ELEC ENG 3BB3:

Cellular Bioelectricity

Notes for Lecture 24

Thursday, March 6, 2014

8. NEURAL ELECTROPHYSIOLOGY

We will look at:

- Structure of the nervous system
- Sensory transducers and neurons
- Neural coding and computation
- Neural synapses, excitation and inhibition
- Generation of EEG signals

Structure of the nervous system:

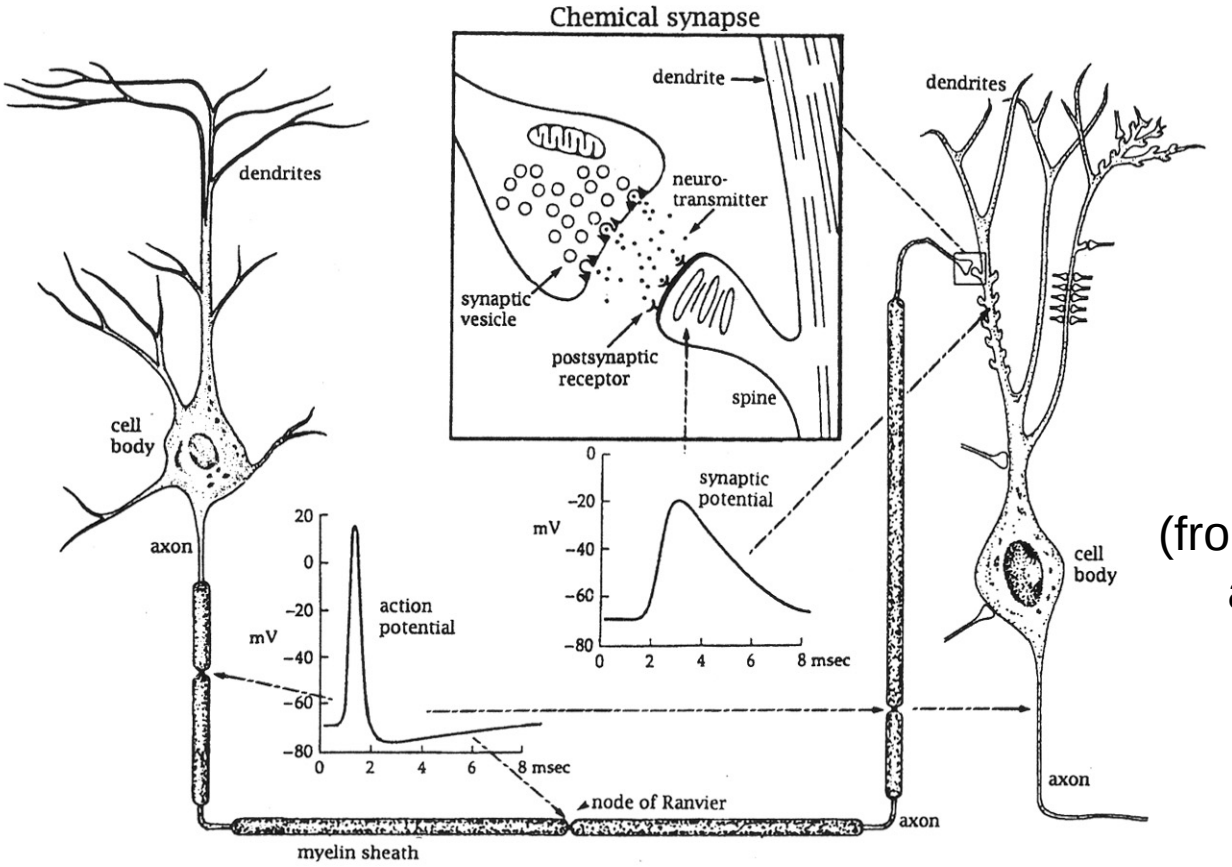
The main functions of the nervous system are to:

- receive and process *sensory information*,
- control *motor functions,*
- *learn*, and
- *integrate* memory, sensory and motor functions.

Structure of the nervous system (cont.):

- The *neuron* is the basic processing unit of the nervous system.
- There are around 10^{12} neurons in the human nervous system.
- There are approximately 10,000 *morphological classes* of neurons, and many more *functional classes*.
- Neurons are connected via electrical or chemical *synapses*. There are about 10^{15} synapses in a human brain.

Structure of the nervous system (cont.):



(from Johnston and Wu)

Figure 1.2 Neurons convey information by electrical and chemical signals. Electrical signals travel from the cell body of a neuron (left) to its axon terminal in the form of action potentials. Action potentials trigger the secretion of neurotransmitters from synaptic terminals (upper insert). Neurotransmitters bind to postsynaptic receptors and cause electric signals (synaptic potential) in the postsynaptic neuron (right). Synaptic potentials trigger action potentials, which propagate to the axon terminal and trigger secretion of neurotransmitters to the next neuron. Adapted from Kandel et al. 1991 and from L.L. Iversen, copyright © 1979 by Scientific American, Inc. All rights reserved.)

Structure of the nervous system (cont.):

(from Koch)

