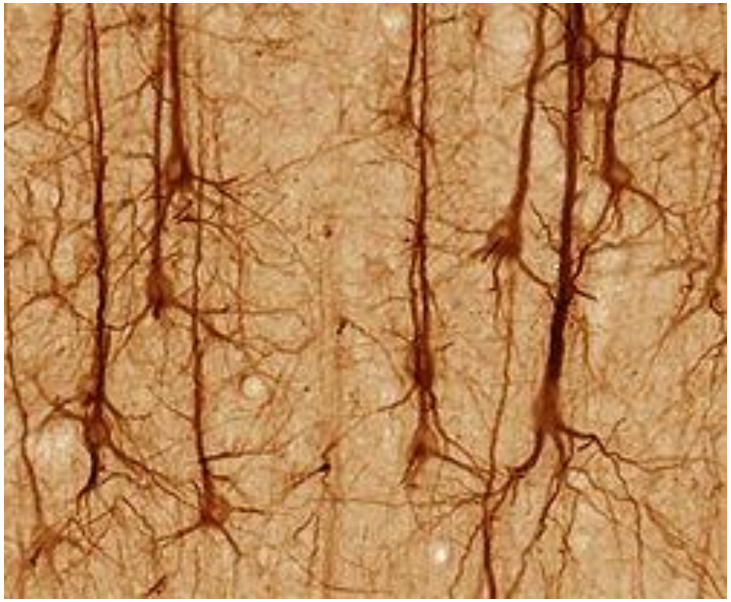


Image: brainmaps.org CC BY.

Neuroanatomy: Who talks to whom?

Cellular physiology: How do they speak?

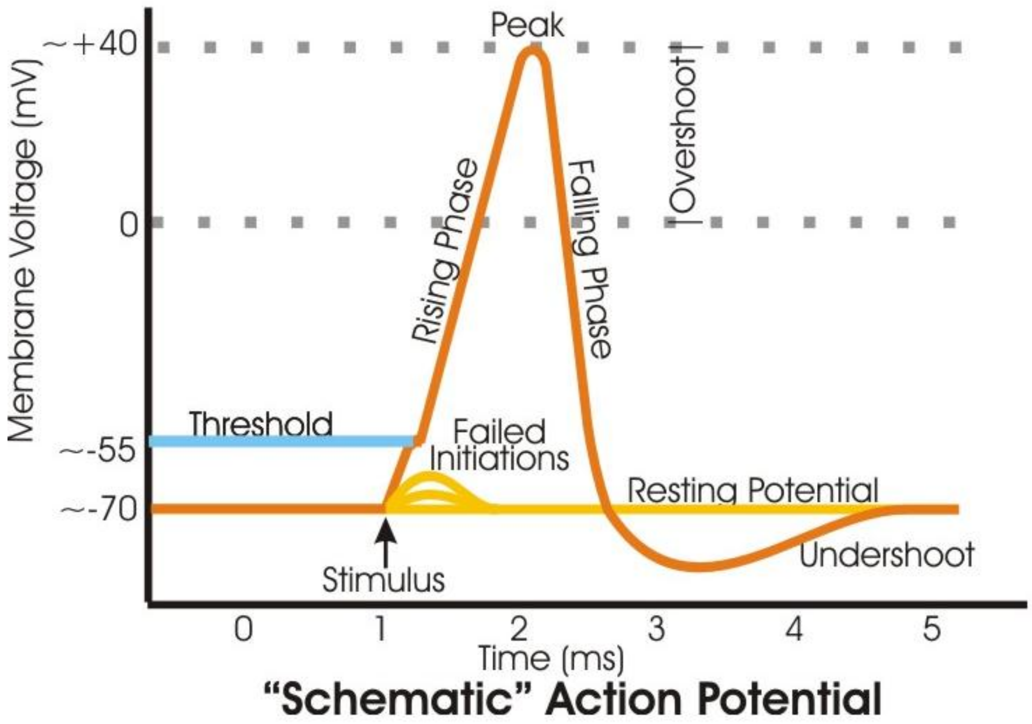


Figure of eddy current depolarization of an unmyelinated fiber removed due to copy right restrictions. See Raffe, Marc R. "Principles of Peripheral Nerve Repair" Chapter 65 in Textbook of Small Animal Orthopaedics. Edited by Charles D. Newton and David M. Nunamaker. J. B. Lippincott Company, 1985.

Neuroanatomy: Who talks to whom?

Cellular physiology: How do they speak?

Systems physiology: What are they saying?

The currency of neurons:
ACTION POTENTIALS (spikes, firing)

Terms like
- Information
- Representation
- Coding

have real, fairly specific meanings.

