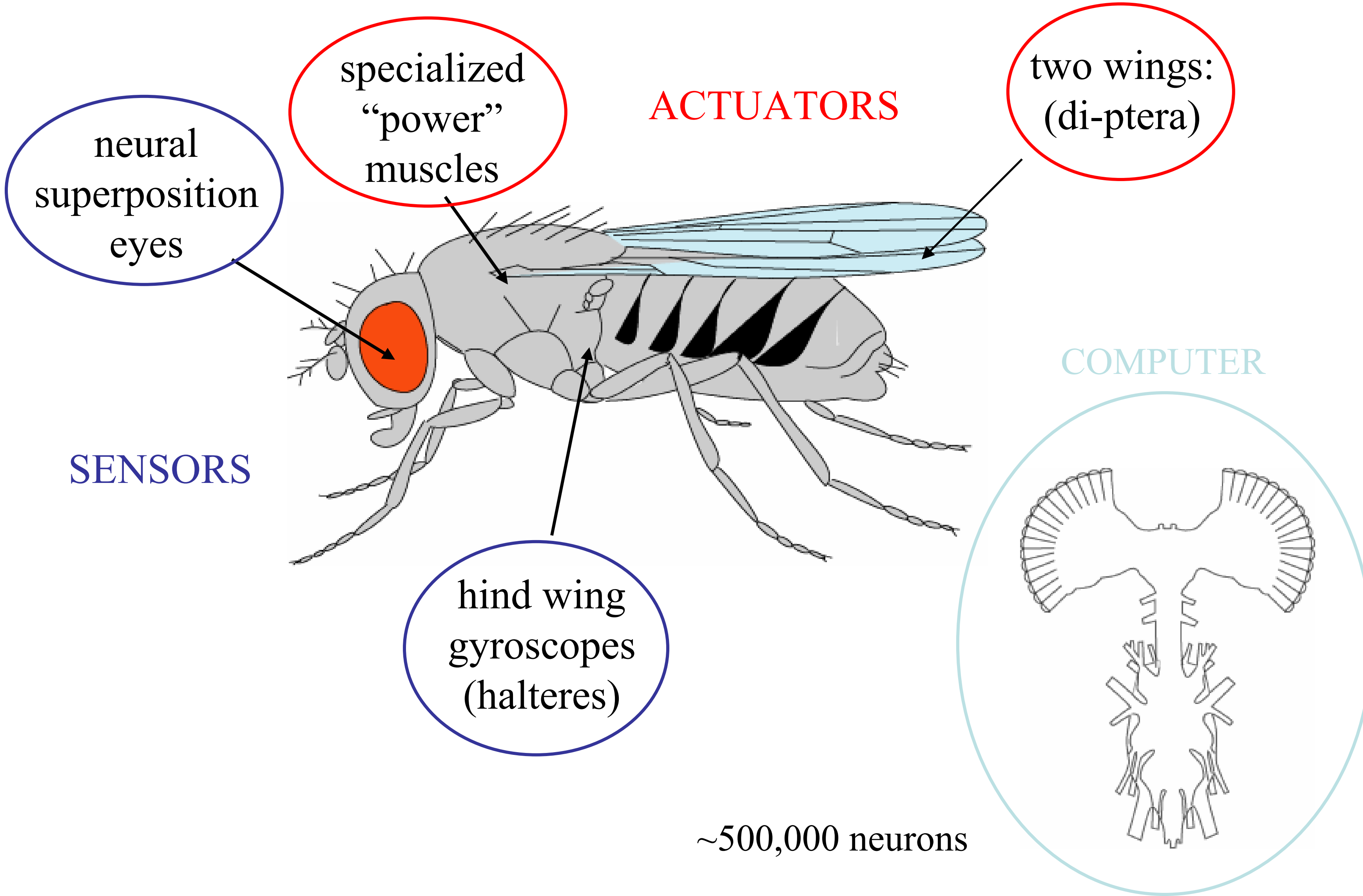
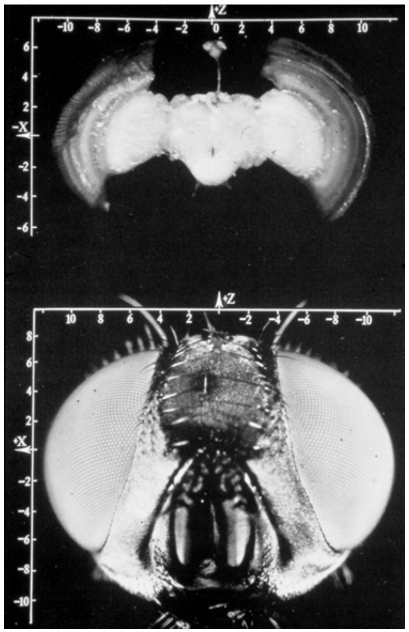
Review from last Dickinson lecture……

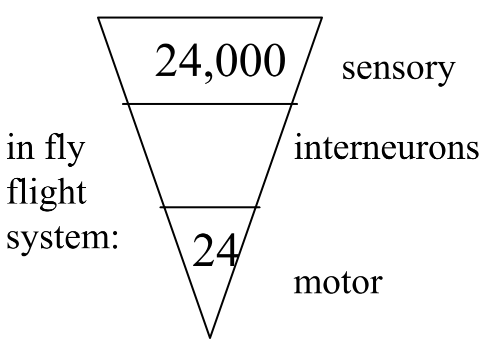


Control Theory Approaches to Biological Sensors

Sensory systems of interest to students of control theory because:

1) Sensory cells dominate most nervous systems.



