The Neurobiology of Animal Movement

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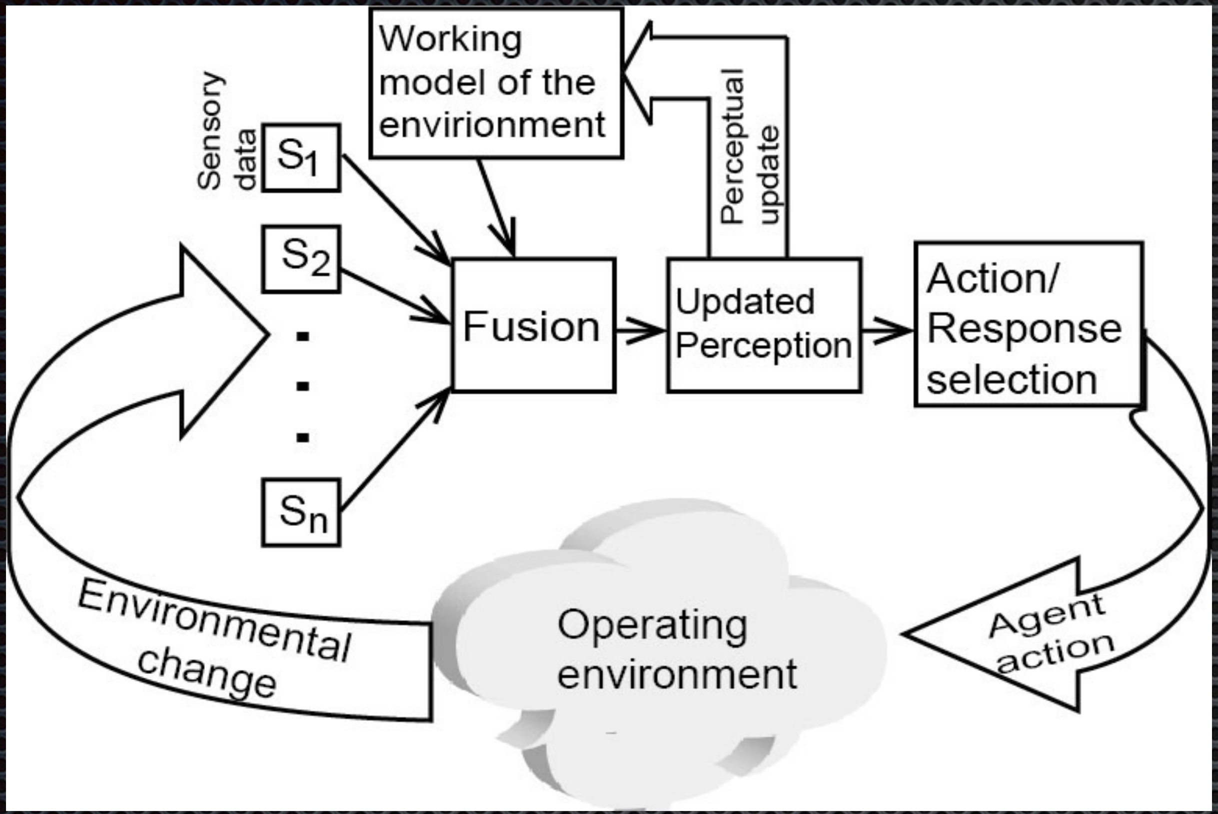
Can autonomy be significantly enhanced through synthetic neuromotor systems?