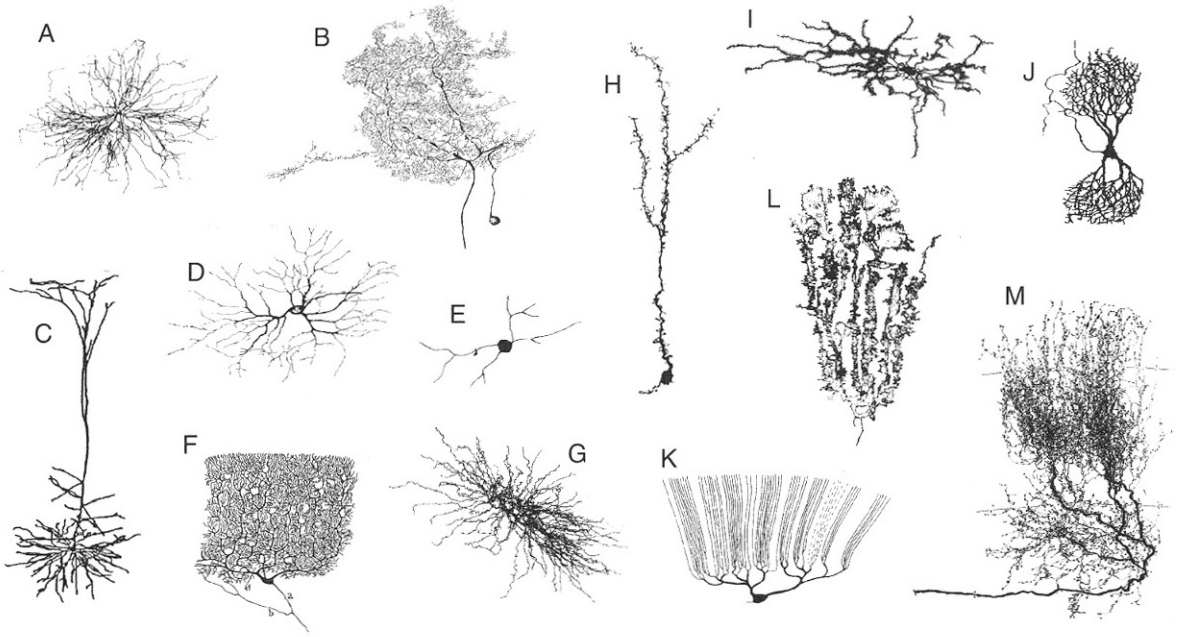


Fig. 3.1 DENDRITIC TREES OF THE WORLD Great variety of dendritic trees (in addition to a glia cell and an axonal tree) observed in the nervous systems of animals. The cells are not drawn to scale. **(A)** α motoneuron in spinal cord of cat (2.6 mm). Reprinted by permission from Cullheim, Fleshman, and Burke (1987). **(B)** Spiking interneuron in mesothoracic ganglion of locust (0.54 mm). Unpublished data from G. Laurent, with permission. **(C)** Layer 5 neocortical pyramidal cell in rat (1.03 mm). Reprinted by permission from Amitai et al., (1993). **(D)** Retinal ganglion cell in postnatal cat (0.39 mm). Reprinted by permission from Maslim, Webster, and Stone (1986). **(E)** Amacrine cell in retina of larval tiger salamander (0.16 mm). Reprinted by permission from Yang and Yazulla (1986). **(F)** Cerebellar Purkinje cell in human. Reprinted by permission from Ramón y Cajal (1909). **(G)** Relay neuron in rat ventrobasal thalamus (0.35 mm). Reprinted by permission from Harris (1986). **(H)** Granule cell from olfactory bulb of mouse (0.26 mm). Reprinted by permission from Greer (1987). **(I)** Spiny projection neuron in rat striatum (0.37 mm). Reprinted by permission from Penny, Wilson, and Kitai (1988). **(J)** Nerve cell in the nucleus of Burdach in human fetus. Reprinted by permission from Ramón y Cajal (1909). **(K)** Purkinje cell in mormyrid fish (0.42 mm). Reprinted by permission from Meek and Nieuwenhuys (1991). **(L)** Golgi epithelial (glia) cell in cerebellum of normal-reeler mouse chimera (0.15 mm). Reprinted by permission from Terashima et al., (1986). **(M)** Axonal arborization of isthmotectal neurons in turtle (0.46 mm). Reprinted by permission from Sereno and Ulinski (1987). The lengths given are approximate and correspond to the maximal extent. Reprinted by permission from Mel (1994).

Structure of the nervous system (cont.):

The three major levels of the *central nervous system* (CNS) are the:

- *spinal cord*,
- *subcortical level* (brainstem, midbrain, cerebellum and thalamus), and
- *cortex*.

The remainder of the nervous system is referred to as the *peripheral* nervous system.

Structure of the nervous system (cont.):

(from Guyten)

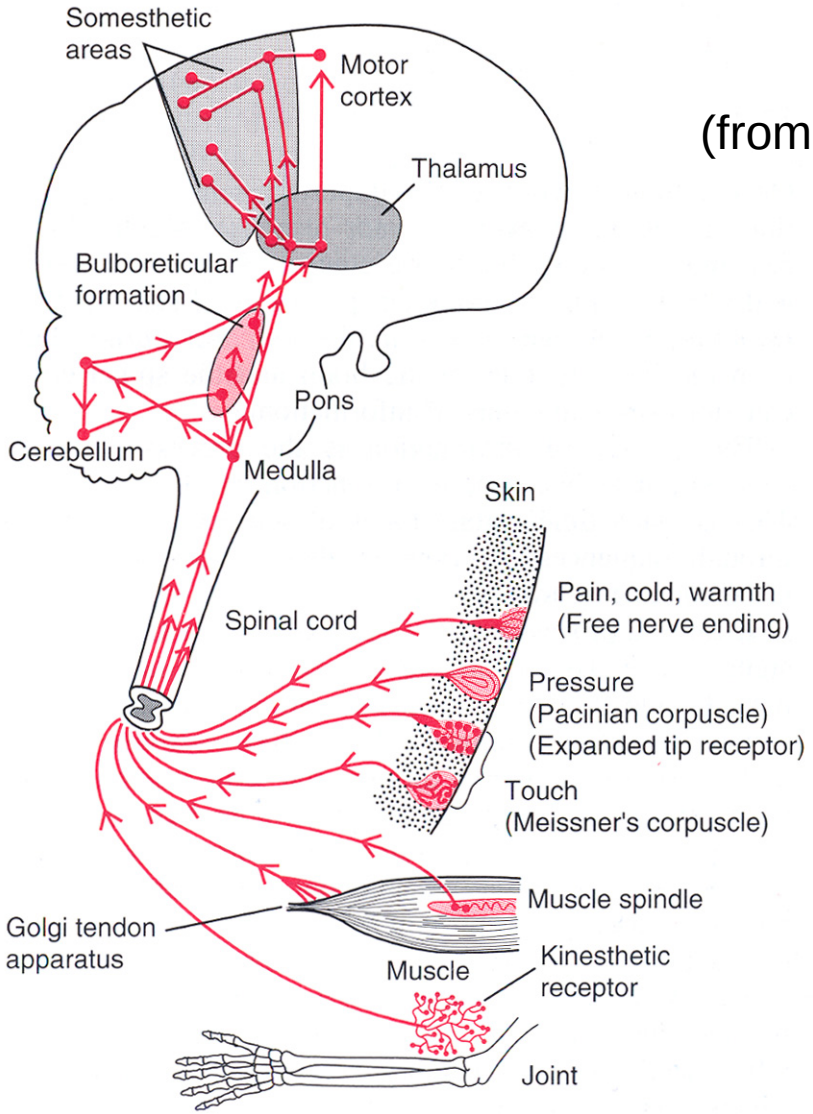


FIGURE 45–2
Somatosensory axis of the nervous system.