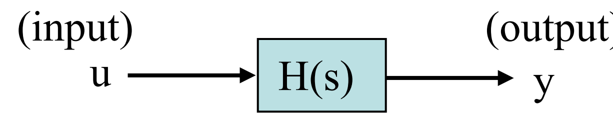


2) Animals make great sensors.

eg. insect eyes operates over 8 orders of magnitudes, compared to a “good” 12 bit CCD

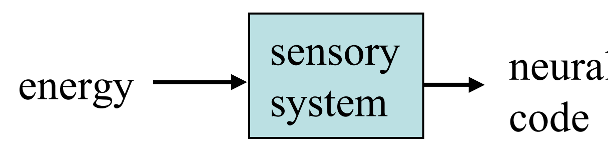
Silk moth malecan detect single molecule.

3) Sensory process extremely amenable to control theory.



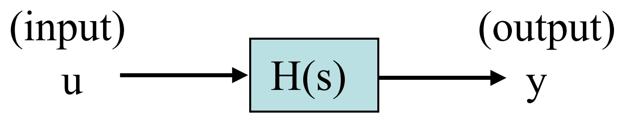
y = H(s) u, where H(s) is transfer function.

we can treat sensory system as transfer function:



Sensory neurons transform energy in the external world into neuronal output.

3) Sensory process extremely amenable to control theory:



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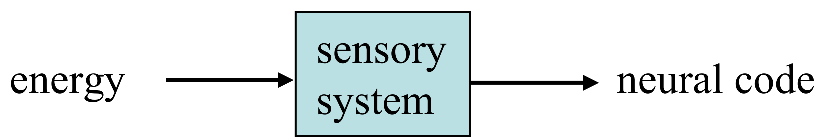
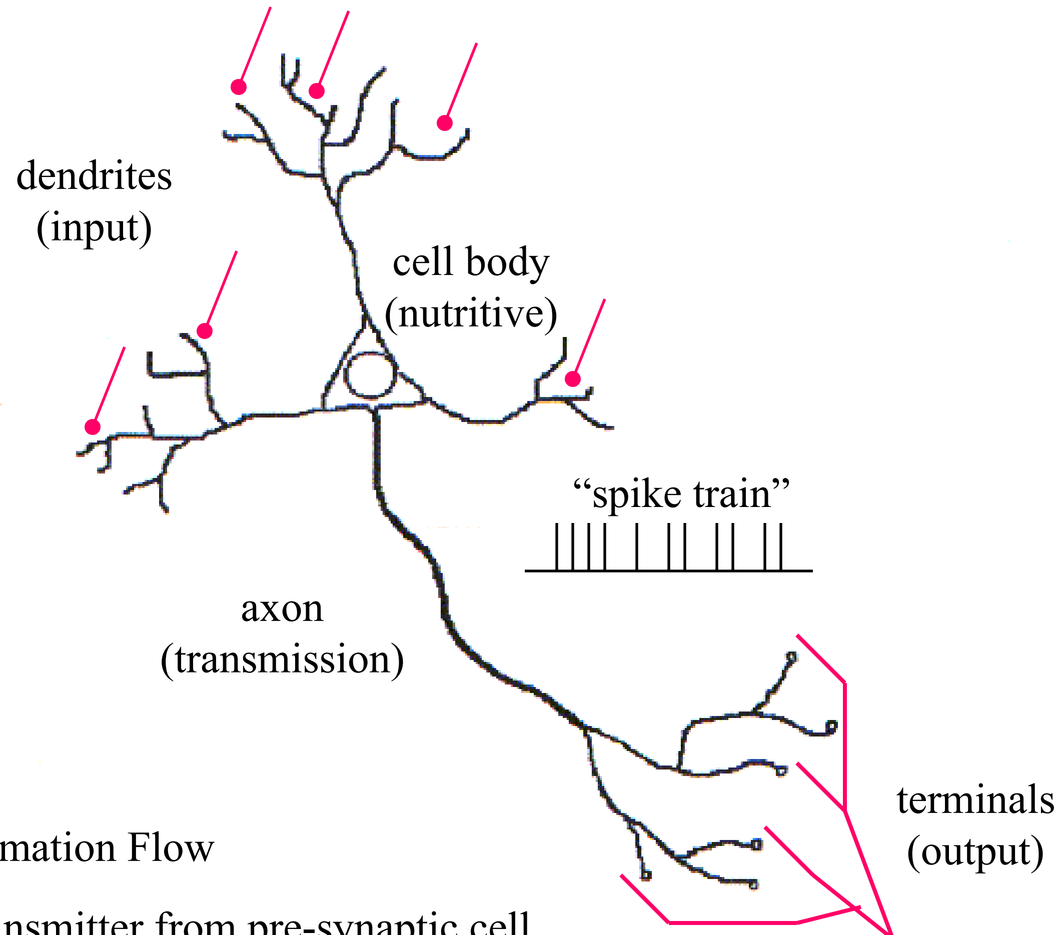


Sensory neurons transform energy in the external world into neuronal output.