Leanring and memory: essential ingredients

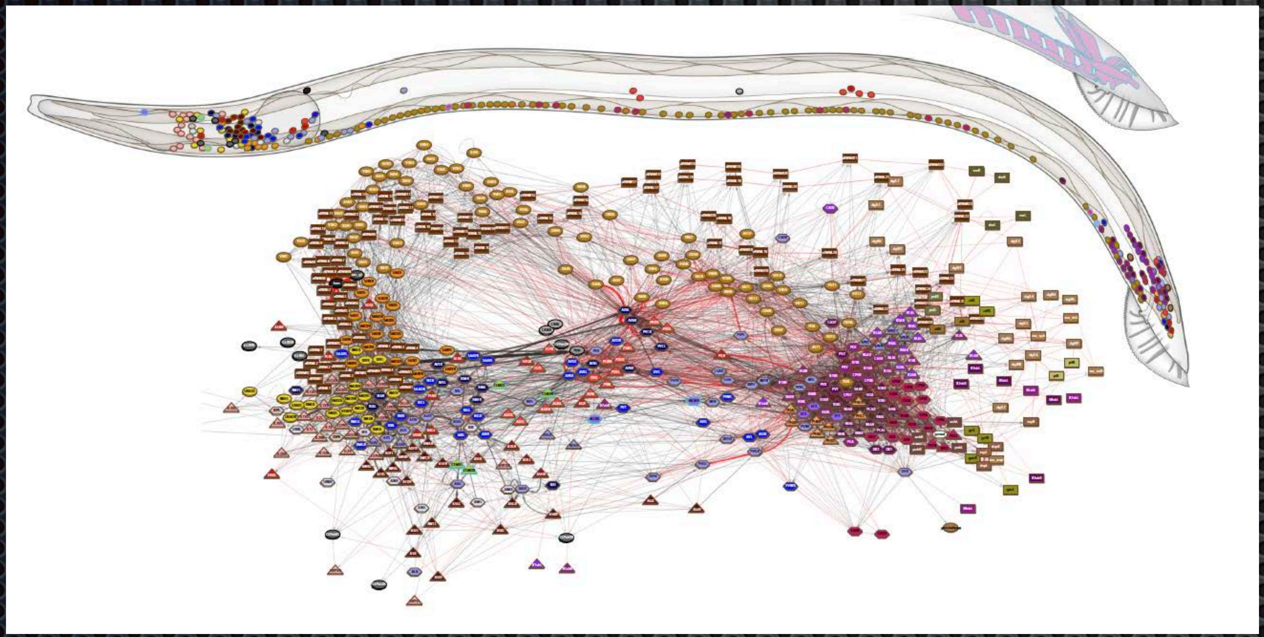


A fundamental distinction between humans and robots in mixed teams is that robots react rapidly to real-time sensor data, whereas humans react to more complex perceptions of the environment in which cognitive processes and prior experience play a role.

The Future: Neuro-inspired autonomy will be informed by emerging advances in unforeseeable ways

- *C. elegans* — all connections from sensory input to end-organ output

Nature https://doi.org/10.1038/s41586-019-1352-7 (July 4, 2019)



	Nodes	Neurons	Muscles	Non-muscle end organs
Hermaphrodite	460	302	132	26
Male	579	385	155	39

	Undirected edges	Directed edges
Hermaphrodite	1,447	4,887
Male	1,755	5,315

The difference between the neuro-biology of *C. elegans* and a higher animal

https://www.youtube.com/watch?v=zLp-edwiGUU

The difference between the neuro-biology of *C. elegans* and a higher animal

Sensory Neurons

Acquire and transmit information from sensory systems to the central nervous system (brain & spinal cord)

~10^2 in *C.elegans*;
~10^9 in humans

Interneurons

Memory, deliberative decision making, emotions, (in primates)

~10^2 in *C.elegans*;
~10^{11} in humans

Motor Neurons

Commands form CNS to muscles and glands

~10^2 in *C.elegans*

Connections:

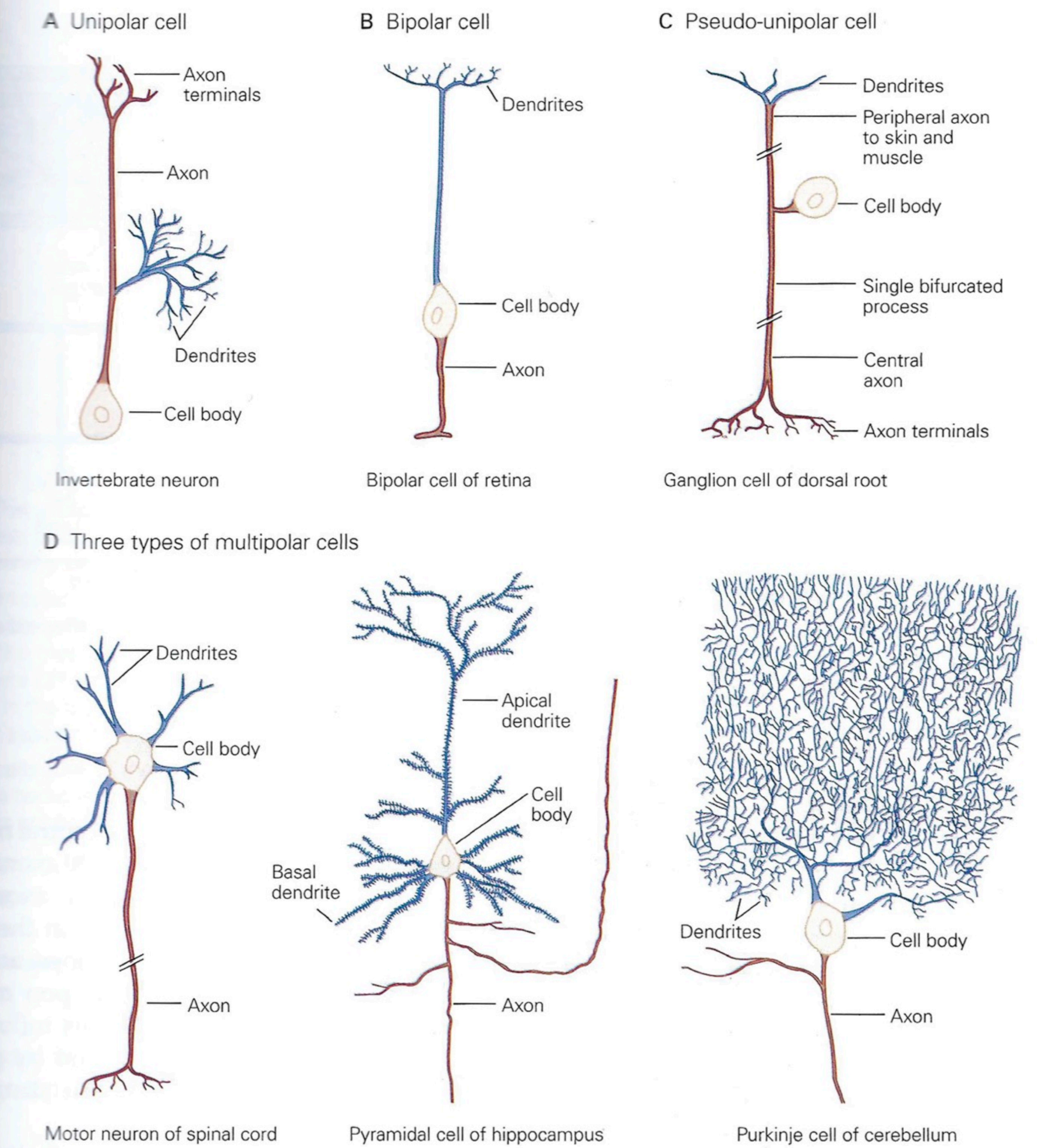
~5 x10^3 in *C.elegans*;
~3 x10^{14} in human adults
~10^{15} in human children

