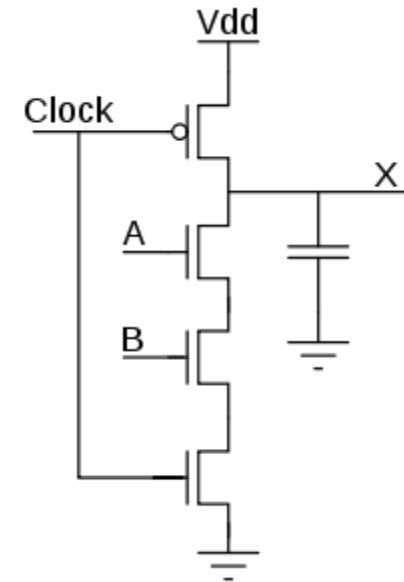


Physical Design of Biological Systems

Insights from the Fly Brain

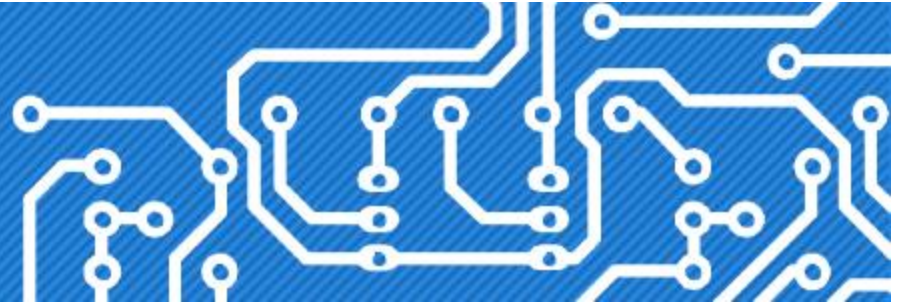


Lou Scheffer
ISPD
March 2021



Who cares how the fly brain works?

International Symposium
on Physical Design



- ISPD a conference about IC design tools, not biology!
- However, biological brains are subject to the same constraints and objectives as chips.
- Detailed implementation methods are different; maybe there are ideas we



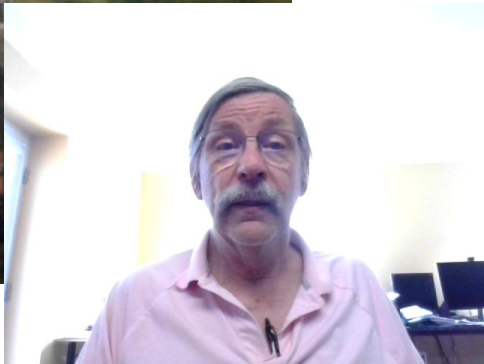
Objective of physical design is the

- S
- F
- C
- k



ogy)





https://upload.wikimedia.org/wikipedia/commons/f/fc/Intel_Costa_12_2007_SJO_105b.jpg