I. Why focus on sensory processing?

II. Information

- Units: Action Potentials
- Rate coding

III. The roach nervous system

The sensory-motor arc

“higher”
functions

sensory
processing

motor
processing

sensory
transduction

motor
output

stimulus

action

The sensory-motor arc

“higher”
functions

sensory
processing

motor
processing

sensory
transduction

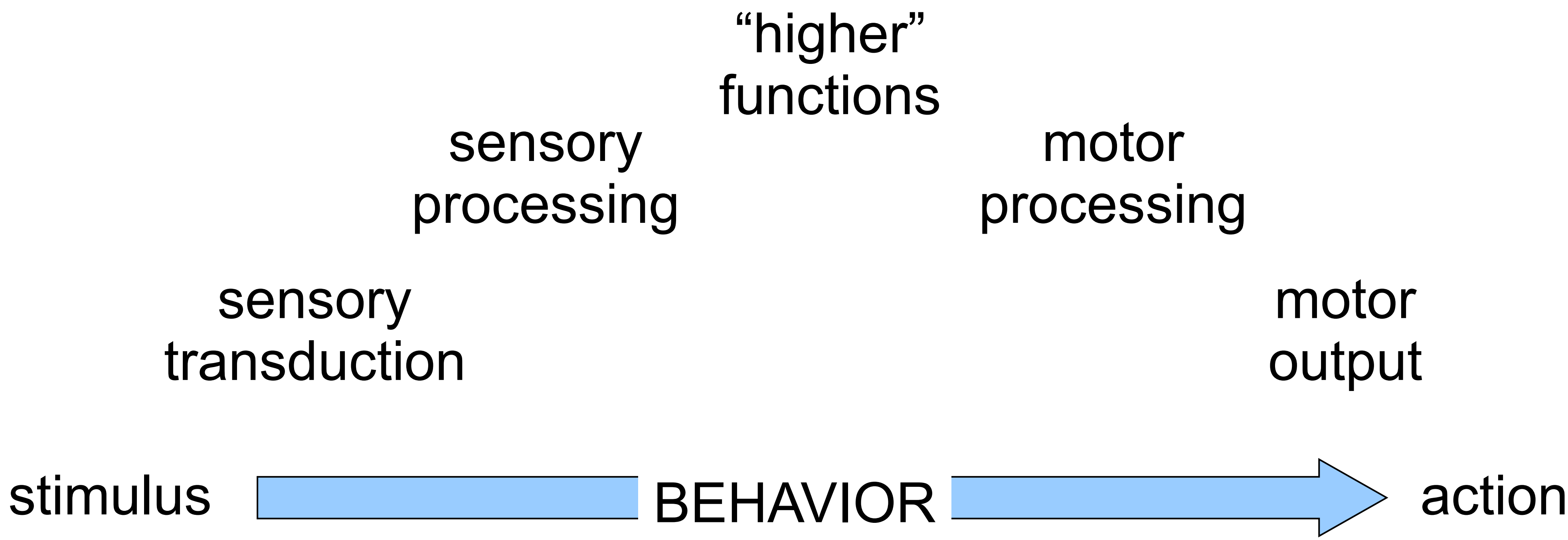
e.g. reflexes,
eye movements

motor
output

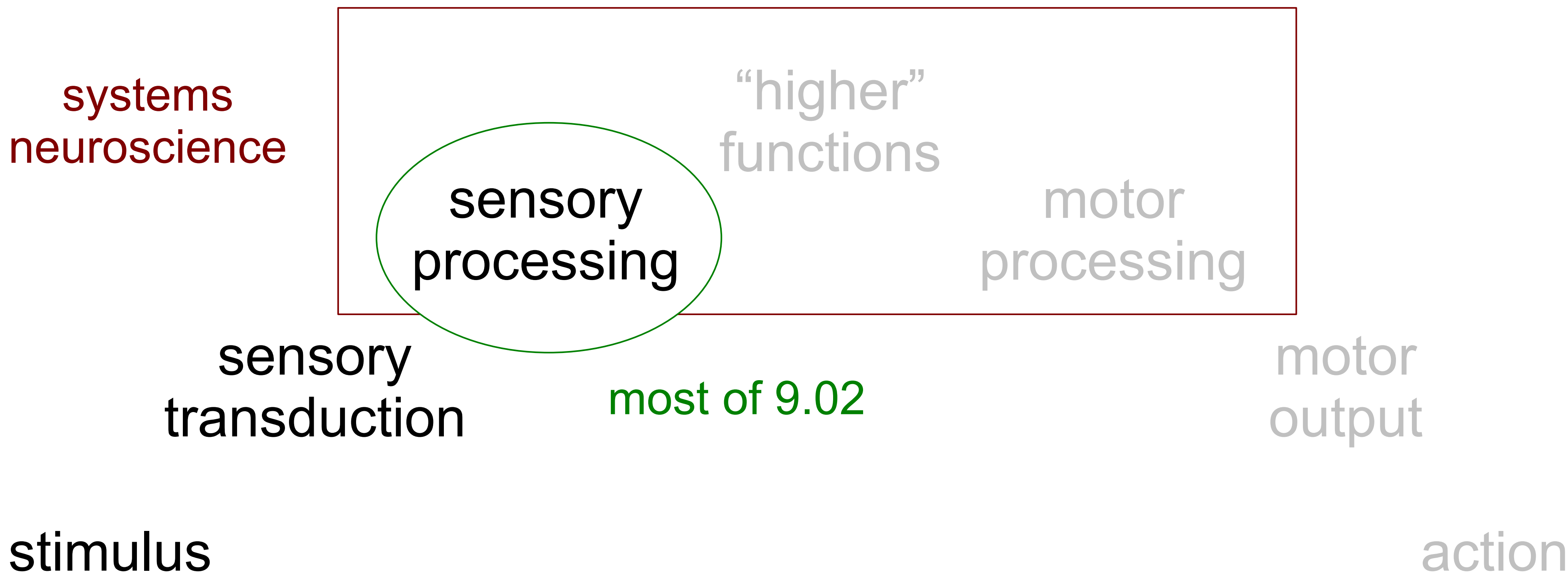
stimulus

action

The sensory-motor arc



The sensory-motor arc



<u>Why the emphasis on sensory processing?</u>

1) Works in anesthetized animals

2) Good control of the "real-world" variable, the stimulus

The nervous system as an information-processing machine.

Information can be quantified.

The *mutual information* between stimulus and neural response can be quantified.

In most cases, we consider neurons to be *rate coding* for a particular aspect of the stimulus.

What could a downstream cell learn by listening to this cell?

Show me the units

Behavior	success rate (% of trials) time engaged in activity (s)
Systems physiology	information (bits) ← In theory! spike rate (spikes/s) ← In practice...
Cellular physiology/ biophysics	voltage (mV) current (nA) conductance (μS)