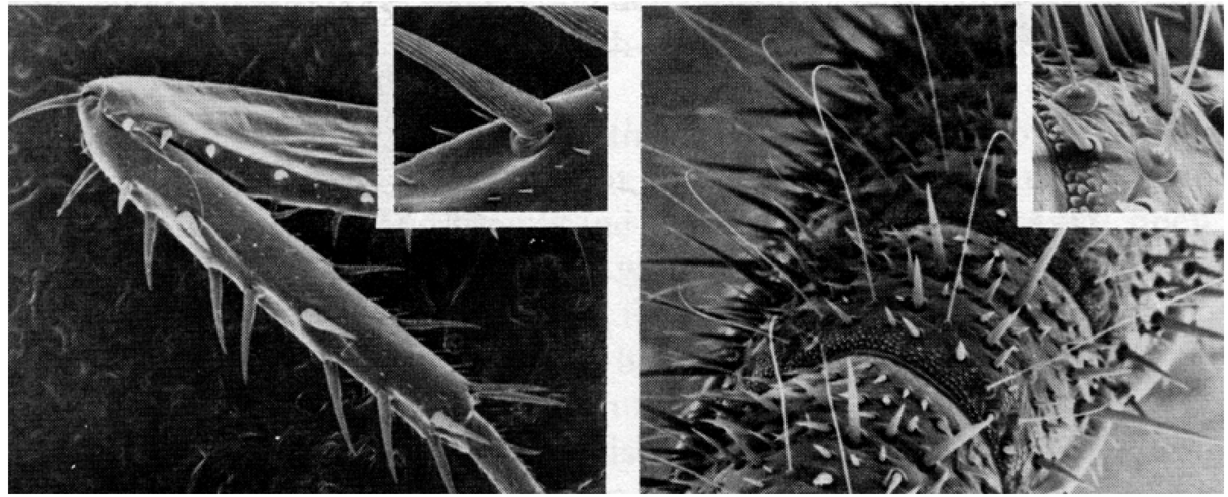
Consider 'basic' neuron….

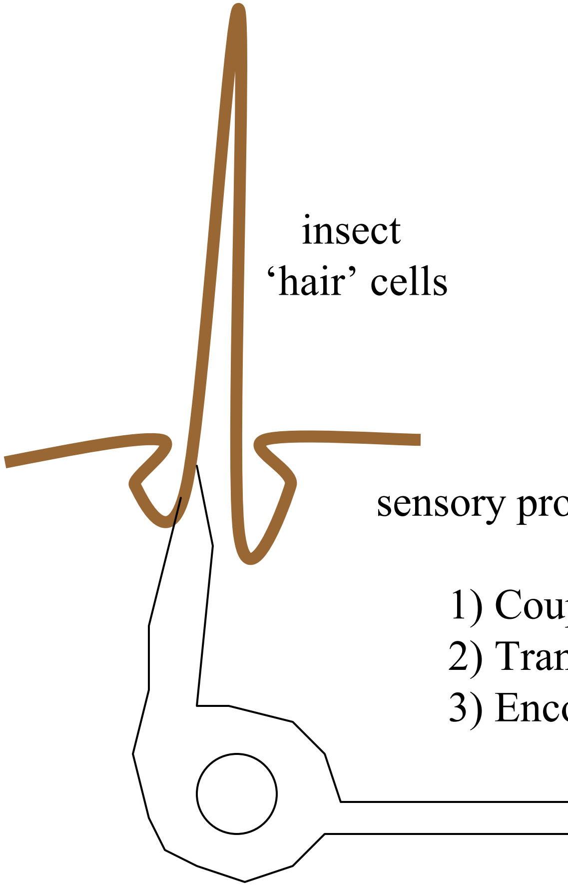


Basic Neural Information Flow

- neuron receives chemical transmitter from pre-synaptic cell
- synaptic input alters DC potential in dendrties
- DC potential in dendrites alters spike rate in axon
- spike rate alters release of chemical transmitter in terminals
- transmitter alters DC potential of post-synaptic cell

Consider sensory neuron….

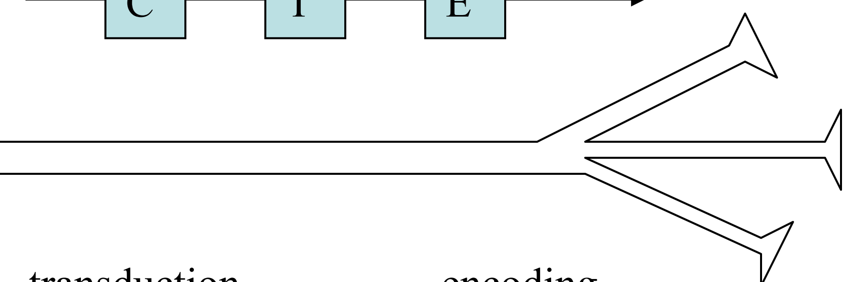




sensory process broken into three steps:

1) Coupling
2) Transduction
3) Encoding

C → T → E

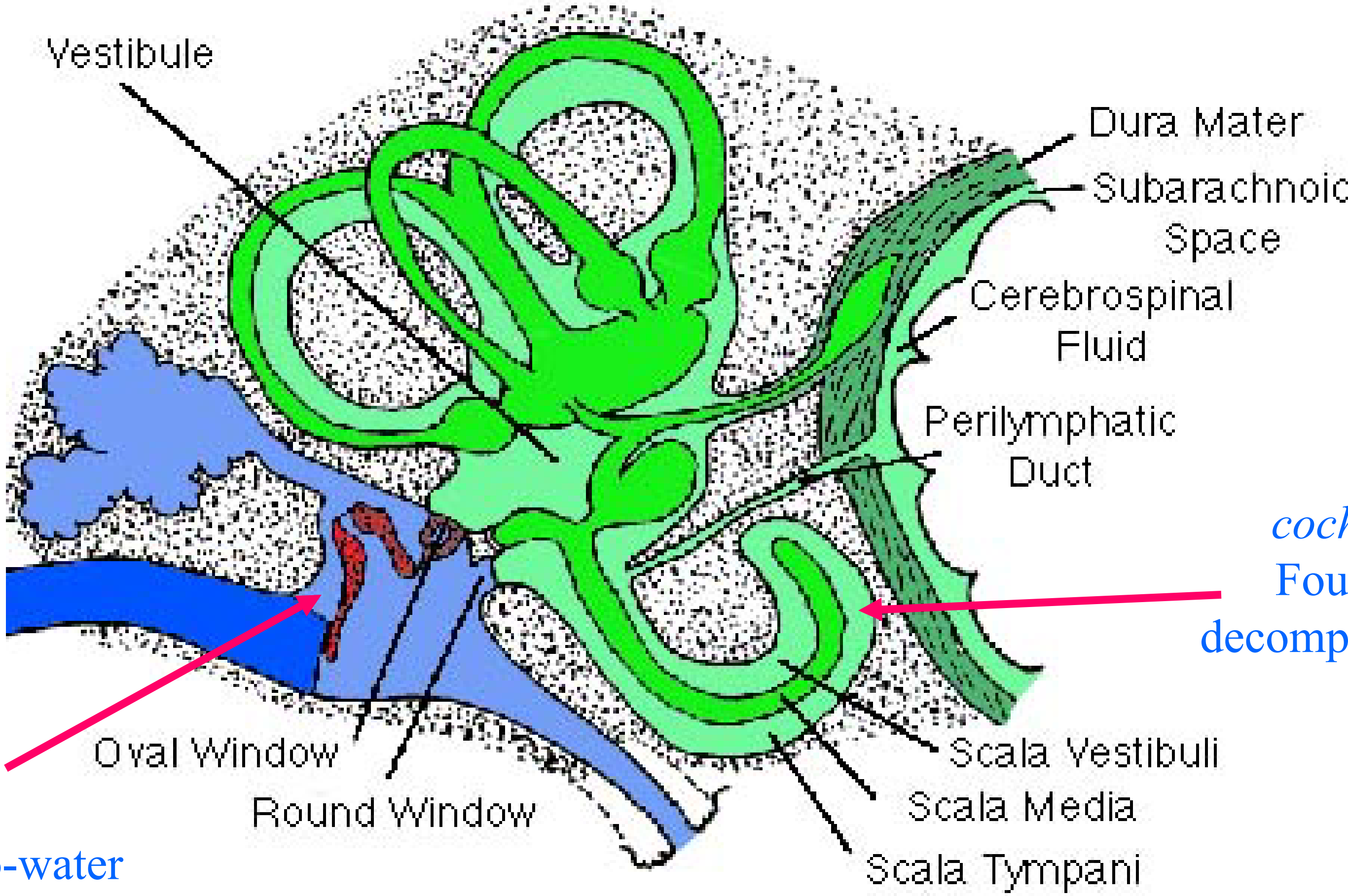


linear cascade of 3 transfer functions

	coupling	transduction	encoding
input	energy in external world	energy at dendrite	trans-membrane potential
output	energy at dendrite	trans-membrane potential	spike rate

1. Coupling

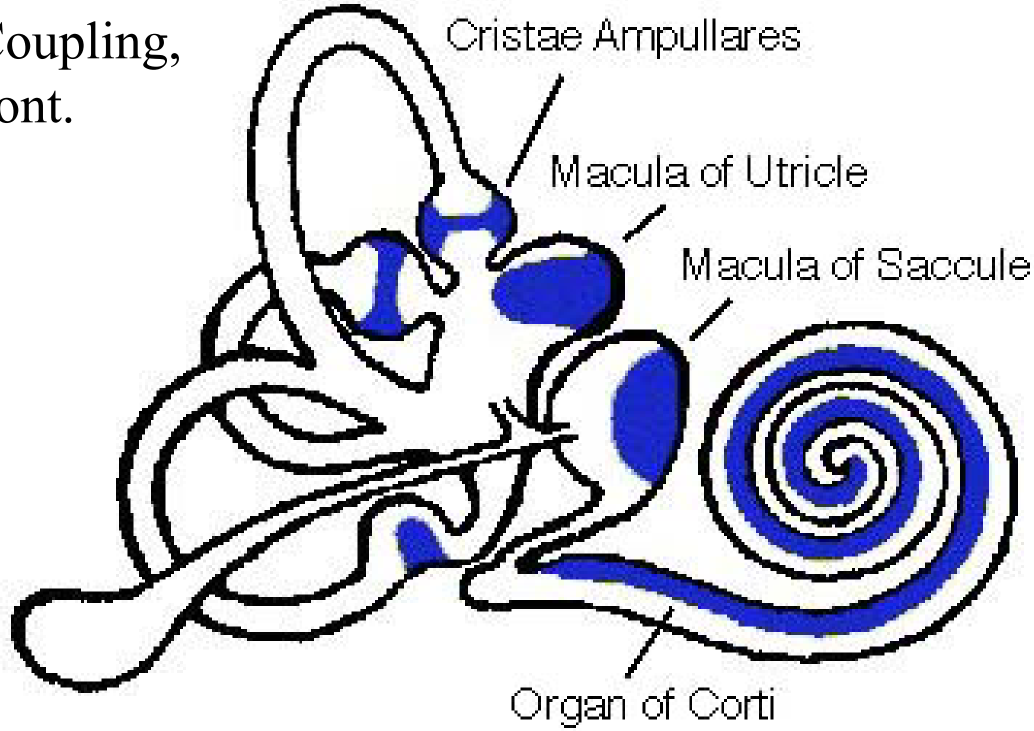
Coupling is performed by non-neuronal accessory structures, e.g. vertebrate inner ear…..