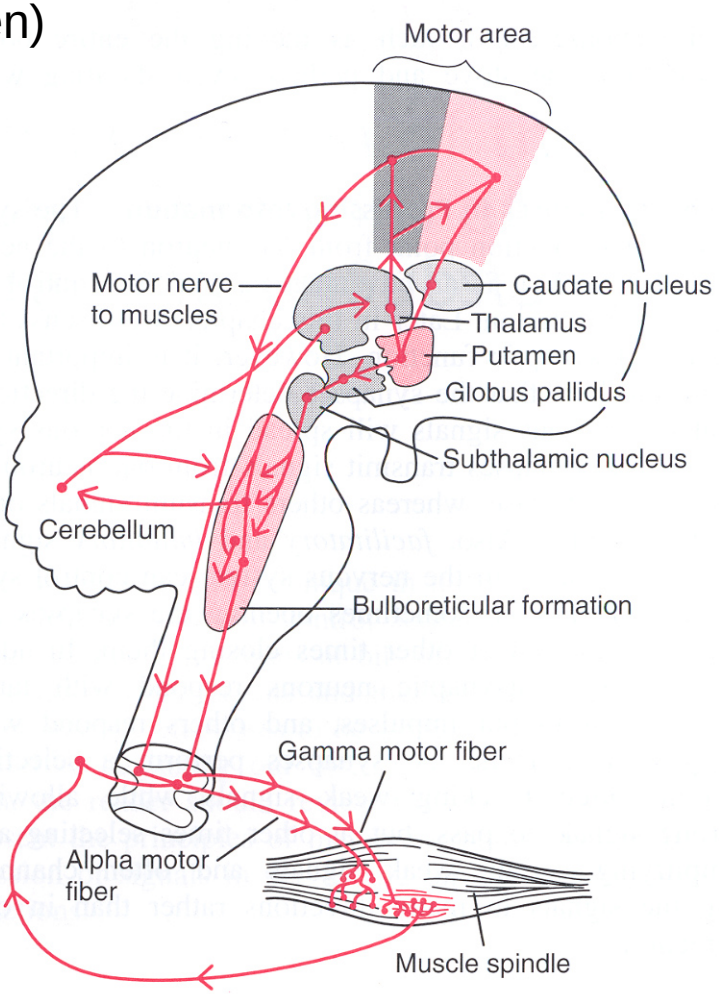


FIGURE 45–3
Skeletal motor nerve axis of the nervous system.

Sensory receptors:

- Transduction from physical signals to neural signals is achieved through *sensory receptor cells*.
- These are specialized excitable cells in the sensory epithelia that typically have a *graded potential* in response to transduction currents, rather than firing action potentials.
- The sensory receptors normally synapse onto spiking neurons.

Sensory receptors (cont.):

For example, inner hair cells (IHCs) in the cochlea (inner ear) produce a graded membrane potential in response to mechanical vibrations in the cochlea that are produced by sound waves.

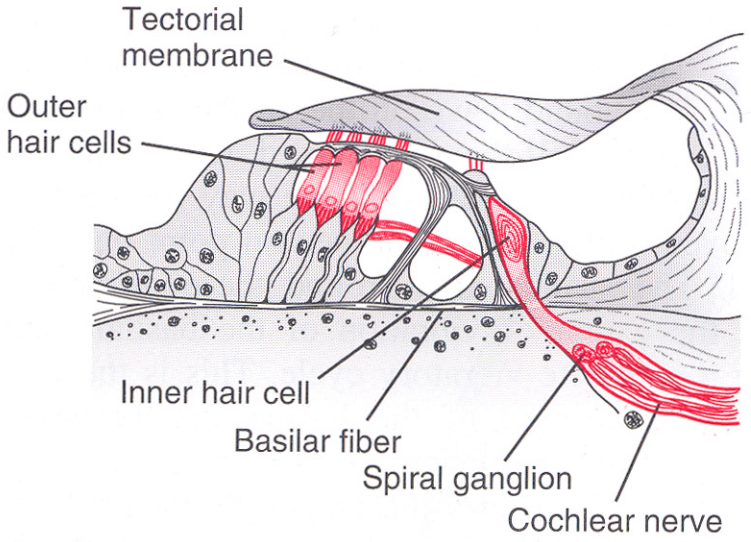


FIGURE 52–7

Organ of Corti, showing especially the hair cells and the tectorial membrane against the projecting hairs.

(from Guyton)