Biochemistry/ molecular biology	concentration (μM) reaction rate (molecules/s) phosphorylation (% of molecules)

The Action Potential

Figure of the transmission of a nerve impulse: resting potential and action potential removed due to copyright restrictions. See http://www.dummies.com/how-to/content/understanding-the-transmission-of-nerve-impulses.html.

ON QUIZ!

http://www.youtube.com/watch?v=ifD1YG07fB8

The Action Potential: from inside and out

Figure 2. Relationship between intracellular and extracellular electrical activities and contractile activity removed due to copyright restrictions.
See Sarna, Sushil K. "In Vivo Myoelectric Activity: Methods, Analysis, and Interpretation." *Comprehensive Physiology Supplement* 16 (2011): 817-63. doi: 10.1002/cphy.cp060121.

The Action Potential: from inside and out

Quiz: What is different about action potentials recorded intracellularly and extracellularly?

Fig. 1. Simultaneous intracellular and extracellular recording from a CA1 pyramidal cell removed due to copyright restrictions. See Henze, Darrell A., Zsolt Borhegyi, et al. "Intracellular Features Predicted by Extracellular Recordings in the Hippocampus In Vivo." *Journal of Neurophysiology* 84, no. 1 (2000): 390-400.

Myelin: What is it FOR?

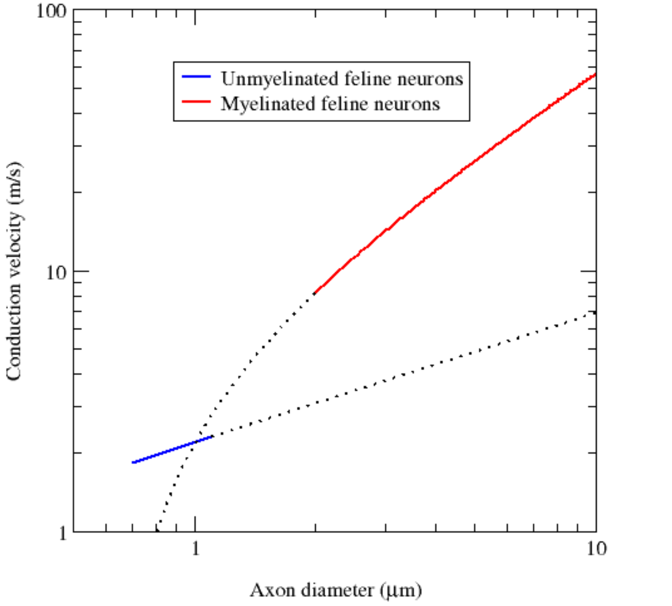
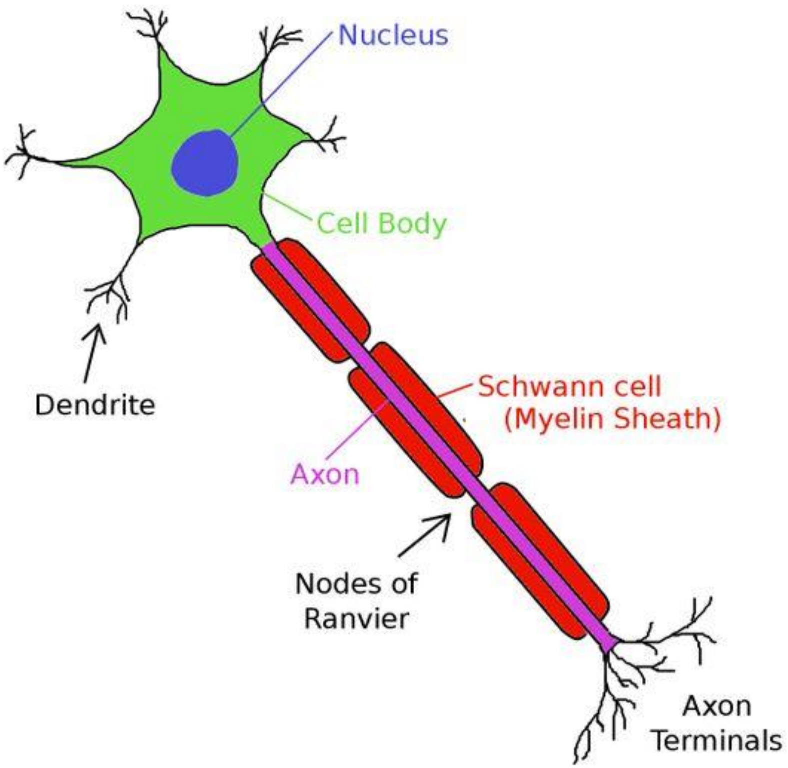
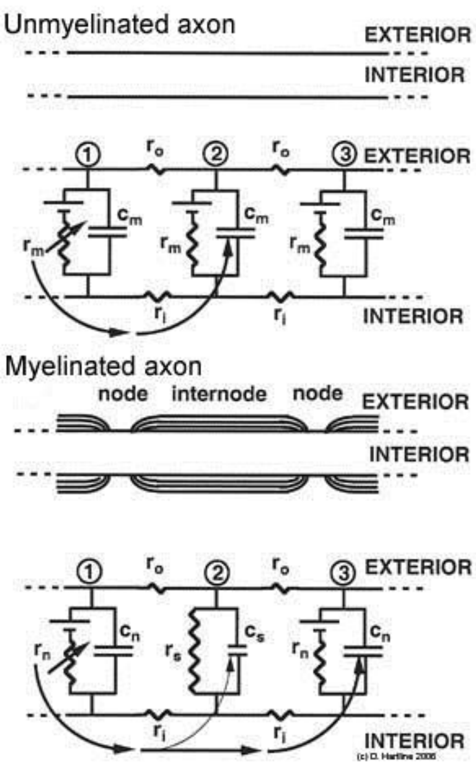