Nerve cell types

Unipolar cells: Two axon branches—one serving as a signal receiving structure

Bipolar cells: a dendritic structure receiving signals from the periphery of the body and an axon that carries information to the central nervous system

Multipolar neurons: a spinal neuron with a modest number of dendrites receives 10,000 contats

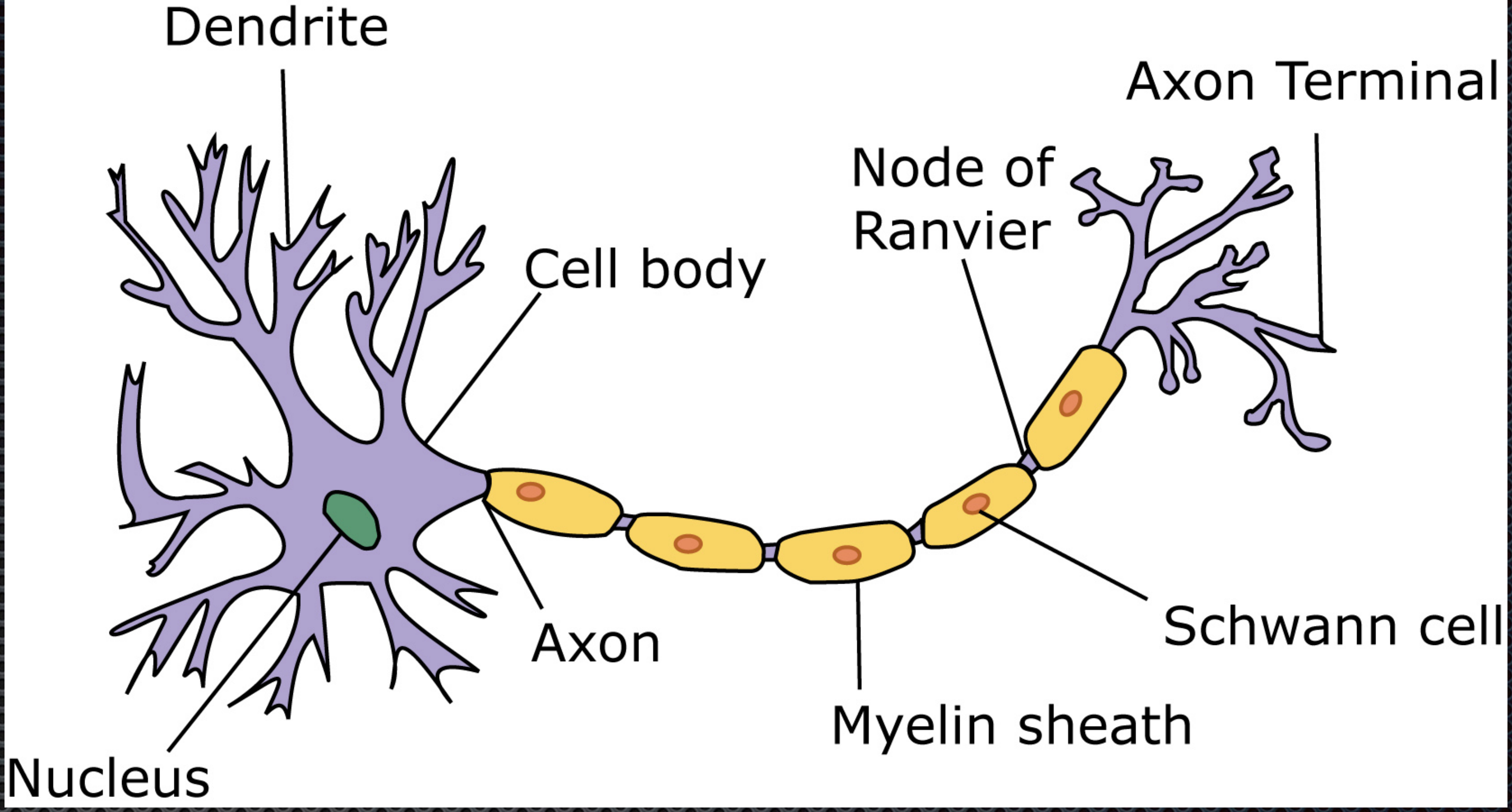


—Thanks to Kandel et al., 2013

How neurons work

Principle of dynamic polarization

Electrical signals in the cell travel in only one direction—from the receiving sites (dendrites) to the trigger region at the base of the axon, and then down the axon to its terminal.