Instead of conditions like this



https://commons.wikimedia.org/wiki/File:Cleanroom_suit.jpg



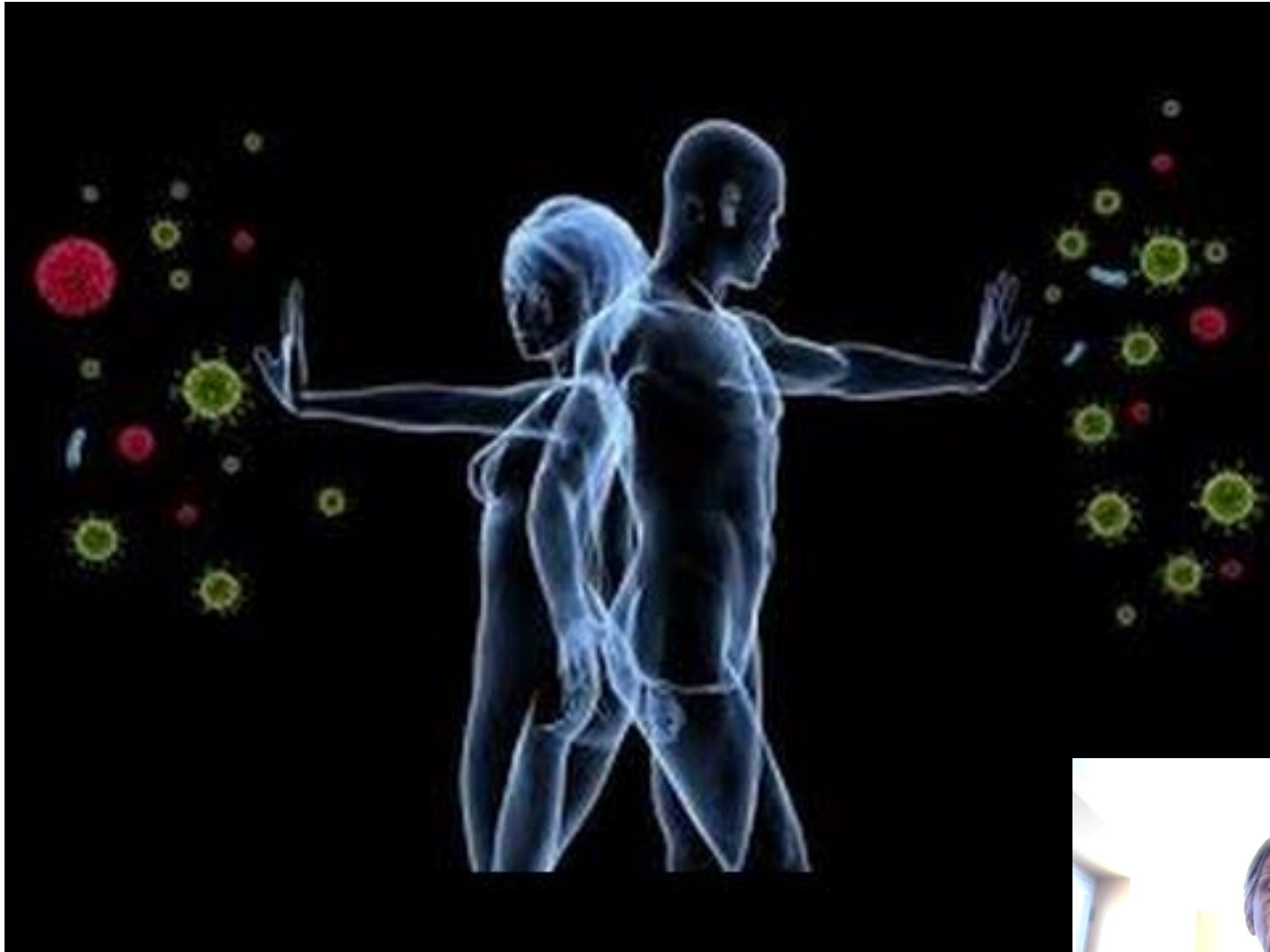
Biology can use conditions like this



https://commons.wikimedia.org/wiki/File:DISCARDED_TIRE_FRAMES_REEDS_IN_A_BACKWATER_OF_THIRUPATI_NARA_-_552255.jpg