Image courtesy of WillowW on Wikipedia. CC BY.

Generally, Bigger means Faster

But we need another way to be fast!





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Myelin: What is it FOR?

Comparison of action potentials (APs) from a representative cross-section of animals[86]

Animal	Cell type	Resting potential (mV)	AP increase (mV)	AP duration (ms)	Conduction speed (m/s)
Squid (*Loligo*)	Giant axon	–60	120	0.75	35
Earthworm (*Lumbricus*)	Median giant fiber	–70	100	1.0	30
Cockroach (*Periplaneta*)	Giant fiber	–70	80–104	0.4	10
Frog (*Rana*)	Sciatic nerve axon	–60 to –80	110–130	1.0	7–30
Cat (*Felis*)	Spinal motor neuron	–55 to –80	80–110	1–1.5	30–120

Feeds the need for speed!

What is a Receptive Field?

The receptive field of a sensory neuron is a region of space in which the presence of a stimulus will alter the firing of that neuron.

The space can be on an animal's body, such as in classic, cutaneous receptive fields (an area of the animal's skin), in the space surrounding an animal, such as an area of auditory space that is fixed in a reference system based on the ears but that moves with the animal as it moves, or in a fixed location in space that is largely independent of the animal's location (Place cells).

Receptive fields have been identified for neurons of the auditory system, the somatosensory system, and the visual system.

Receptive fields on Skin

Receptive fields on Retina

Information Theory – Quantifying uncertainty

Information is also called **entropy** or **uncertainty**.

What is the information content of a random variable X?

How uncertain are we about X?

How many yes/no questions would it take (on average) to determine X?

Example: A fair six-sided die...

Information Theory – Quantifying uncertainty

Information is also called **entropy** or **uncertainty**.

What is the information content of a random variable X?

How uncertain are we about X?

How many yes/no questions would it take (on average) to determine X?

Example: A fair six-sided die...
The value can be determined with two or three well-chosen questions.
$\log_2(6) = 2.58$

A fair 32-sided die would require five questions. $\log_2(32) = 5$

If a variable X has N equally probable values, its information content is

$$H(X) = \log_2(N) \text{ bits}$$

Information Theory – more details <u>(not on quiz)</u>

H(X) can be defined when probabilities p_i are <u>not</u> equal:

$$H(X) = -\sum p_i \log_2(p_i) \quad i = 1,\ldots,N$$

H(X) can be defined for a <u>continuous variable</u> – depends on the resolution with which it is measured.

Mutual Information

Two random variables X and Y

$$I(X;Y) = H(X) - H(X|Y)$$

"conditional information" (or uncertainty)
How uncertain are we about X
once we know the value of Y?

How much does knowledge of Y reduce our uncertainty about X?

Example: X is the value of a six-sided die.
Y is whether that die is odd or even.