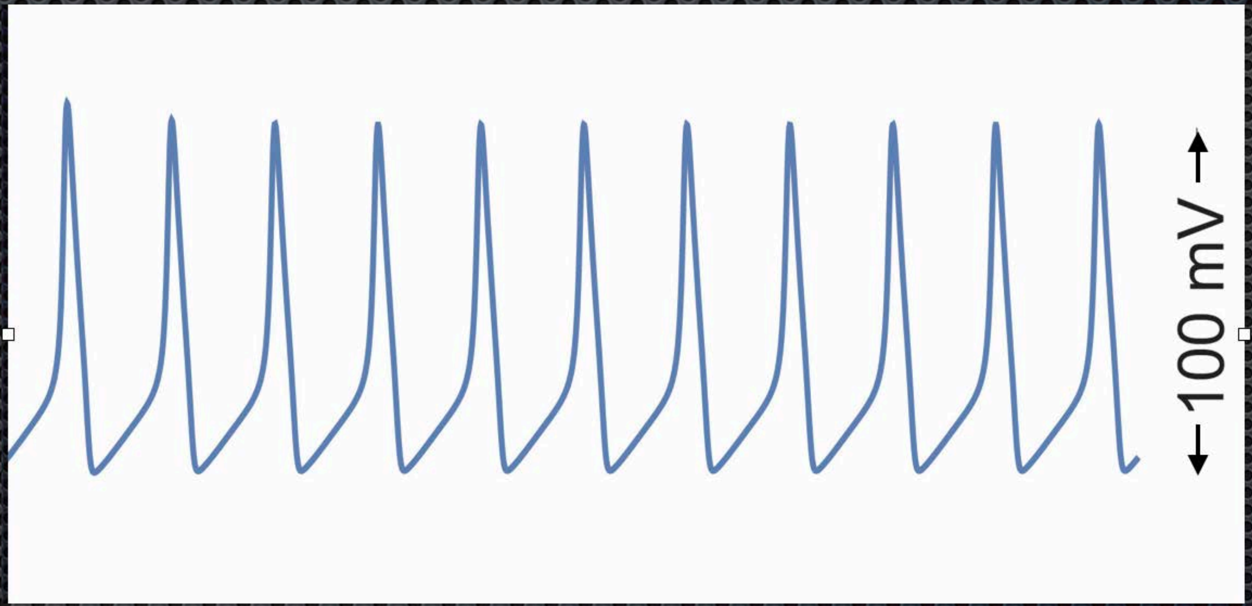
Principle of connectional specificity

Nerve cells do not connect randomly with one another, but rather they make connections only with specific postsynaptic target cells.

Axons carry signals over distances ranging from 0.1 mm to 2 m.

How neurons work

- Axons carry signals over distances ranging from 0.1 mm to 2 m.
- The signals are always sequences of voltage spikes—with the peak of the spike being 100 mV above baseline.
- Signal spikes that convey information about, say, odors are identical to the spikes that convey information about vision.



<u>Fundamental principle of brain function</u>: Information is conveyed not by the form of a transmitted signal, but rather by the pathway over which the signal travels.

How neurons work — The Hodgkin-Huxley Model

- Alan Hodgkin and Andrew Huxley proposed a model in 1952 to explain the ionic mechanisms underlying the initiation and propagation of action potentials in the squid giant axon.

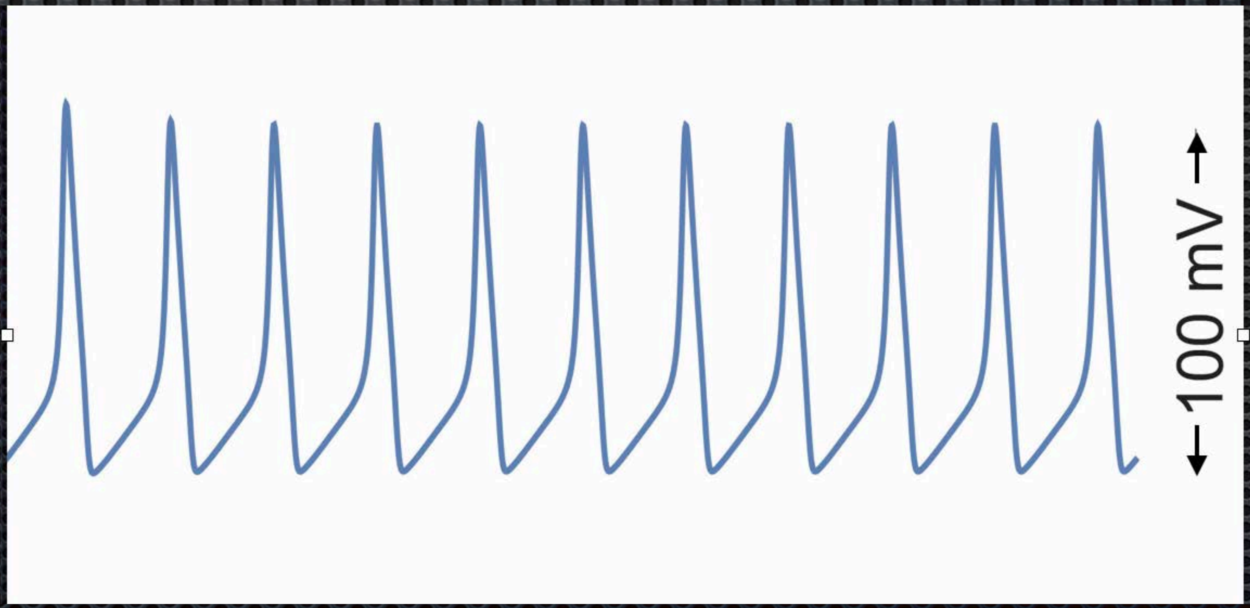
- They received the 1963 Nobel Prize in Physiology or Medicine for this work.