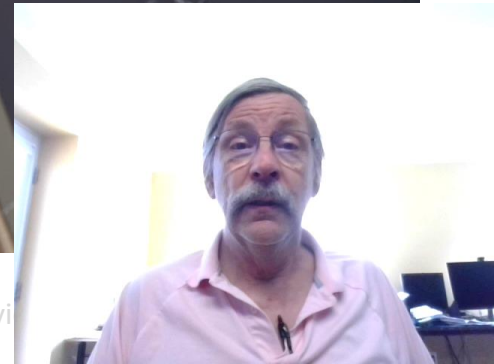
Defends against novel threats



<https://www.youtube.com/watch?v=F3-yE1a9pmQ>



Repairs itself

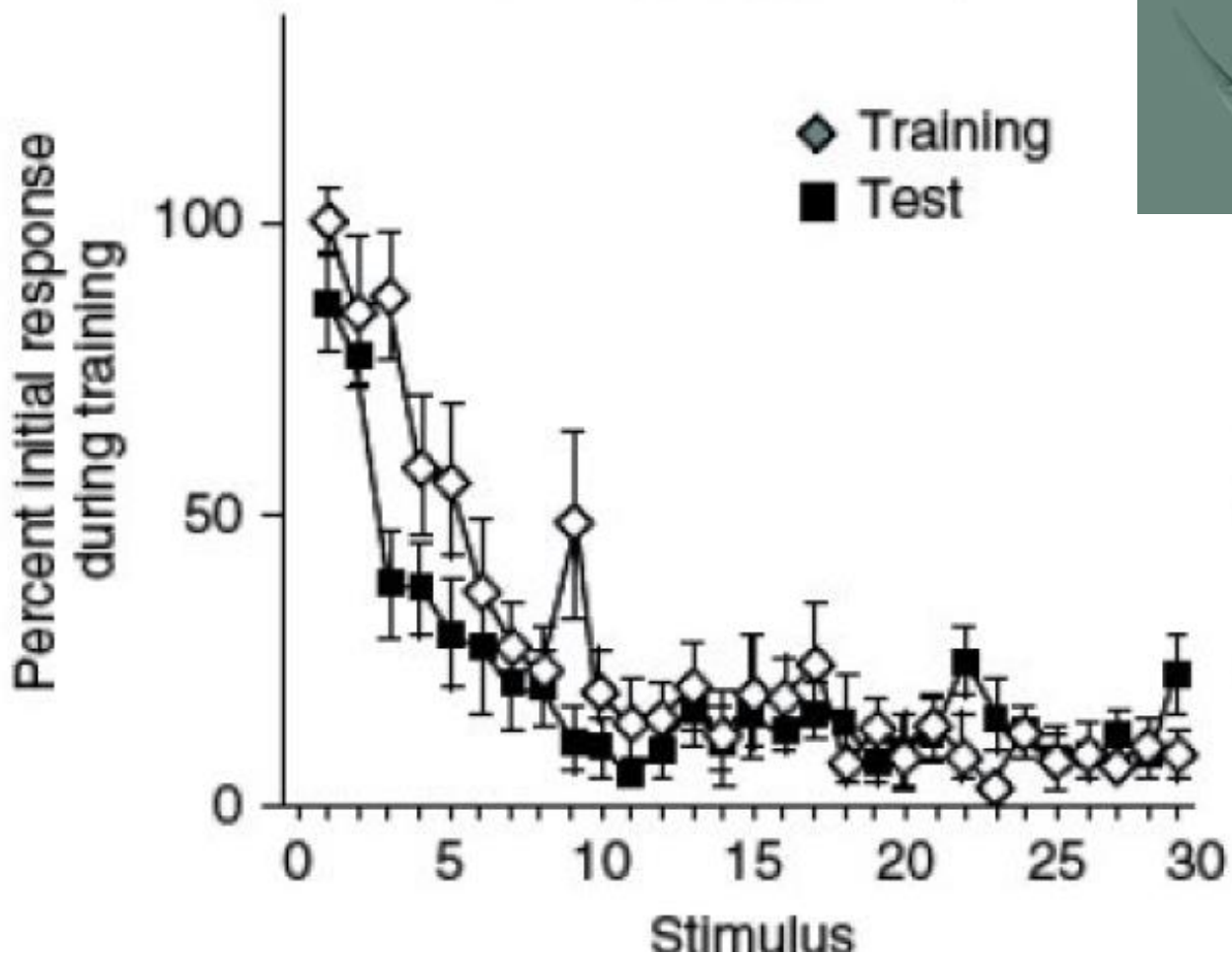


Life learns and adapts (Unsupervised)