$H(X) = 2.58$ bits. $H(X|Y) = \log_2(3) = 1.58$ bits. $I(X;Y) = 1$ bit

Mutual Information

Two random variables X and Y: $I(X;Y) = H(X) - H(X|Y)$

How much does knowledge of Y reduce our uncertainty about X?

Variable X might be a stimulus, drawn from some stimulus set
e.g. mechanical deflection of the spines on a cockroach leg.

Which spine or spines?
Deflected in which direction?
By how much (displacement angle, or force)?

Mutual Information

Two random variables X and Y: $I(X;Y) = H(X) - H(X|Y)$

How much does knowledge of Y reduce our uncertainty about X?

Variable Y might be the <u>response</u> of a particular cell
e.g. number of action potentials fired per second.

Mutual information between X and Y would quantify what we learn about which stimulus was presented (from among the set) by listening to the cell.

Mutual Information

Two random variables X and Y: $I(X;Y) = H(X) - H(X|Y)$

How much does knowledge of Y reduce our uncertainty about X?

$0 \le I(X;Y)$	knowing Y can't <u>decrease</u> our knowledge of X
$I(X;Y) \le H(X)$	Y can't tell us more about X than there is to know
$I(X;Y) \le H(Y)$	Y can't tell us more about X than Y's own information

If X and Y are independent, then $H(X|Y) = H(X)$ and $I(X;Y) = 0$.
Y tells us nothing about X.

If Y specifies X exactly, then $H(X|Y) = 0$ and $I(X;Y) = H(X)$.

Do we actually measure mutual information, in bits?

Not very often.

1. Requires a very large amount of data to approximate the joint probability distribution.
2. Measured information depends on experimenter's choice of stimulus set.

But we do find one variable (Y, the activity of a neuron) that varies systematically with a “real-world” variable (X, the stimulus, motor output, or behavioral).

“Y represents X” $\Longleftrightarrow$ $I(X;Y) > 0$

Rate Coding

Assumption: a neuron represents information Y by its firing rate (spikes/second).

Alternatives: represent information by spike timing (e.g. auditory sound source localization) or by spike phase (e.g. hippocampal place cells, relative to theta oscillation).

Why do we adopt the rate coding approximate description of mutual information?

Because in a great number of cases, it works.

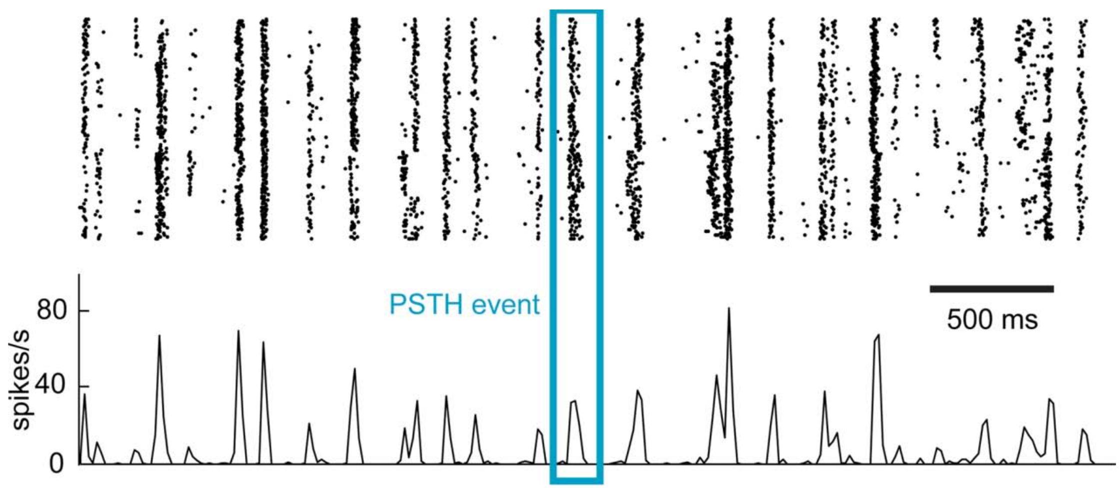
How much information in a neuron's output rate?

“A few bits” (exact quantification is tricky)

Fixed stimuli, ~8 distinguishable levels of firing rate = 3 bits

Figure 1B. Firing properties of two classes of neurons in layer 2/3 somatosensory cortex removed due to copyright restrictions. See Tateno, T., and H. P. C. Robinson. "Rate Coding and Spike-Time Variability in Cortical Neurons With Two Types of Threshold Dynamics." *Journal of Neurophysiology* 95, no. 4 (2006):2650-63. doi: 10..1152/.jn..00683..2005

Time-varying stimuli, ~1 bit/spike



How much information in the stimulus?

Potentially quite a lot – the range of potential stimuli is vast.

$I(X;Y) \le H(Y)$

(the amount of info that the cell can provide about the stimulus is limited by the information content of the cell's output)

Goal: Find a succinct description of <u>which</u> few bits in X are represented by Y

Typically this is intensity along some “axis”.

-- Sound pressure at a particular frequency.
-- Orientation of a bar of light at a particular location on the retina.
-- Concentration of certain molecules at the olfactory epithelium.
-- Proximity to a certain location (place field).