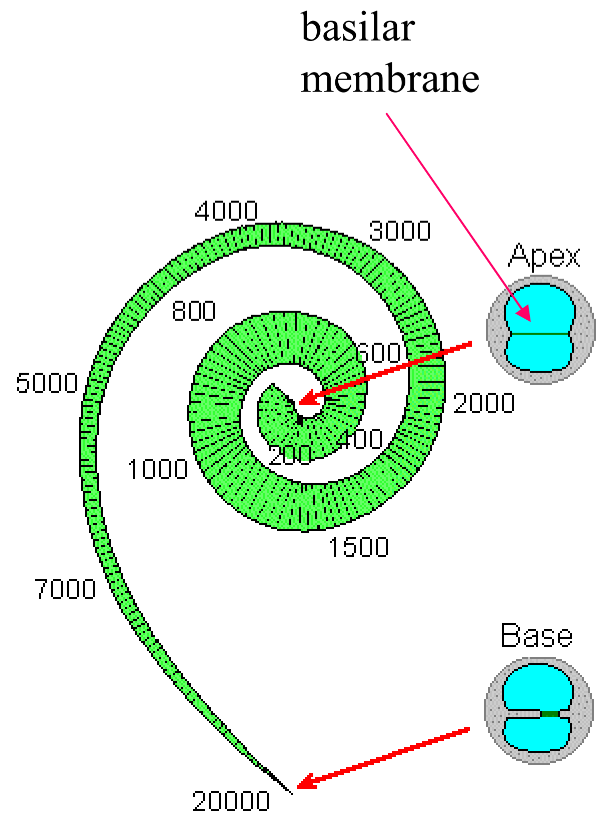


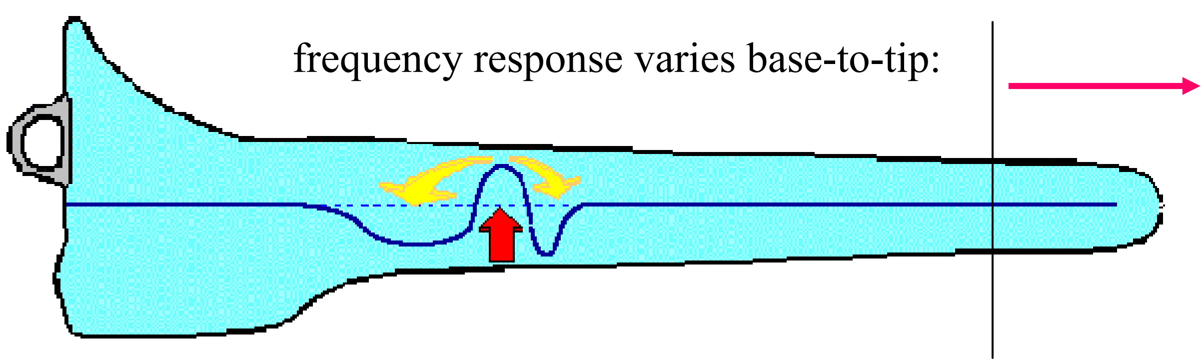
cochlea
Fourier decomposition

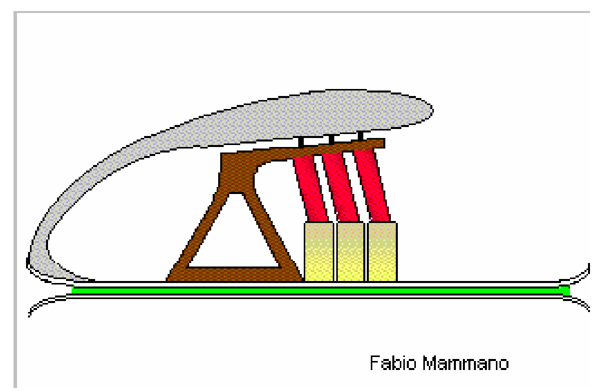
ear ossicles
match air-to-water impedance

Coupling, cont.



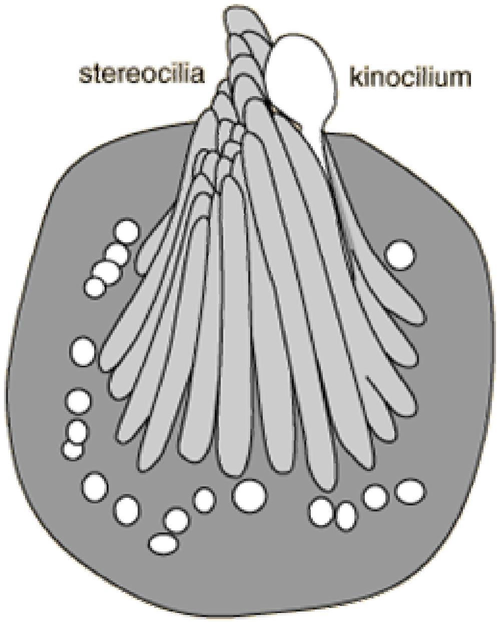




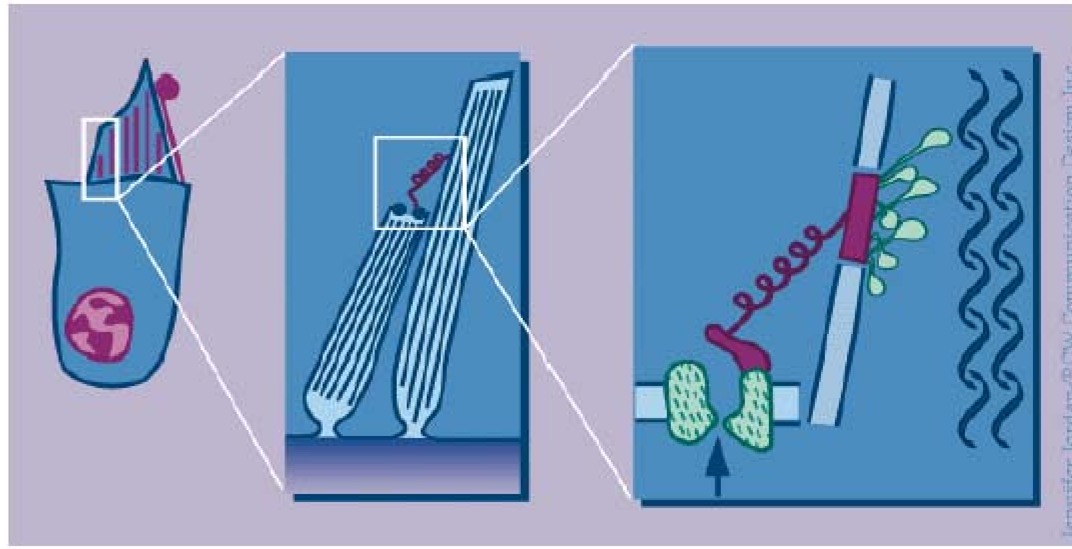


2. Transduction

One at dendrite, energy must activate ion channel to change current flow across membrane….