302 neurons

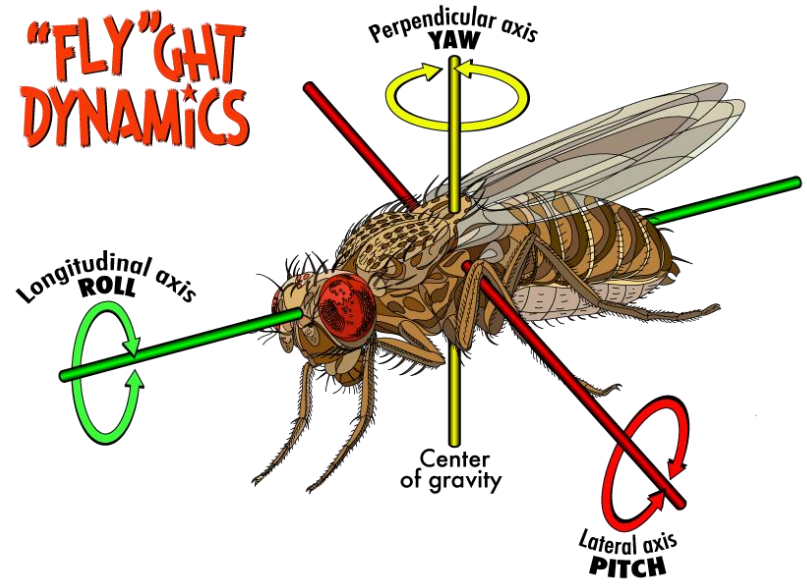
Training-only control



Biology uses way less power



2-6S MINI Stack
MINI F405
35A 4IN1
XF5806 400MW