$$I = C_m \frac{\mathrm{d}V_m}{\mathrm{d}t} + \bar{g}_{\mathrm{K}} n^4 (V_m - V_K) + \bar{g}_{\mathrm{Na}} m^3 h (V_m - V_{Na}) + \bar{g}_l (V_m - V_l),$$

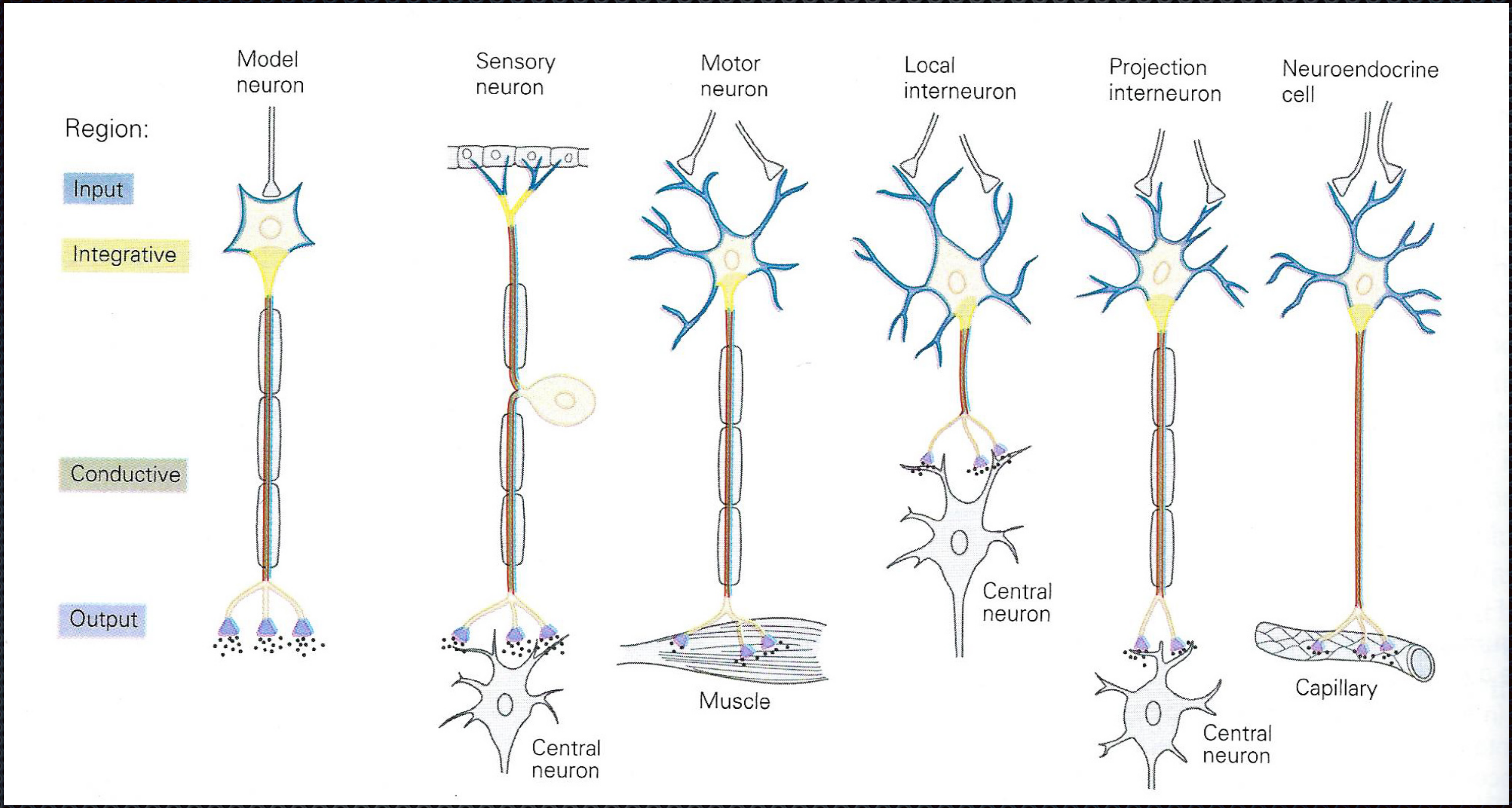
$$\frac{dn}{dt} = \alpha_n(V_m)(1-n) - \beta_n(V_m)n$$