Somatic Sensory Nerve Endings

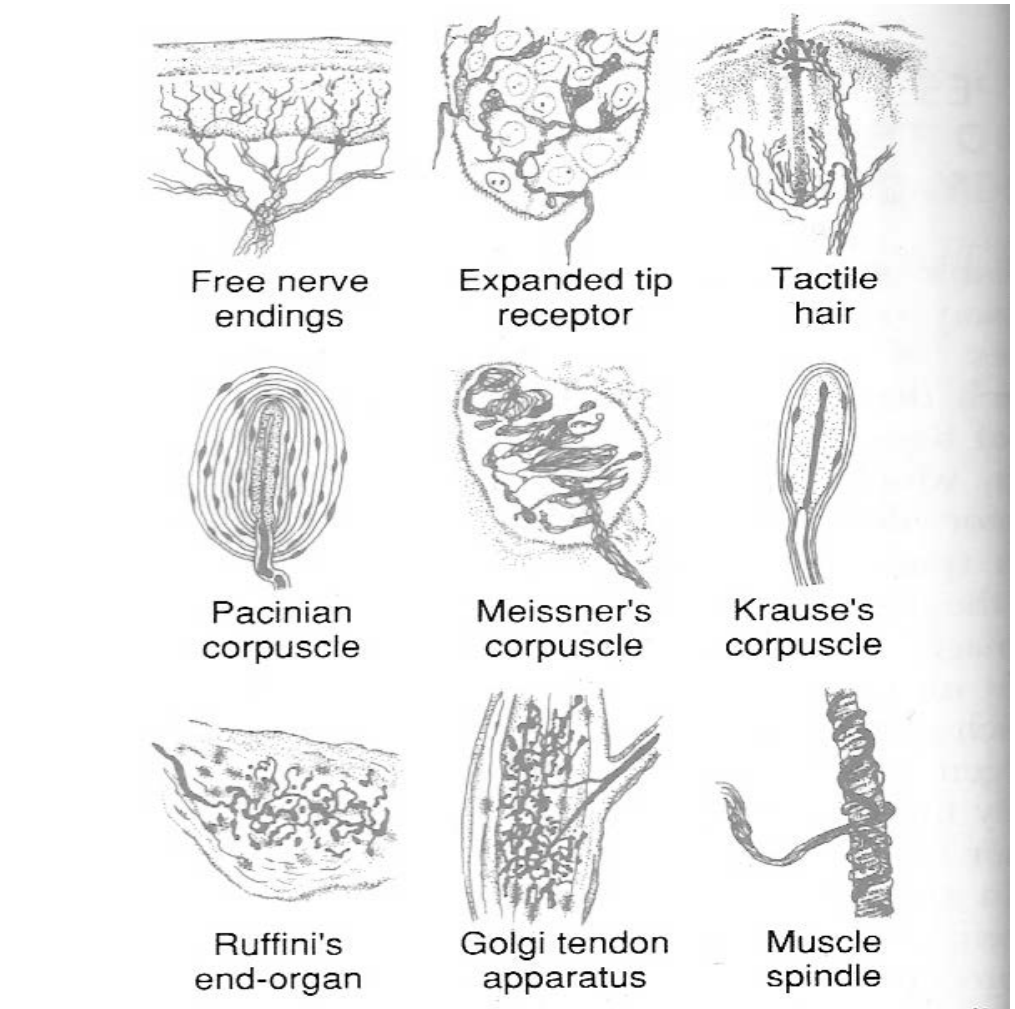


Figure 46–1. Several types of somatic sensory nerve endin

Somatic Receptors
e.g. Iggo Dome

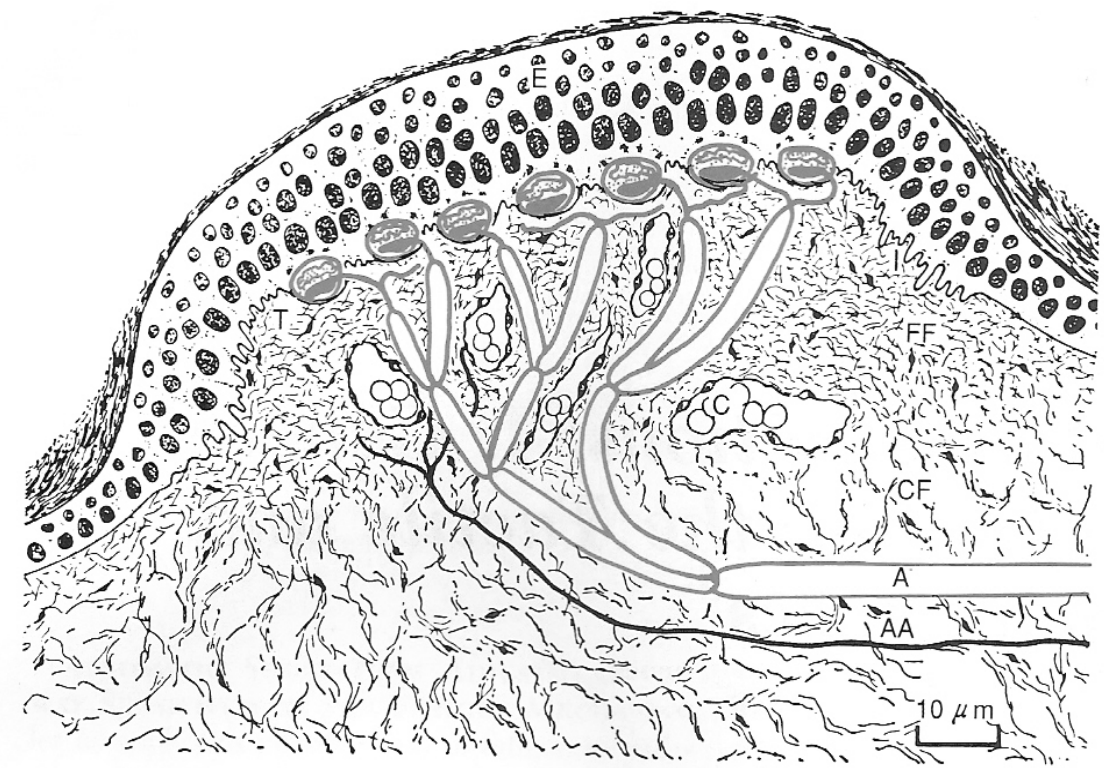


Figure 47–1. Iggo dom
Note the multiple numb
kel's discs innervated
large myelinated fiber a
tightly the undersurface
thelium. (From Iggo and
*siol., 200:*763, 1969.)

Pacinian Corpuscle

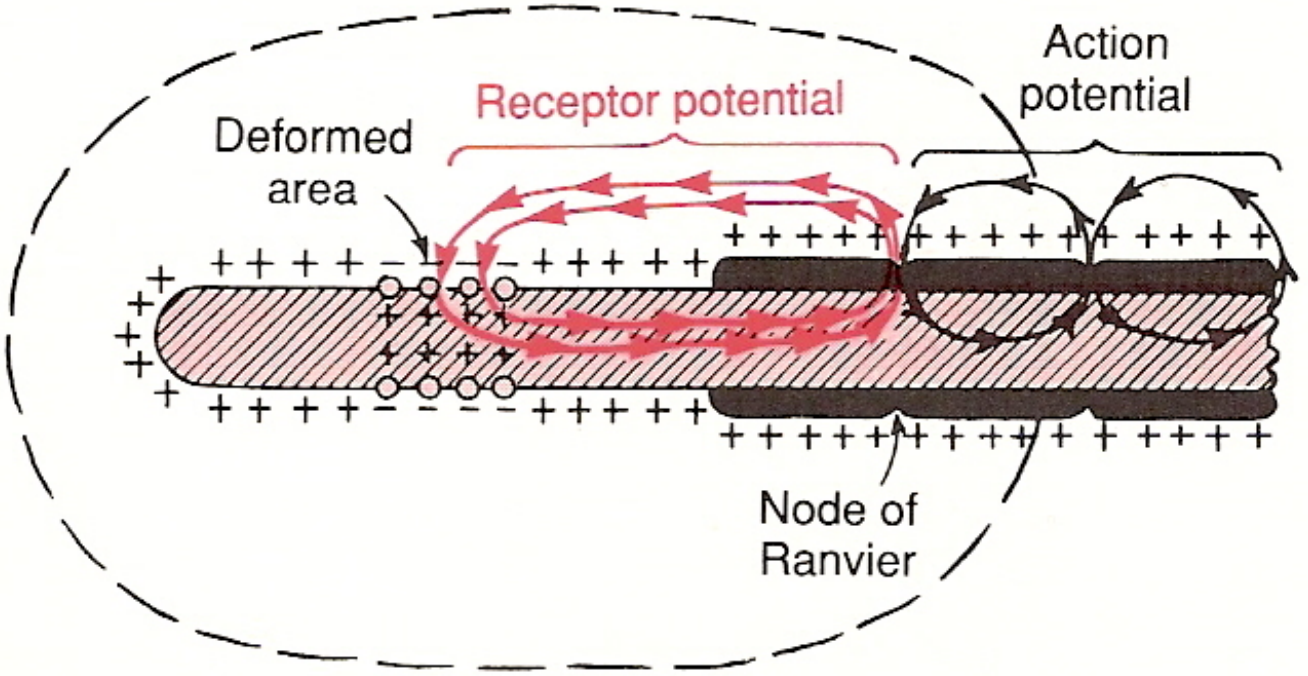


Figure 46–3. Excitation of a sensory nerve fiber by a receptor potential produced in a pacinian corpuscle. (Modified from Loëwenstein: *Ann. N. Y. Acad. Sci., 94:*510, 1961.)