Adapted from electron-scanning micrograph at 16,800x . A. J. Hudspeth, R. Jacobs, Science News, Oct 20, 1984.

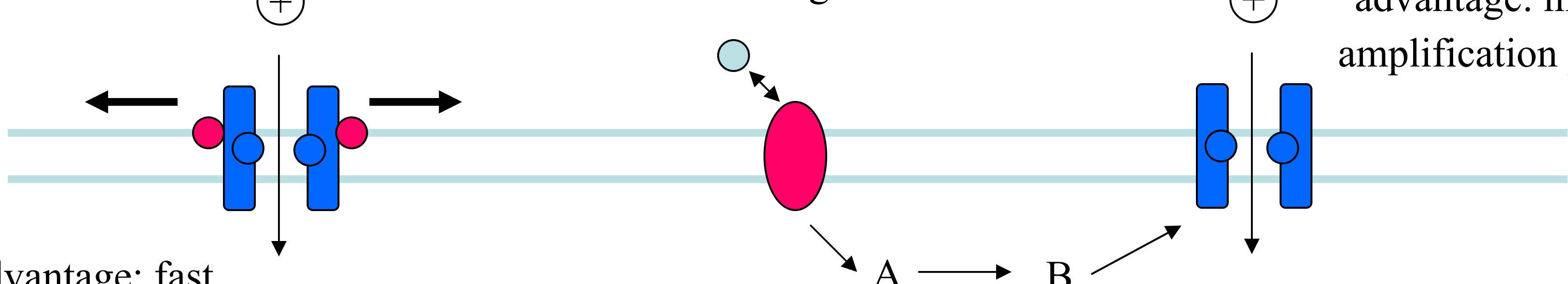


In general, 2 kinds of transduction processes:

direct:

2nd messenger mediated:

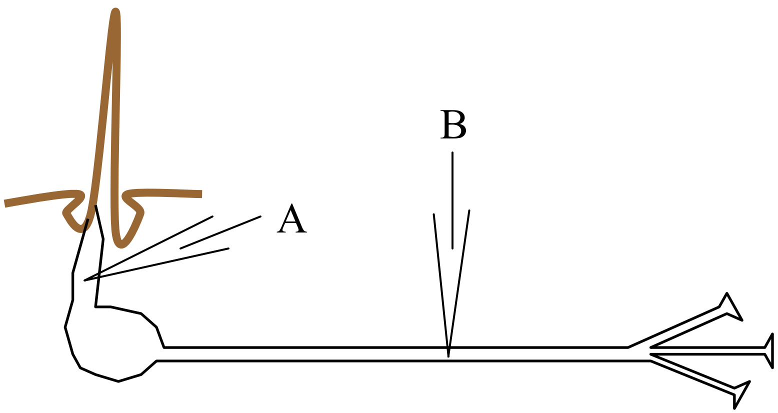
advantage: high gain amplification possible

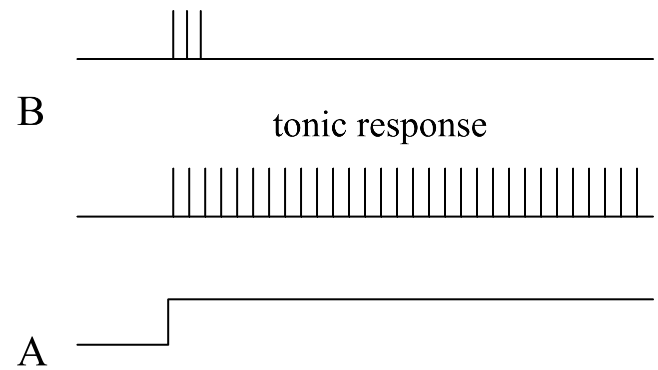


advantage: fast

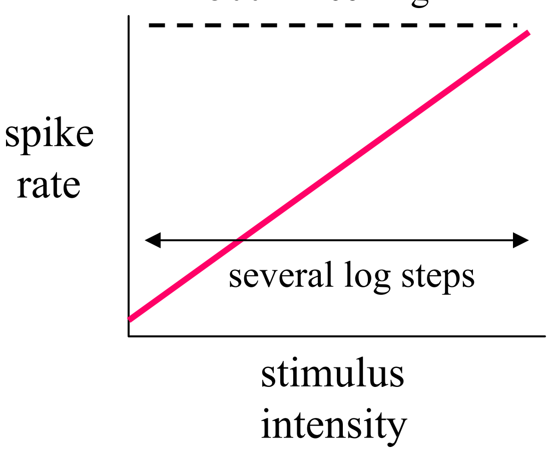
3. Encoding

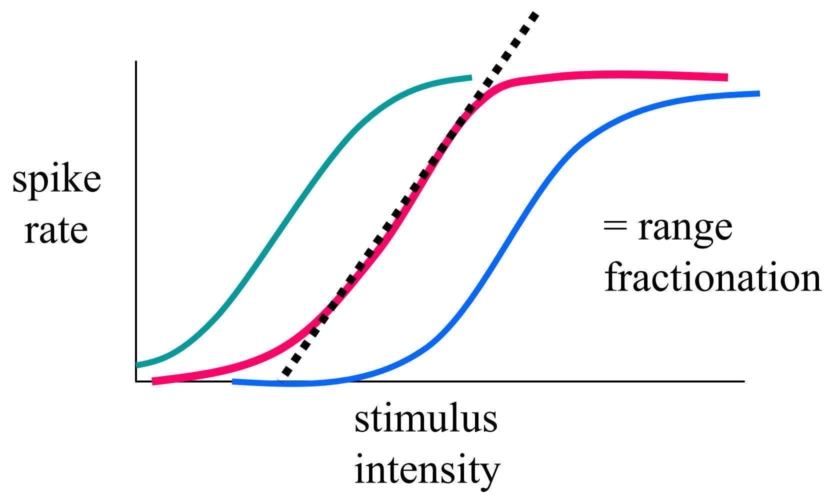
Spike encoding is need for long distance transmission