This describes the **receptive field** or **response properties** of the cell.

Review

Sensory processing is a favored focus of study because:
1: It works under anesthesia
2: The real-world variable is the stimulus, under good experimental control

The nervous system is an information-processing machine.

Information and mutual information can be quantified, in bits.

The information content of a cell's output is small – a few bits – and encoded by the cell's firing rate (usually).

The neurophysiologist's job is to identify which few bits those are among the (much larger) information content of the stimulus.

Presumably, that information is used by downstream neurons to generate appropriate behavior.

The cockroach nervous system.

A diagrammatic representation of the insect nervous system removed due to copyright restrictions. See: http://www.earthlife.net/insects/anatomy.html.

Image removed due to copyright restrictions. See: http://www.adinstruments.com/solutions/education/ltexp/cockroach-ventral-nerve-cord.

Cockroach leg mechanoreceptors

Primary mechanoreceptors have cell body in the leg, send output to thoracic ganglia.

Image removed due to copyright restrictions. See: http://users.marshall.edu/~zill/Poster2003Fig5sensanatf.jpg.

The role of spines?

Robert Fuller, TED talk
Watch from 57 sec

Locomotion in insects

A diagrammatic representation of the insect nervous system removed due to copyright restrictions. See: http://www.earthlife.net/insects/anatomy.html.

Insects have a central pattern generator (CPG) in each thoracic ganglion, capable of generating rhythmic output to drive that leg.

Thoracic ganglia are connected to each other, maintaining appropriate phases between legs.

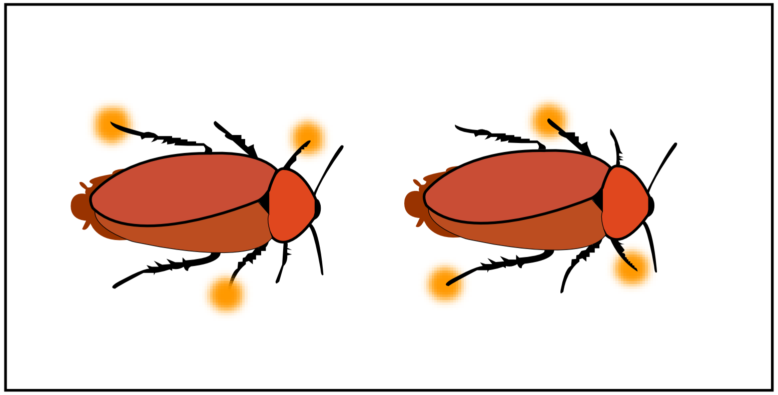


Image by MIT OpenCourseWare.

"alternating tripod"

Inputs from the "head ganglia" (supra- and sub-esophageal) can set the system in motion, as can reflexive inputs (see tomorrow's recitation paper).

Locomotion in insects

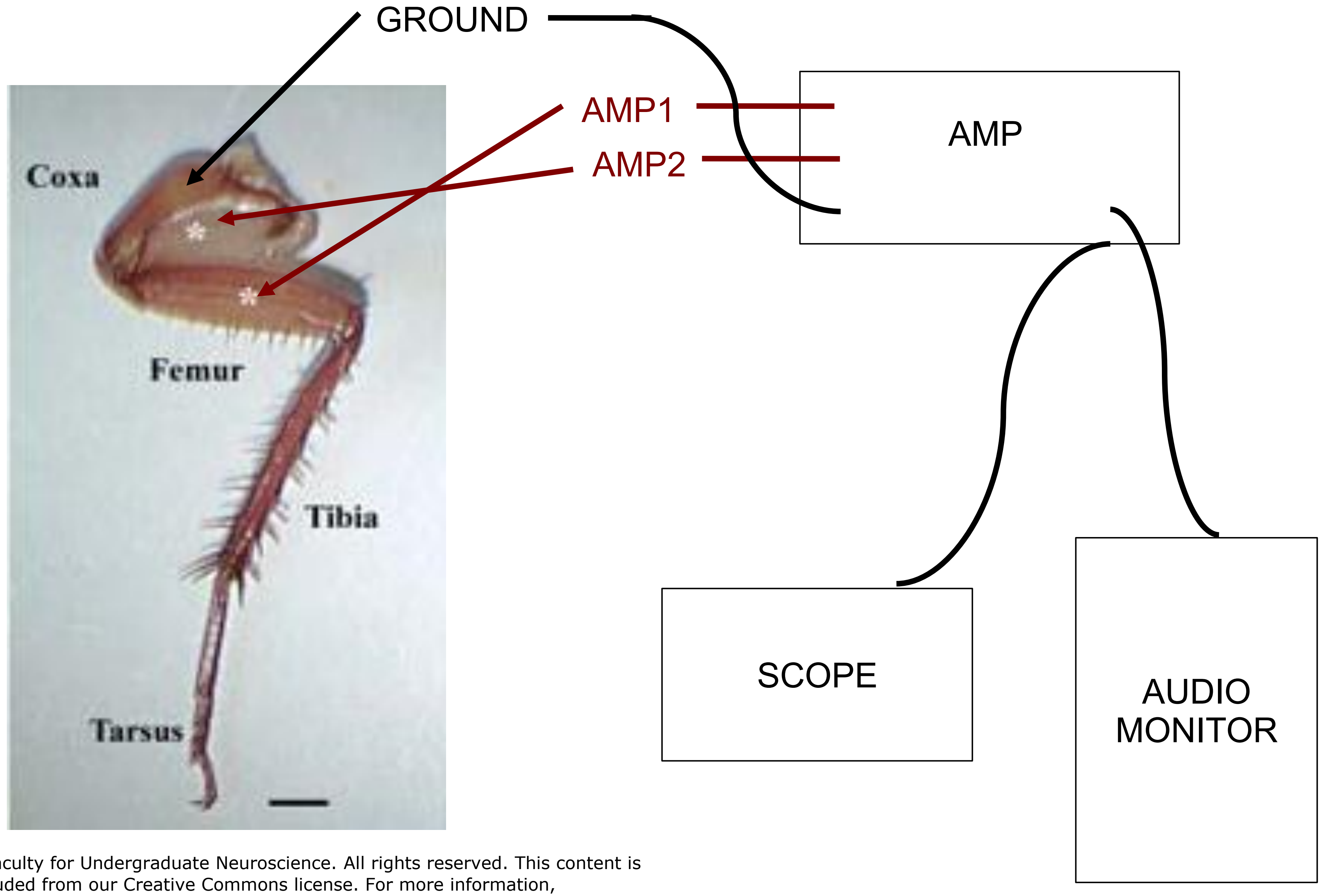
Cockroach locomotion has been modeled and reproduced in a robot.