$$\frac{dm}{dt} = \alpha_m(V_m)(1-m) - \beta_m(V_m)m$$

$$\frac{dh}{dt} = \alpha_h(V_m)(1-h) - \beta_h(V_m)h$$

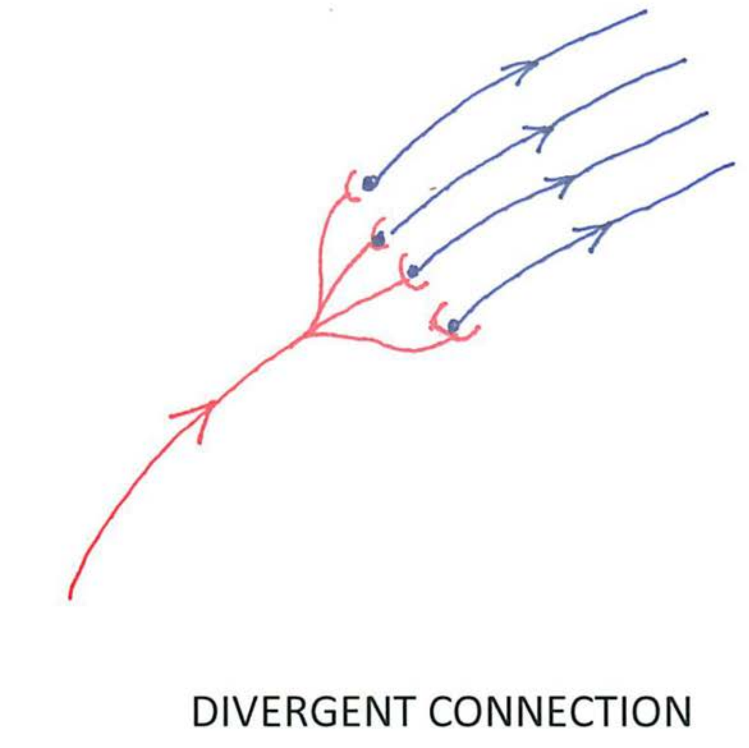


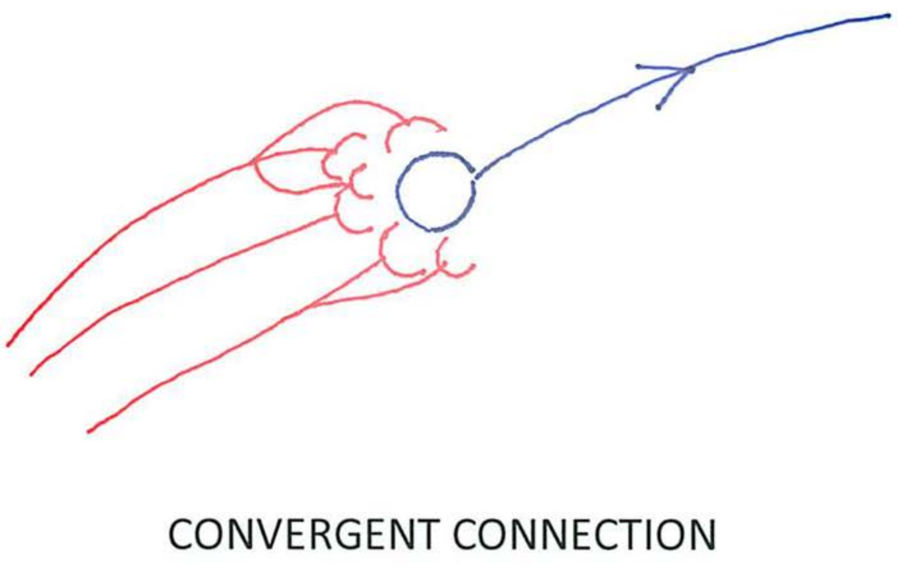
Types of neurons by function



—Thanks to E. Kandel et al., 2013

Types of neuronal connections

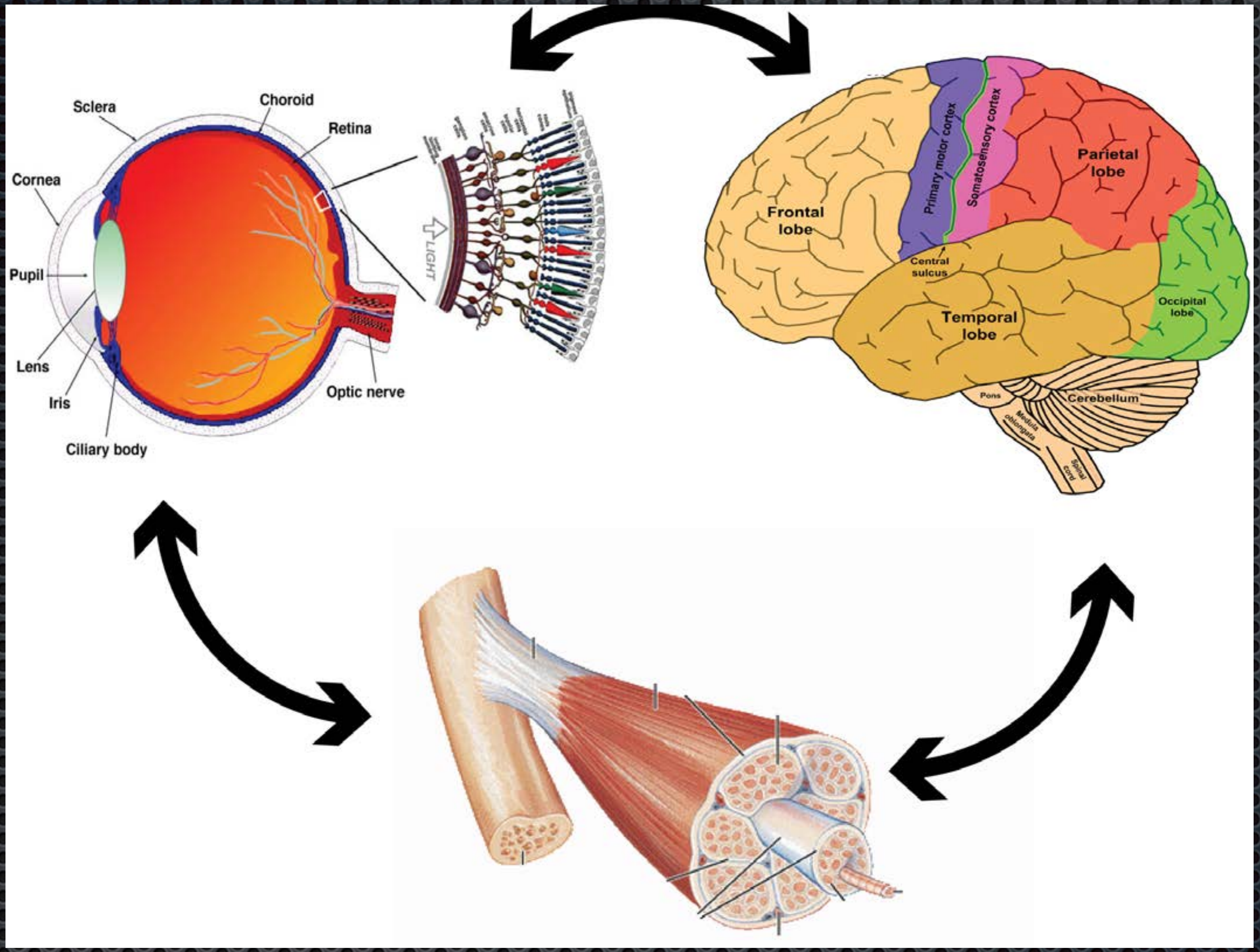




Sensory neurons typically contact several neurons, and these neurons in turn may diverge even more—the net effect is to spread sensory information more widely in the brain.

Motor neurons, on the other hand, typically have multiple incoming connections from multiple neurons.

Control over feature-actuator networks with channel intermittency:



$$\dot{x} = Ax + Bu$$

$$y = Cx$$

$$x \in \mathbb{R}^n, \quad u \in \mathbb{R}^m, \quad y \in \mathbb{R}^q$$

$$m \gg 1, \; q \gg 1$$

One of the advantages of large numbers of control inputs

Theorem: Suppose A, B is a controllable pair with A, B $n \times n$ and $n \times m$ matrices respectively. Let $u_0(t) \in \mathbb{R}^m$ be the optimal control steering the system from $x_0 \in \mathbb{R}^n$ to $x_1 \in \mathbb{R}^n$ having minimum cost

$$\eta = \int_0^T \|u(t)\|^2 \, dt.$$

Let $\bar{b} \in \mathbb{R}^n$ and consider the augmented $n \times (m+1)$ matrix

$\hat{B} = (B \vdots \bar{b})$. The $(m+1)$-dimensional control input $\hat{u}_0(t)$ that steers

$$\dot{x}(t) = Ax(t) + \hat{B}\hat{u}(t)$$

from $x_0 \in \mathbb{R}^n$ to $x_1 \in \mathbb{R}^n$ so as to minimize

$$\hat{\eta} = \int_0^T \|\hat{u}(t)\|^2 \, dt$$

has optimal cost $\eta_1 \leq \eta_0$.

Other advantages of large numbers of control inputs?

$$\dot{x} = Ax + Bu$$
$$y = Cx$$

$$A = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \vdots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix}$$