Receptor Potential of Pacinian Corpuscle

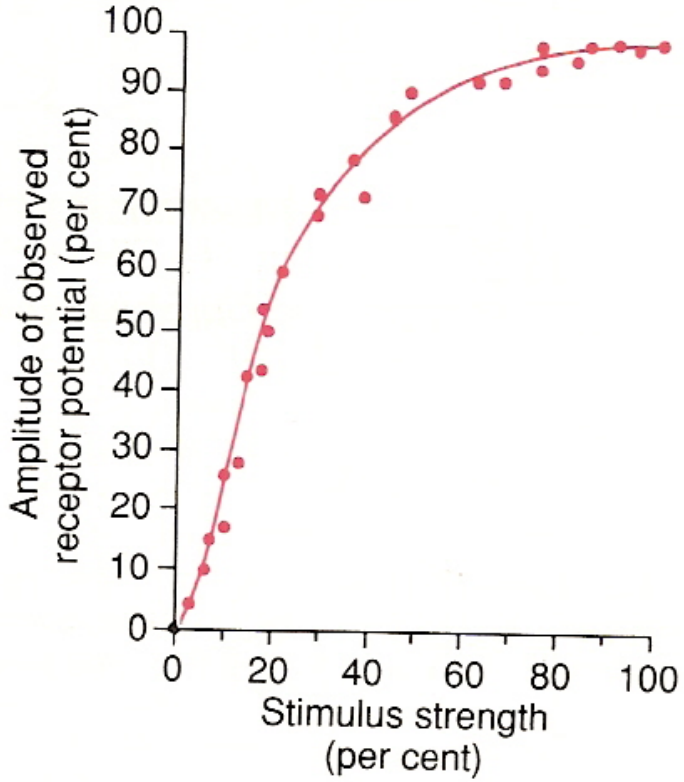
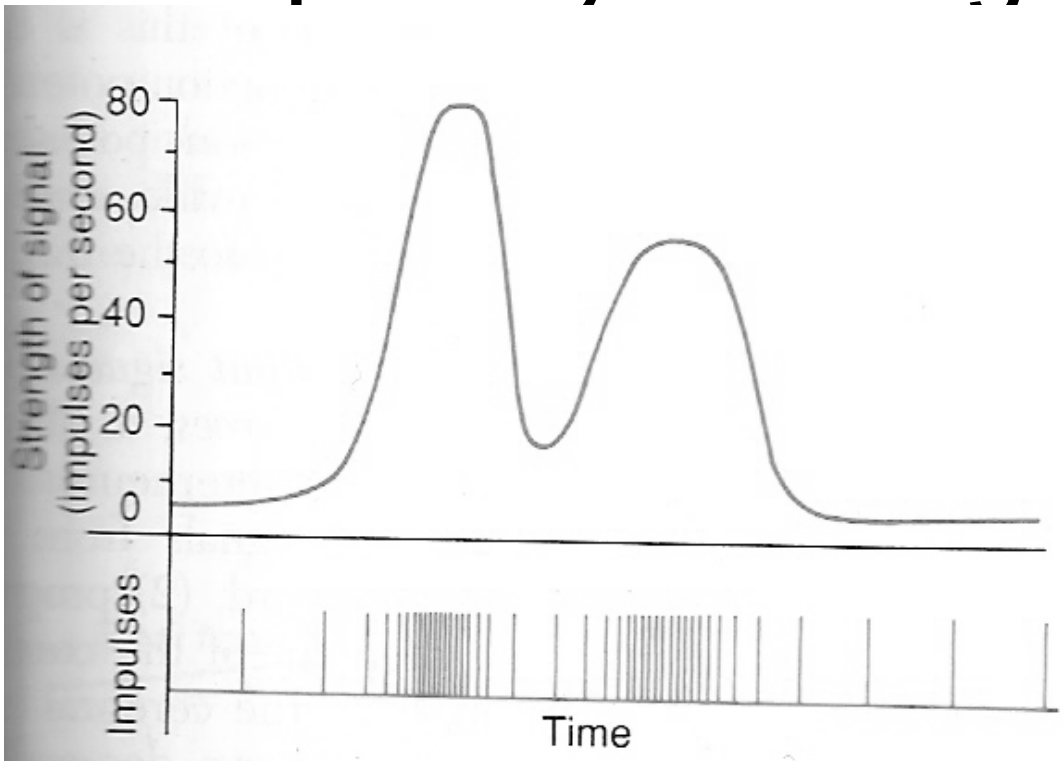


Figure 46–4. Relation of amplitude of receptor potential to strength of a mechanical stimulus applied to a pacinian corpuscle. (From Loëwenstein: *Ann. N. Y. Acad. Sci., 94:*510, 1961.)

Frequency Coding



46–8. Translation of signal strength into a frequency-
ulated series of nerve impulses, showing *above* the
gth of signal and *below* the separate nerve impulses.
s an example of *temporal summation*.

Receptor Adaptation

- Decay of response when sensory stimulus is continuous
- For Pacinian corpuscle fluid redistributes in receptor to make pressures equal
- Slowly adapting receptors provide continuous input to brain (tonic – e.g. muscle spindles)

Receptor Adaptation

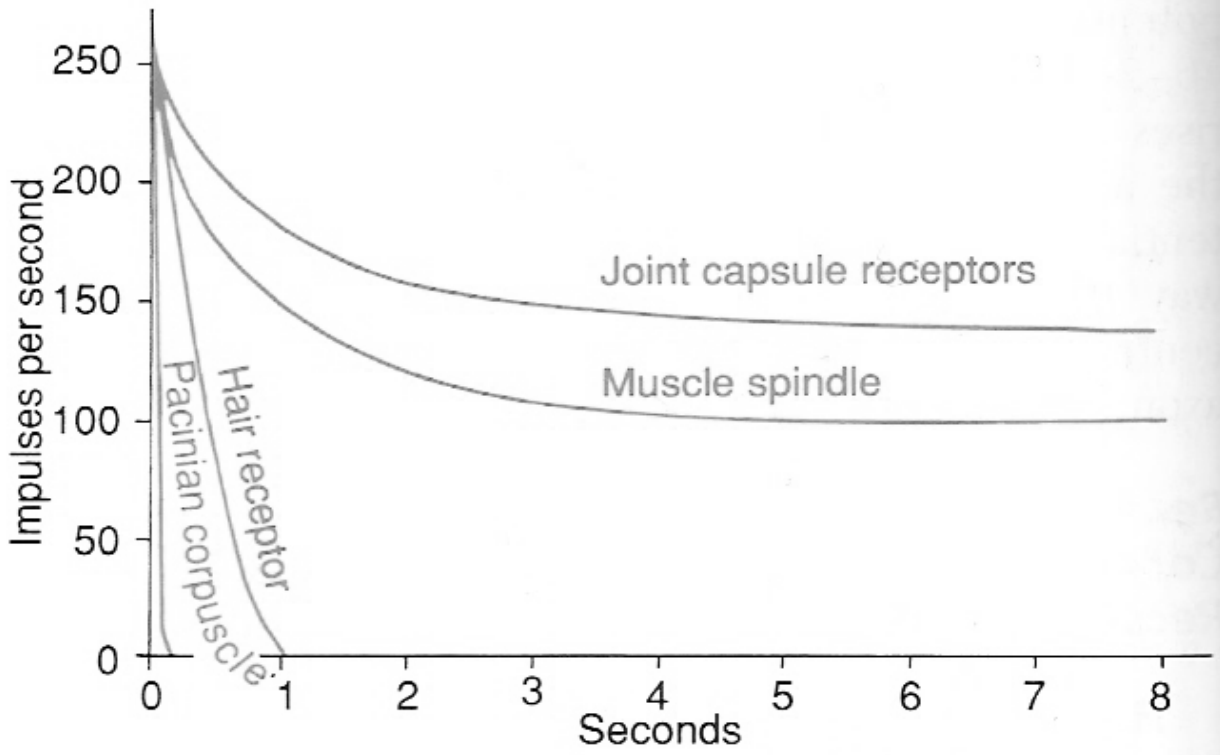


Figure 46–5. Adaptation of different types of receptors, showing rapid adaptation of some receptors and slow adaptation of others.