3D mechanoskeletal model cockroach leg

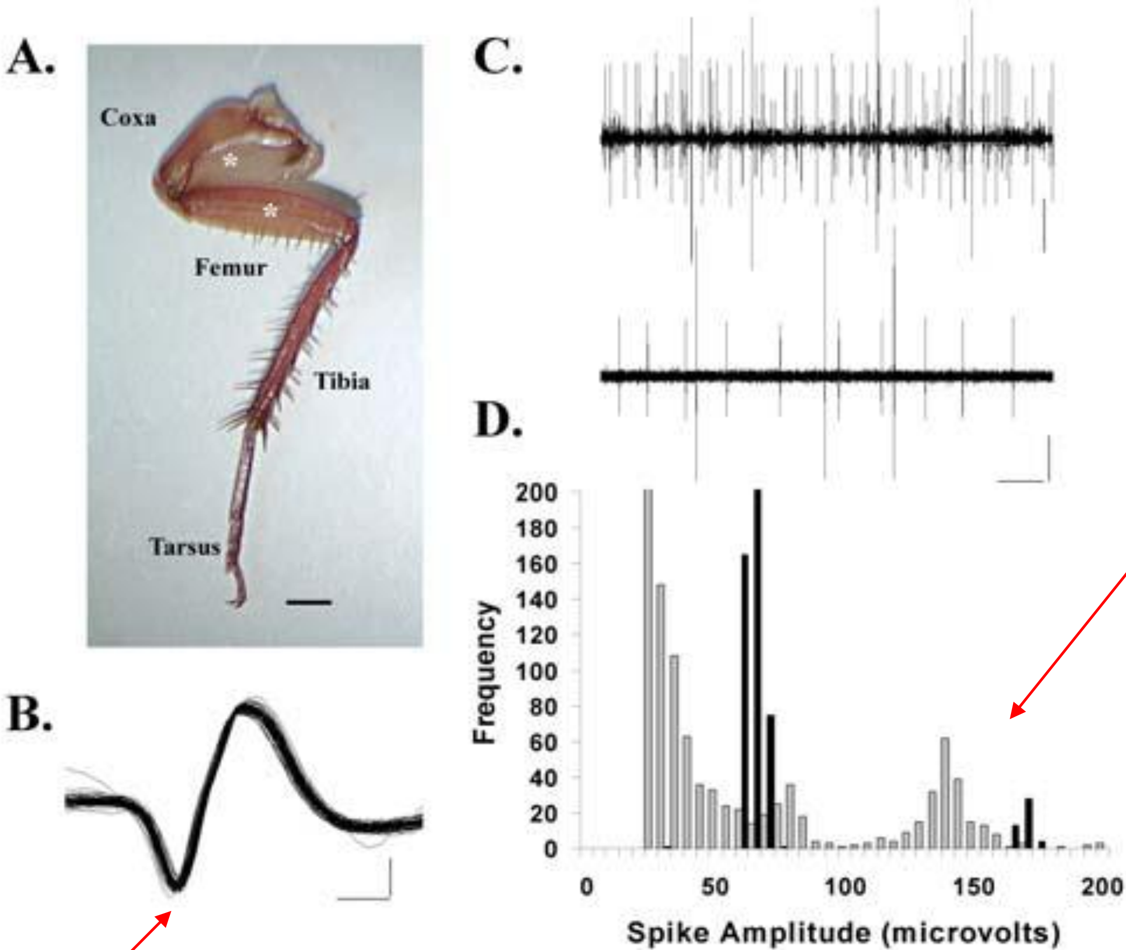
Robo roach image removed due to copyright restrictions.
See: http://www.abc.net.au/catalyst/stories/2577277.htm.