Problem with encoding is limited dynamic range.

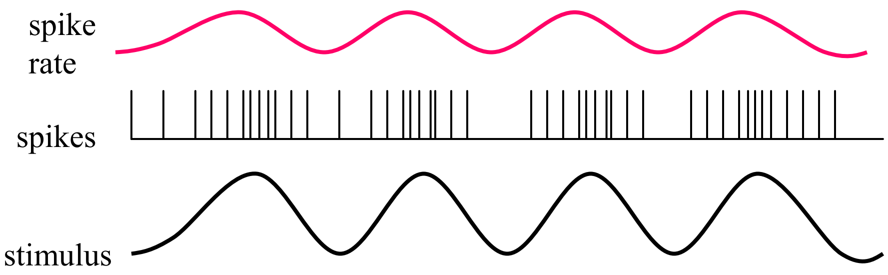




Encoding, cont…

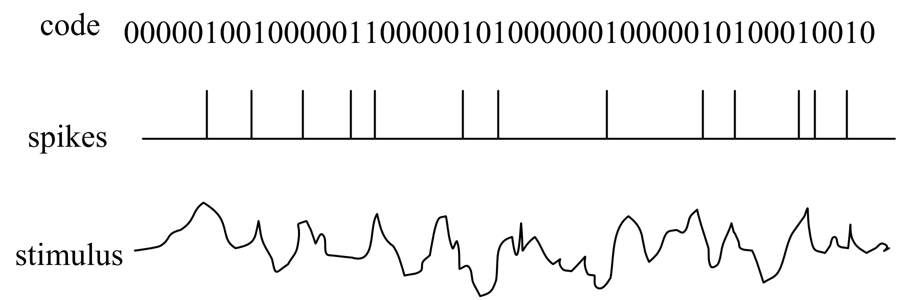
How do neurons actually encode information?

1) rate code



magnitude of stimulus encoded
by spike frequency

1) temporal code



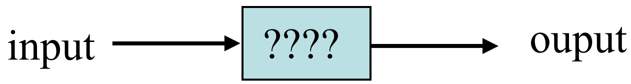
temporal features of simulus encodes by precise
position of spikes

Who/what decides whether a cell is using a rate code vs. a temporal code?

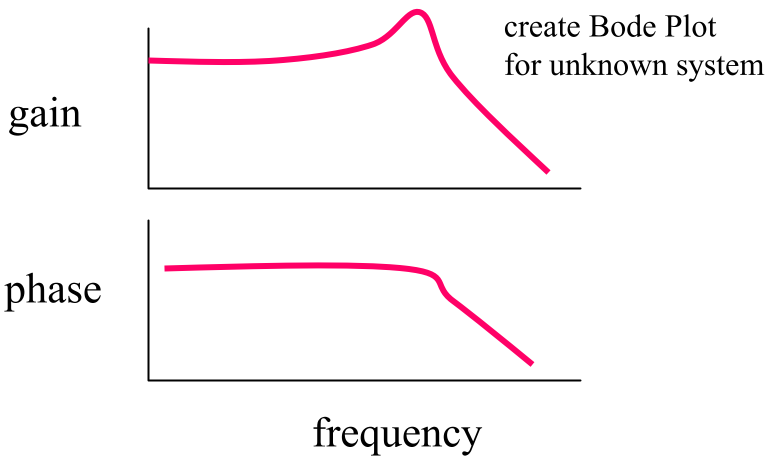
Systems Indentification

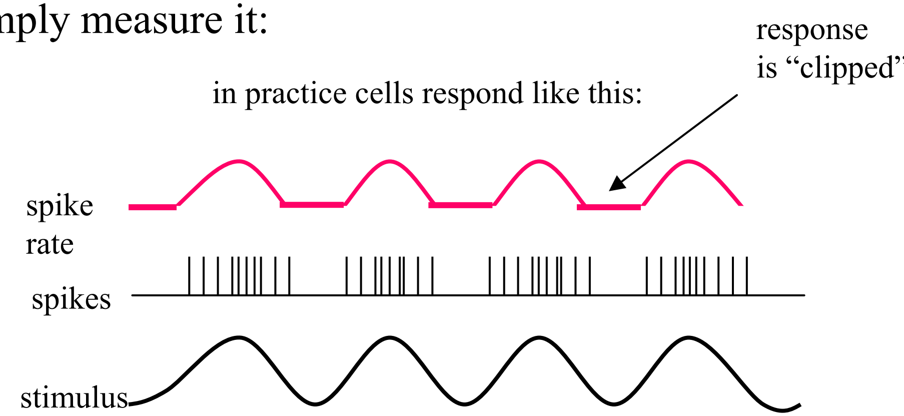
How do we characterize sensory cells? – or any ‘unknown system for that matter?

employ “Systems Indentification”:



instead of designing a transfer function, simply measure it:

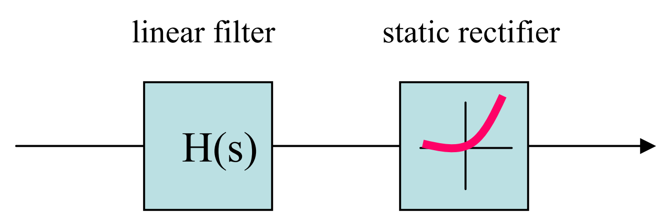




fit measured response to particular model, e.g.

$$H(s) = \frac{1}{ms^2 + bs + k}$$

solve for m,b,k via least squares



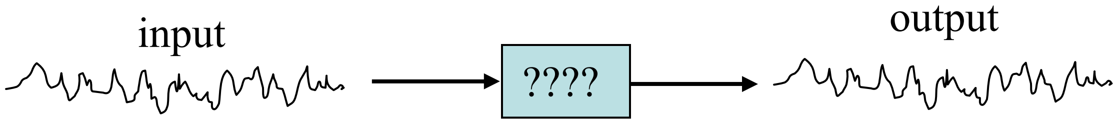
This cascade describes many sensory cells.

Identification methods using noise….

Systems ID leads to interesting trick with sensory cells….

Sine wave analysis takes time, a shortcut is to use noise:

'white' noise contains all frequencies with gaussian amplitudes



How do you extract H(s)?
If input, u(t) is noise, then system, h(t) may be found by:

$$h(\tau) = \frac{1}{PT}\int_0^{\infty} y(t)u(t-\tau)d\tau$$

= cross correlation of input and output

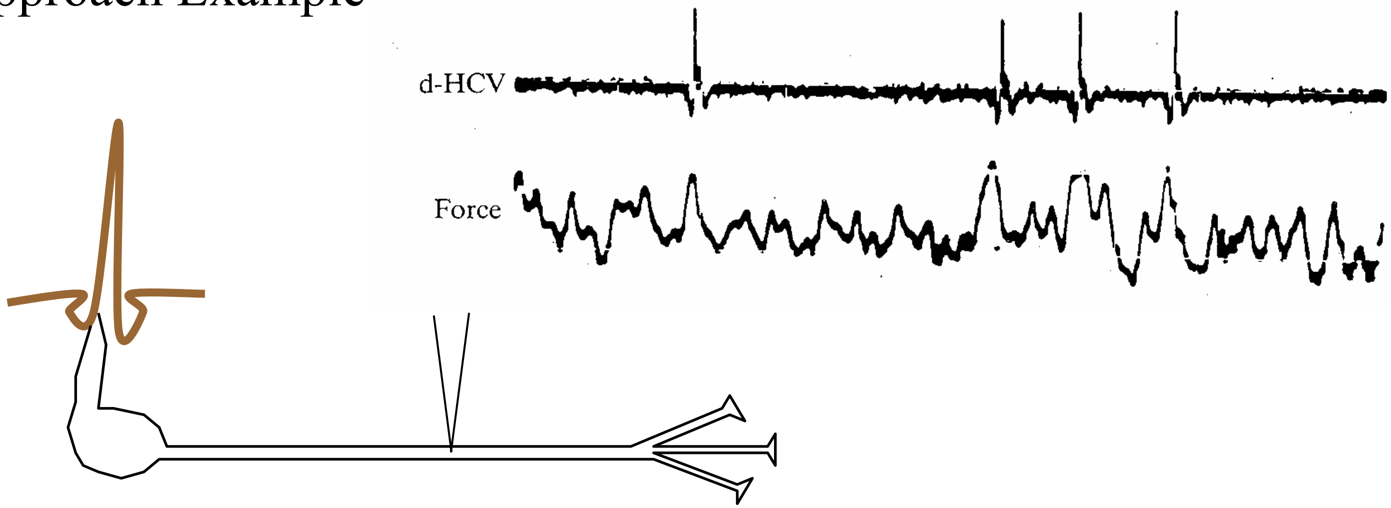
If input, output, y(t) is spike train, such that y(t) = 1 during spike, 0 elsewhere, then:

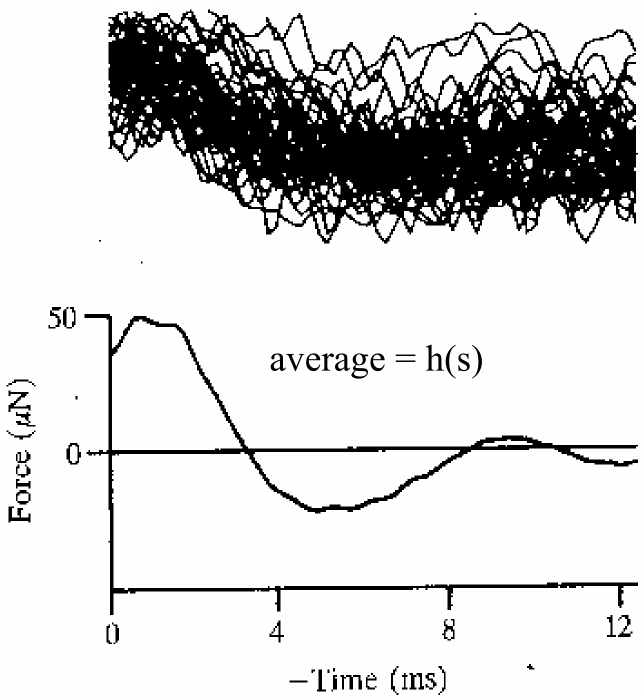
$$h(\tau) = \frac{1}{PT}\sum_{k=1}^{K} u(t-\tau)\Delta\tau$$

= signal average of input preceding each spike!

thus, system equals input "most likely to succeed"
= reverse correlation technique

Noise Approach Example





Fourier Transform

Bode plots for different cells