Neuronal Cell Body properties

- Resting membrane potential -65 mV (vs -90 mV for large peripheral axons) to allow both excitation and inhibition
- Cell dendrites and body (soma) have few sodium channels so individual excitatory post synaptic potentials (EPSP) do not result in action potentials
- Cell body potential is uniform because of geometry and electrolytic conductance
- Action potential generated in initial segment of axon (axon hillock) because it has 7 times number of sodium gates as cell body

Summation of Inputs

- EPSPs and IPSPs from typically ACh rise in 1-2 ms and return to baseline within 15 ms due to diffusion of ions
- Other neurotransmitters can excite or inhibit for 100s of ms, sec, min or hours
- A single input only raises or lowers post synaptic membrane by .5 to 1 mV
- Many simultaneous inputs are spatially summated
- If a presynaptic neuron fires at a high enough rate the single synapse response can be temporally summated giving that synapse much greater possibility of exciting the cell to produce an AP

Neurons:

- Almost all neurons in the CNS of vertebrates are spiking cells.
- The threshold potential and action potential waveform are dependent on the types of ion channels that are present in a particular cell.
- The synaptic input that is required to reach threshold is dependent on the arrangement of the synapses on the dendritic tree and soma, as well as the membrane properties.

Multiple Input Effect on Cell

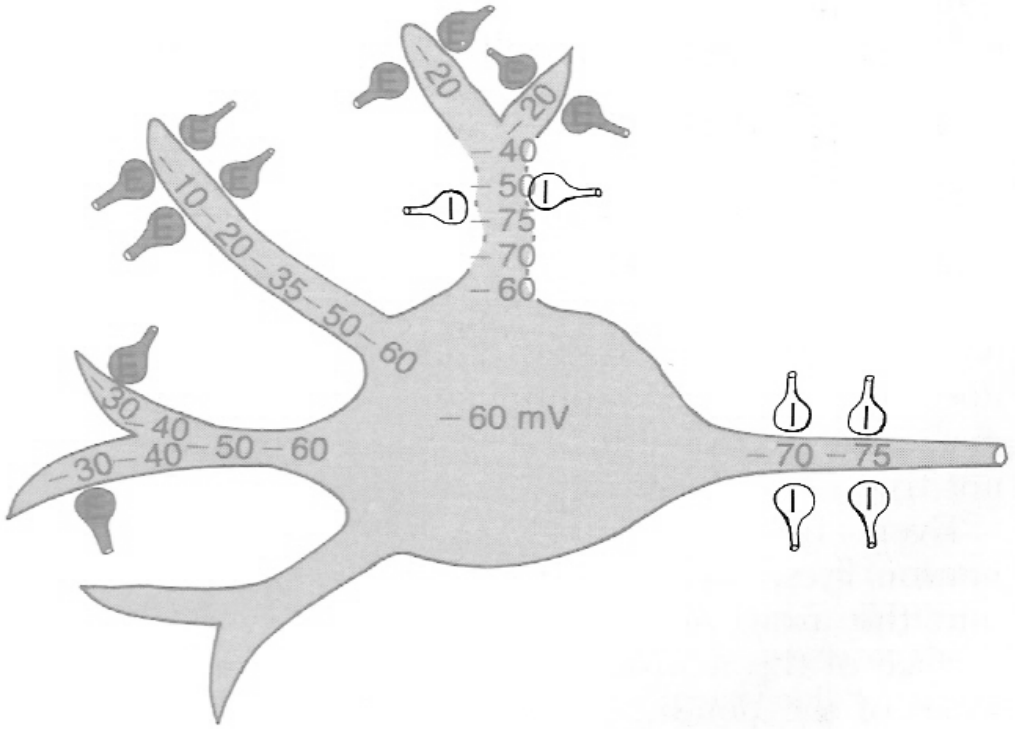


Figure 45–11. Stimulation of a neuron by presynaptic terminals located on dendrites, showing, especially, decremental conduction of excitatory electrotonic potentials in the two dendrites to the left and inhibition of dendritic excitation in the dendrite that is uppermost. A powerful effect of inhibitory synapses at the initial segment of the axon is also shown.

Neural computation:

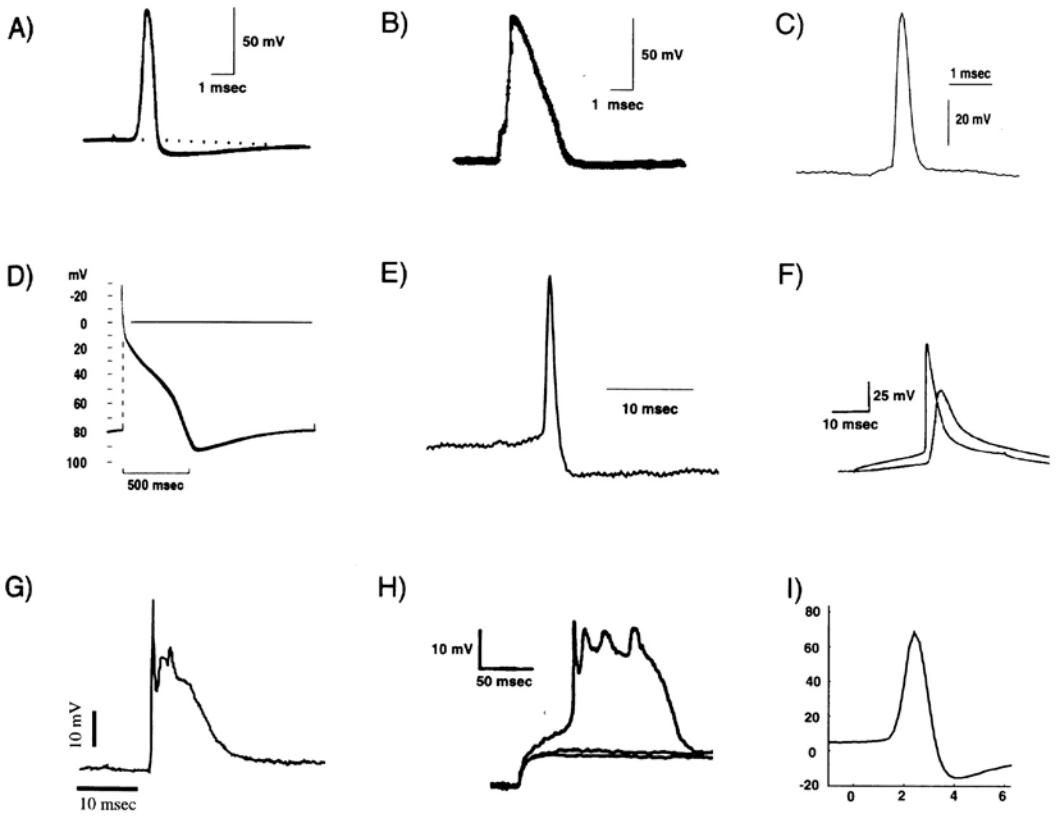
The simplest view of neural computation is that postsynaptic potentials add together linearly, and if the threshold potential is reached, then an AP is generated.