$$\text{Tall}\left\{ C = \begin{pmatrix} c_{11} & \cdots & c_{1n} \\ c_{21} & \cdots & c_{2n} \\ \cdots & \cdots & \cdots \\ \vdots & \vdots & \vdots \\ c_{q1} & \cdots & c_{qn} \end{pmatrix} \right.$$

$$B = \underbrace{\begin{pmatrix} b_{11} & b_{12} & \cdots & b_{1m-1} & b_{1m} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{nm-1} & b_{nm} \end{pmatrix}}_{\text{Long}}$$

Classes of standard inputs from which to choose:

Proposition Let $\dot{x} = Ax + Bu$ be controllable, and let the $m \times n$ matrix K be chosen such that the eigenvalues of $A + BK$ are in the open left half plane and the vector v is is chosen to satisfy

$$(A + BK)x_g + Bv = 0.$$

Then the m control inputs

$$u_j(t) = v_j + k_{j1}x_1(t) + \cdots + k_{jn}x_n(t)$$

steer the system toward the goal x_g.

Definition Let P be a projection matrix with k $1's$ on the main diagonal and zeros elsewhere. The system defined above is said to be *k-channel controllable with respect to P* if for all $T > 0$, the matrix

$$W_P(0,T) = \int_0^T e^{A(T-s)} BPB^T e^{A(T-s)^T} \, ds.$$

is nonsingular.

Standard inputs resilient to channel dropouts:

Theorem Consider the linear system $\dot{x} = Ax + Bu$ in which the number of control inputs, m, is strictly larger than the dimension of the state, n and in which rank $B = n$. Let the gain K be chosen such that $A + BK$ is Hurwitz, and assume that

i) P is a projection in the definition and the systerm is ℓ-channel controllable with respect to P;

ii) $A + BPK$ is Hurwitz;

iii) the solution $\hat{A}$ of $B\hat{A} = A$ is invariant under P—i.e., $P\hat{A} = \hat{A}$; and

iv) BP has rank n.

The the *standard* control inputs defined on the previous slide steer the system toward the goal point x_g whether or not the $(m - \ell)$ input channels that are mapped to zero by P are available.