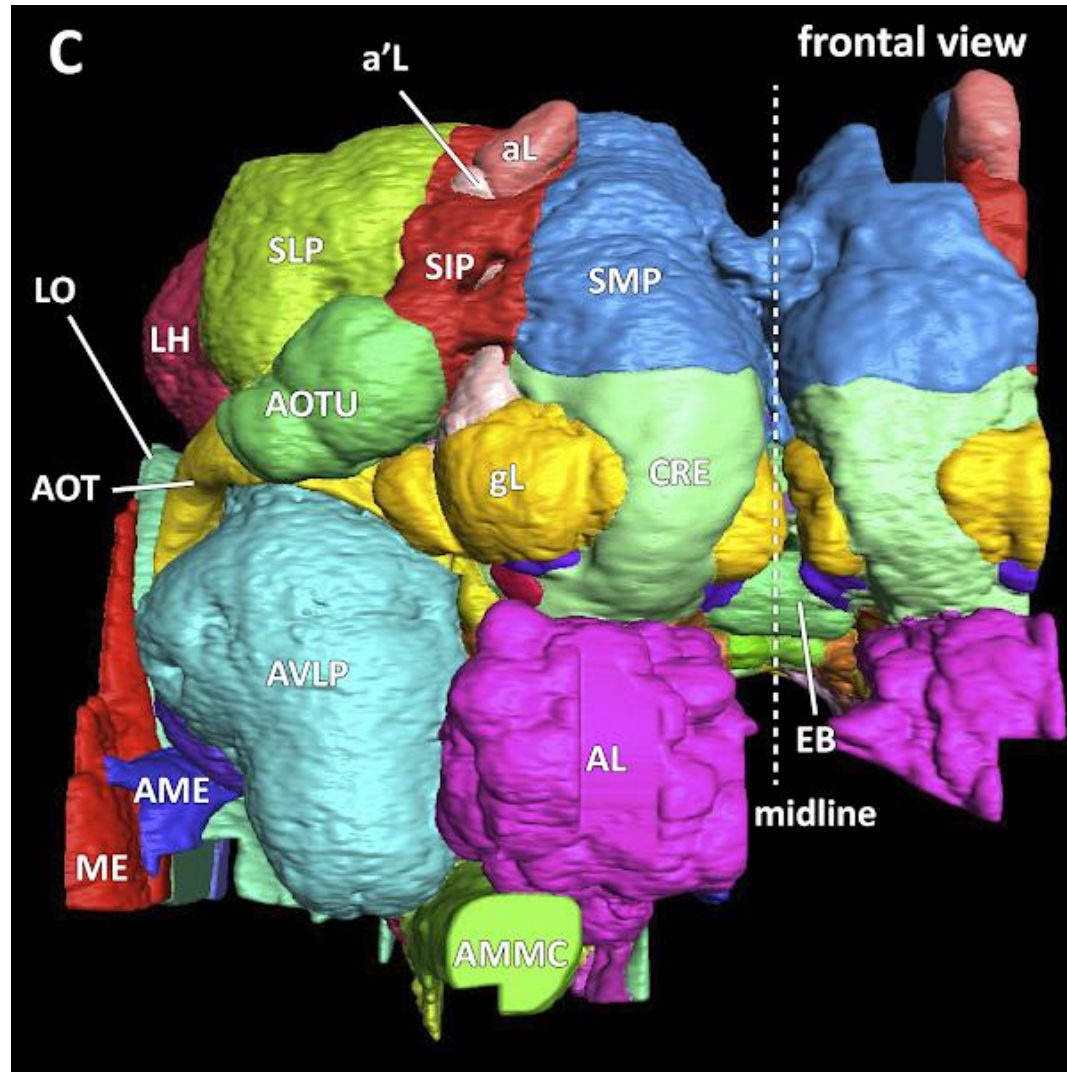


- 125 nW

<https://whyfiles.org/2015/fruit>

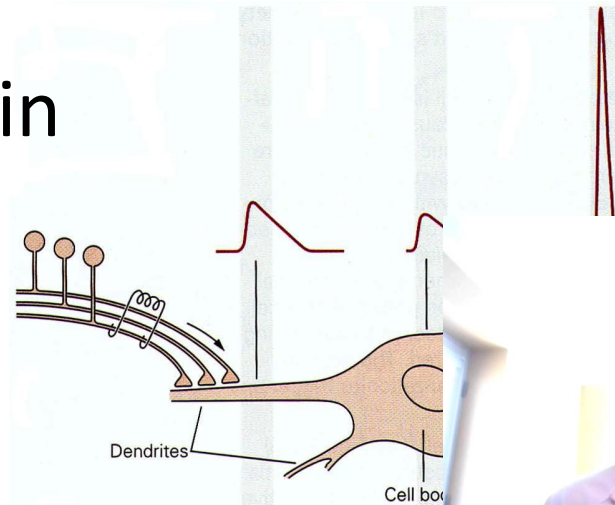
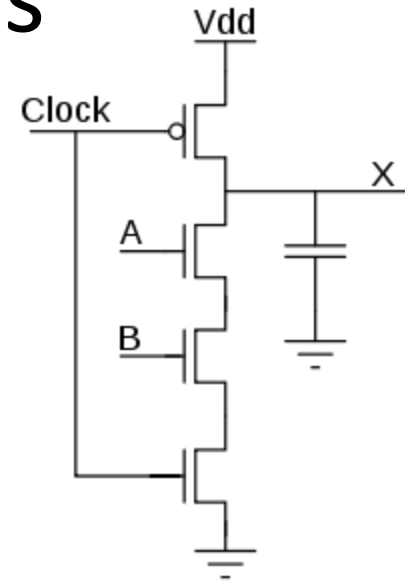