However, more sophisticated computations can also be performed by neurons.

These include:

- multiplication,
- division, and
- coincidence detection.

Neurons (cont.):



(from Koch)

Fig. 6.1 ACTION POTENTIALS OF THE WORLD Action potentials in different invertebrate and vertebrate preparations. Common to all is a threshold below which no impulse is initiated, and a stereotypical shape that depends only on intrinsic membrane properties and not on the type or the duration of the input. **(A)** Giant squid axon at 16° C. Reprinted by permission from Baker, Hodgkin, and Shaw (1962). **(B)** Axonal spike from the node of Ranvier in a myelinated frog fiber at 22° C. Reprinted by permission from Dodge (1963). **(C)** Cat visual cortex at 37° C. Unpublished data from J. Allison, printed with permission. **(D)** Sheep heart Purkinje fiber at 10° C. Reprinted by permission from Weidmann (1956). **(E)** Patch-clamp recording from a rabbit retinal ganglion cell at 37° C. Unpublished data from F. Amthor, printed with permission. **(F)** Layer 5 pyramidal cell in the rat at room temperatures. Simultaneous recordings from the soma and the apical trunk. Reprinted by permission from Stuart and Sakmann (1994). **(G)** A complex spike—consisting of a large EPSP superimposed onto a slow dendritic calcium spike and several fast somatic sodium spikes—from a Purkinje cell body in the rat cerebellum at 36° C. Unpublished data from D. Jaeger, printed with permission. **(H)** Layer 5 pyramidal cell in the rat at room temperature. Three dendritic voltage traces in response to three current steps of different amplitudes reveal the all-or-none character of this slow event. Notice the fast superimposed spikes. Reprinted by permission from Kim and Connors (1993). **(I)** Cell body of a projection neuron in the antennal lobe in the locust at 23° C. Unpublished data from G. Laurent, printed with permission.

Reverberant Circuits

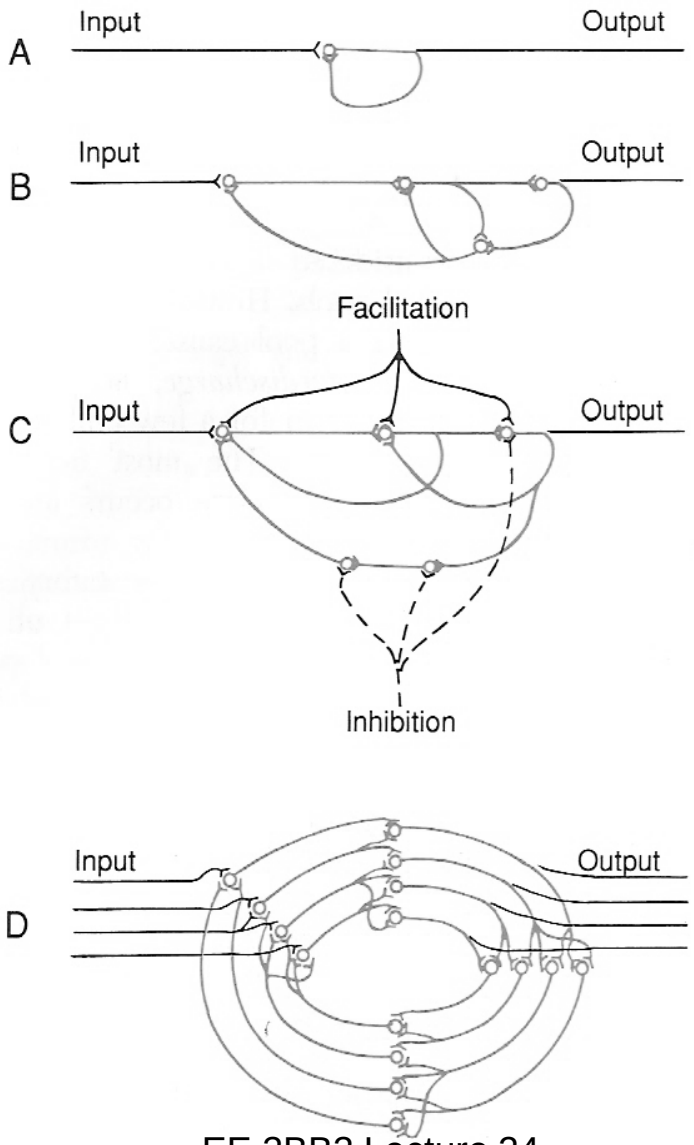


Figure 46–14. Reverberatory circuits of increasing complexity.

Facilitation and Inhibition

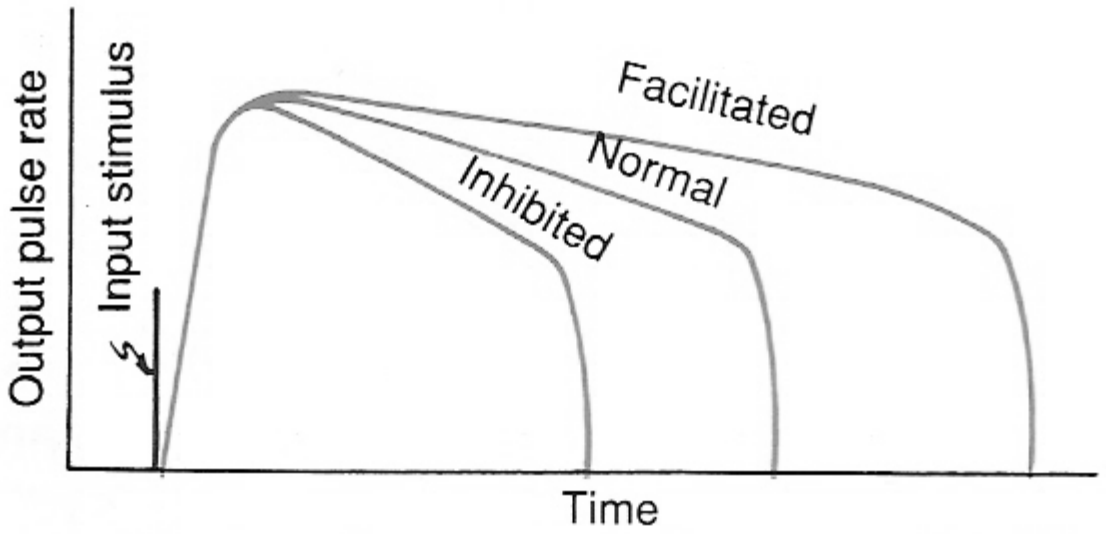


Figure 46–15. Typical pattern of the output signal from a reverberatory circuit after a single input stimulus, showing the effects of facilitation and inhibition.