Image removed due to copyright restrictions.

The central pattern generators in the thoracic ganglia receive mechanosensory information from the legs and adjust their output accordingly.


GROUND
AMP1
AMP2
Coxa
Femur
Tibia
Tarsus
AMP
SCOPE
AUDIO
MONITOR

Observing multiple cells?



Spike waveforms

RL Ramos, A Moiseff, JC Brumberg 2007

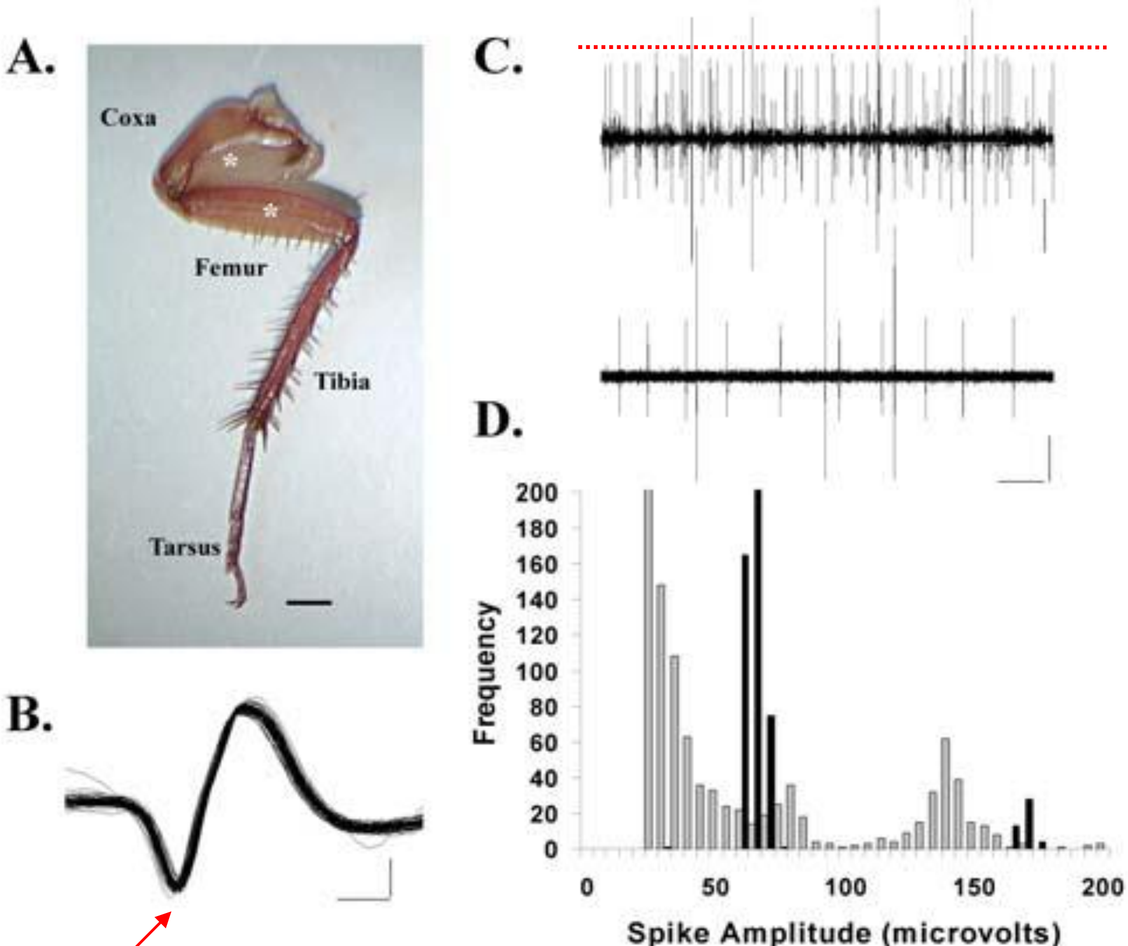
All spikes from a single cell will be similar in amplitude. (as measured at a particular point in the extracellular space)

What determines spike amplitude?

Cell body size/axon diameter.

Proximity of the electrode tip.

Observing multiple cells?



Isolate largest spikes with oscilloscope trigger level.

Spike waveforms

RL Ramos, A Moiseff, JC Brumberg 2007

"If I were a thoracic ganglion cell, what would I learn about the world by listening to these mechanoreceptors, and why would that be useful?"

Fair Game for Quiz

Sensory Motor Arc, why important for Systems Neuroscience

Functional parts of a Neuron

Action Potential Mechanics*

Myelin

Receptive Fields

Rate Coding

Cockroach (Neuro)Anatomy

Practical items for Lab

Anything you cover in recitation

9.17 Systems Neuroscience Lab
Spring 2013