Why now? We are beginning to understand biological computation



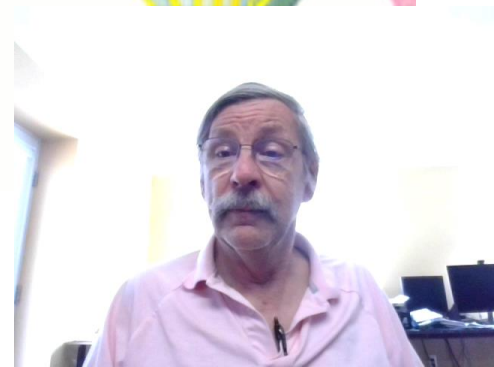
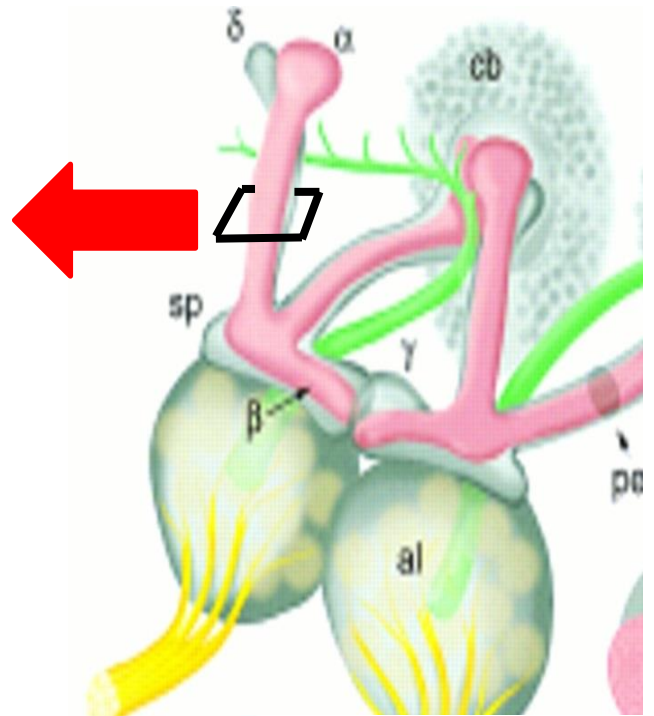
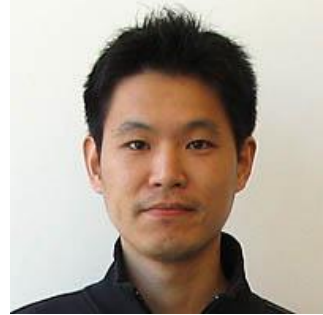
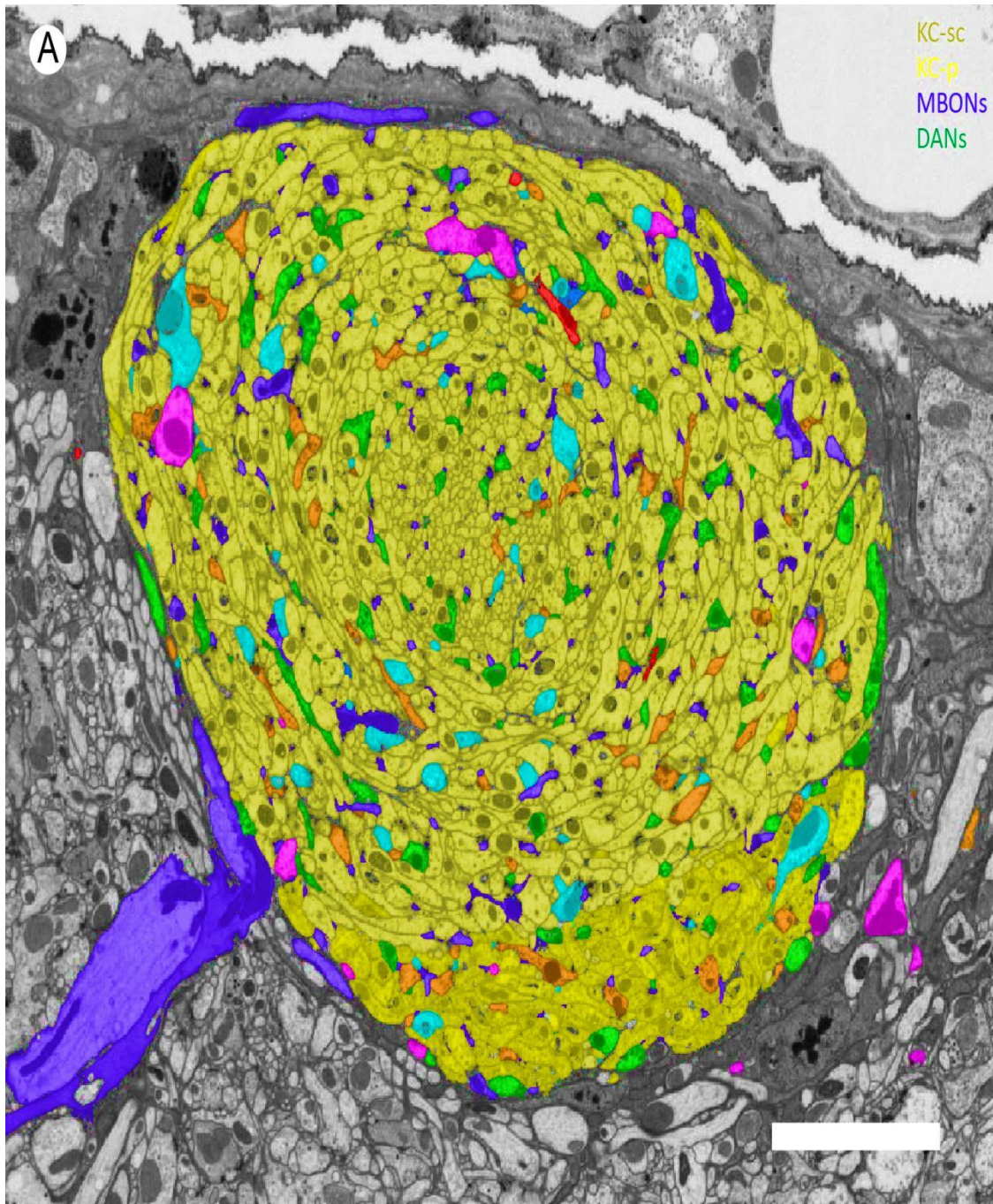
Nervous systems and electronics have a lot of similarities