Neural coding:

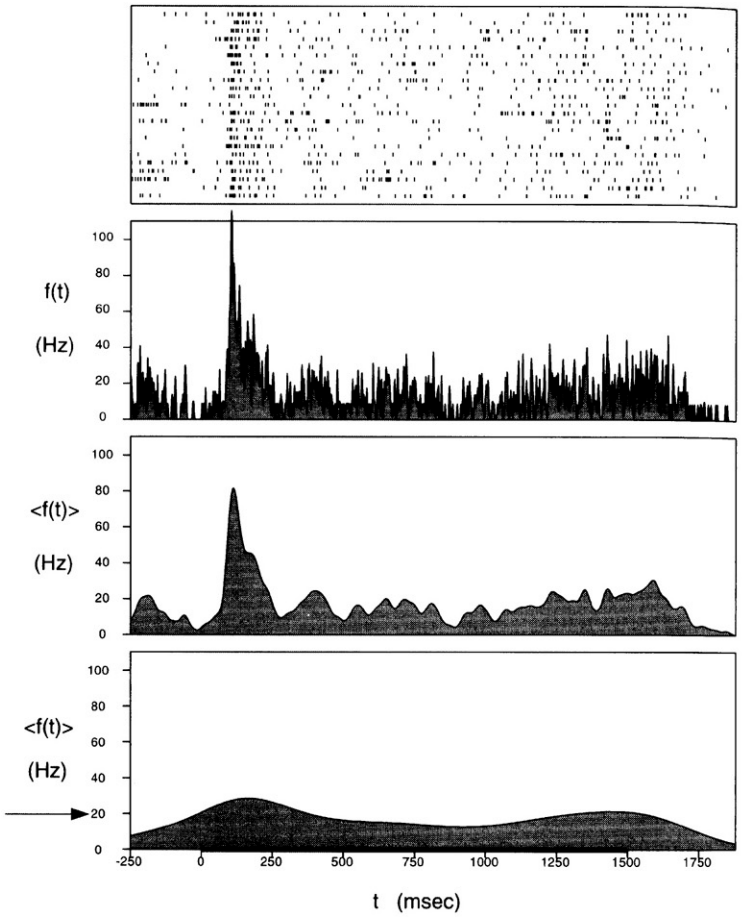
The *waveform* of any action potentials generated in a particular neuron is practically independent of the synaptic input that excited the neuron.

Consequently, all the information that is conveyed by neurons must be contained in the **timing** and/or **rate** of action potentials.

In addition, it will typically be important *which* neurons are firing at a particular time, producing a **spatial** or **population** code.

Neural coding (cont.):

The difference between timing and rate coding depends somewhat on the time scale used to compute the “rate”.



(from Koch)

Fig. 14.1 What Is the Firing Rate Definition of the *firing rate*. The starting point is numerous trials in which the same stimulus is repeatedly presented to the animal and the spikes generated by some cell are recorded. These are shown in the *raster diagram* at the top, taken from a cell in cortical area V4 in the awake monkey. The stimulus—a grating—is flashed on at 0 and lasts until 1500 msec. Twenty-three of these trials are averaged, smoothed with a Gaussian of 2-msec standard deviation σ and normalized. This averaging window is so small that it effectively defines the instantaneous firing rate $f(t)$. These plots are known as *poststimulus time histograms* (PSTHs). The two lower plots illustrate an *average firing rate* $\langle f(t) \rangle$ obtained from the raster diagrams using Gaussian smoothing with σ set to 20 and 200 msec. In many experiments, only the average number of spikes triggered during each trial, corresponding to a very large value of σ (see arrow at 19.5 Hz), is used to relate the cellular response to the behavior of the animal. It is important to realize that a single neuron only sees spike trains and not a smoothly varying firing rate. Unpublished data from D. Leopold and N. Logothetis, printed with permission.

The Neuronal Pool

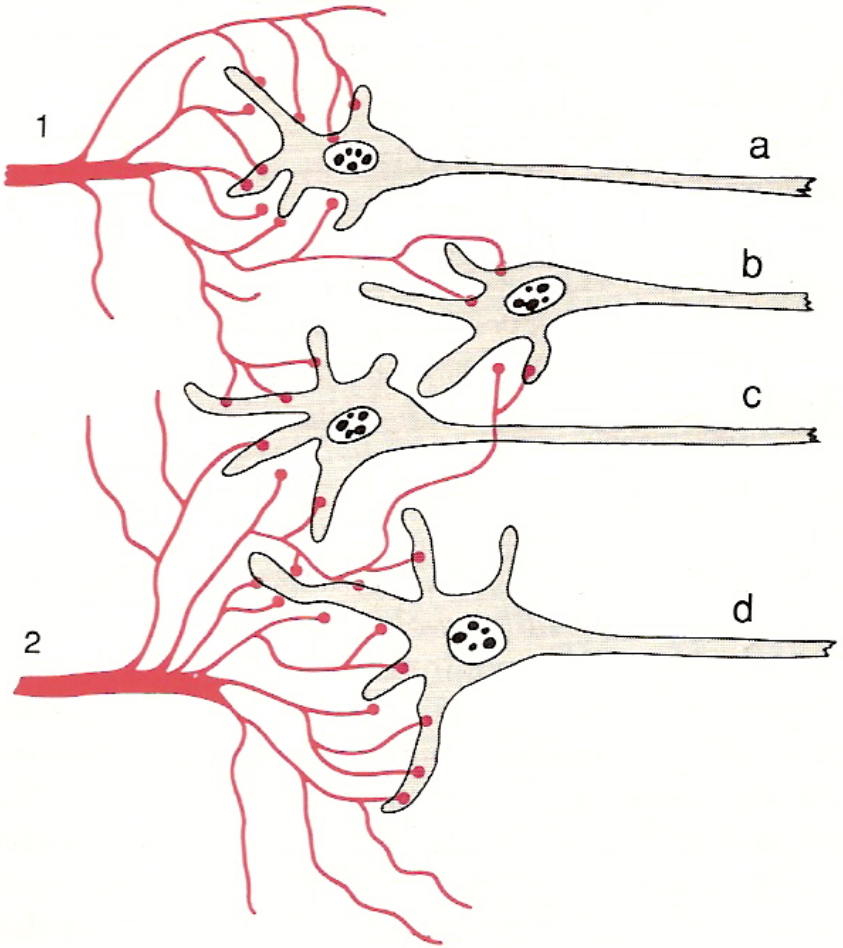


Figure 46–9. Basic organization of a neuronal pool.

Threshold and Subthreshold Stimulation

- Large numbers of synapses must discharge simultaneously for cell to “fire”
- In neuron pool some neurons are in excited or liminal state if they fire due to a given input.
- In neuron pool some neurons in subthreshold or subliminal state if they have synaptic inputs but insufficient to “fire”