—Reference: JB, "Perceptual Control with Large Feature and Actuator Networks," IEEE Conference on Decision and Control, 2019. Also, https://arxiv.org/abs/1903.10259.

Geometry/topology plays a role in sensory motor control of animal movement

Hafting et al., (2005). "Microstructure of a spatial map in the entorhinal cortex," *Nature* 436, DOI: 10.1038/nature03721

John O'Keefe, May-Britt and Edvard Moser

M. Hasselmo

Hasselmo and Brandon, (2012). "A model combining oscillations and attractor dynamics for generation of grid cell firing," *Front. Neural Circuits,* DOI: 6:30.10.3389/fncir.2012.00030

Emergent geometry of the entorhinal cortex

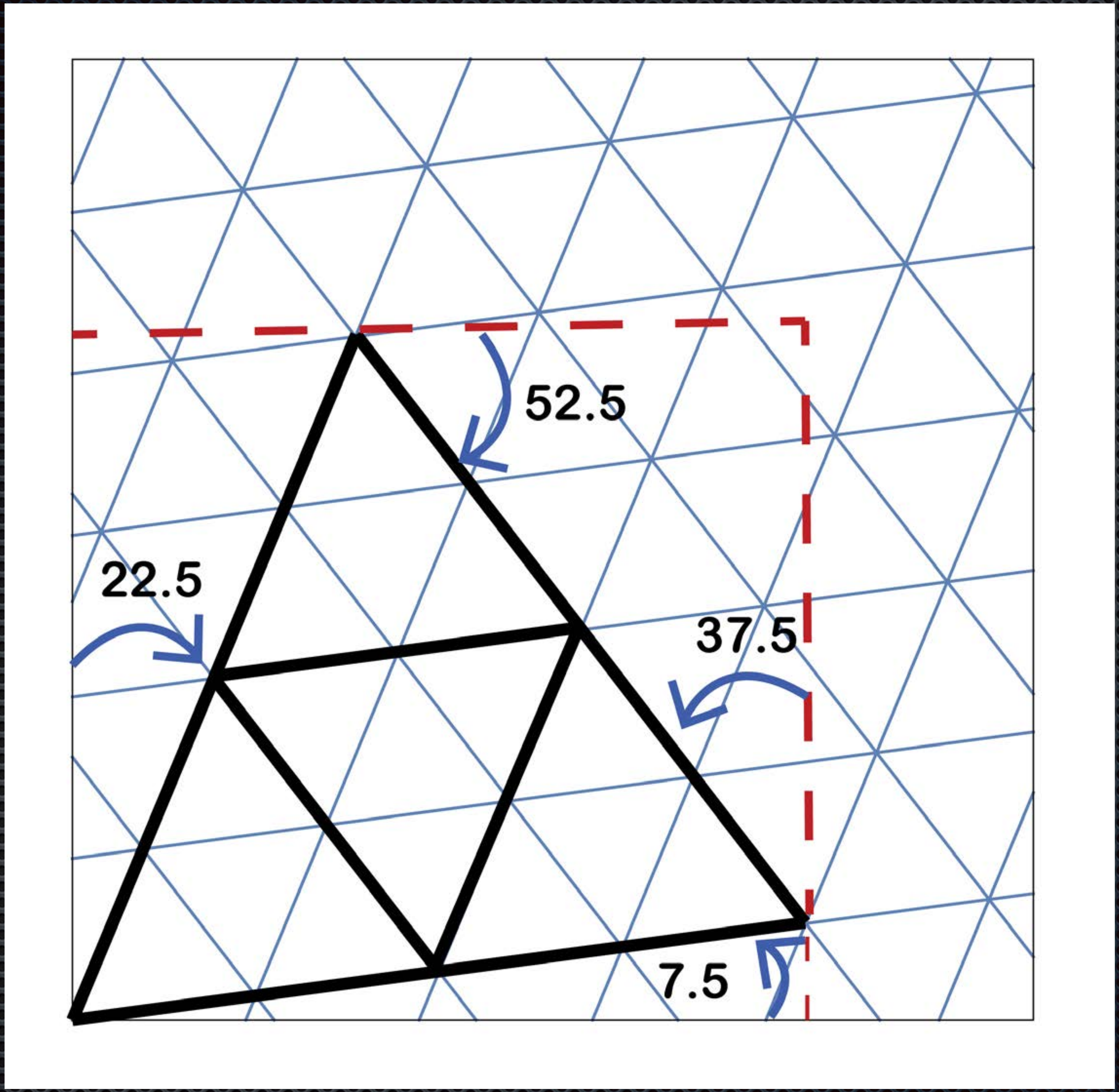
A feature network is a field of sensed elements that causes the emergence of a network of firing neuronal patterns. The firing patterns of grid cell neurons create a triangular grid pattern.

— Moser and Moser, 2010

Emergent geometry of the entorhinal cortex

Consistent across animal subjects. In this case the features are the four sides of the experimental arena, and the emergent neuronal firings show up as a set of hexagonal grids of various length scales.

Emergent geometry of the entorhinal cortex



Consistent across animal subjects.

Feature networks and how they convey information

Stretch Goal: Understand how brain networks encode sensory perceptions and recruit motor neurons to create appropriate motion responses.

Modest Goal: Design perception-based robot navigation that plausibly replicates what is observed in the natural world.

Images and definitions in todays lecture are from . . .