- Basic operation is electrical
- Combine multiple inputs + a nonlinearity
- Use EE methods to understand the brain
- Use knowledge of the brain to improve EE

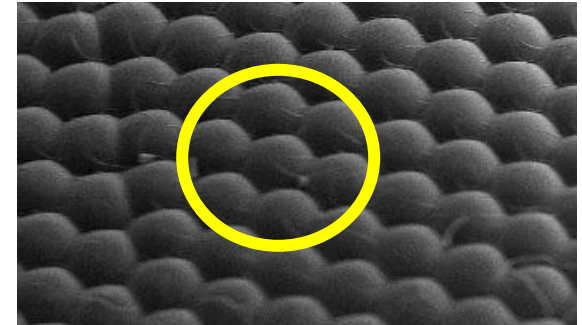
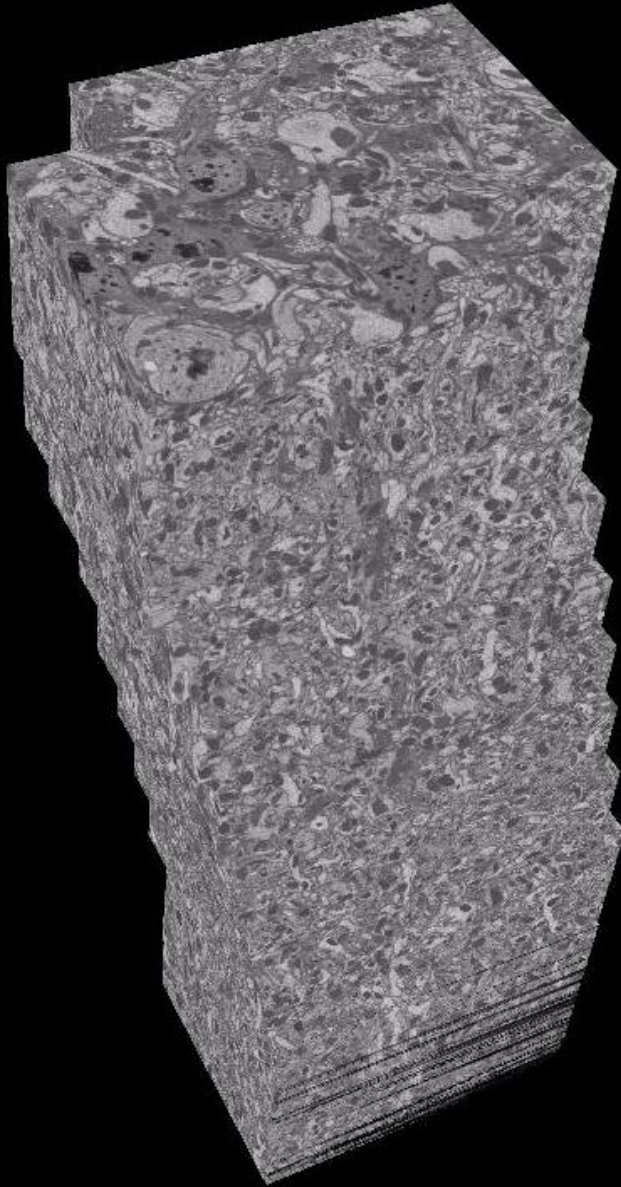


<https://commons.wikimedia.org/wiki/File:DIand.svg>

<https://upload.wikimedia.org/wikipedia/commons/thumb/b/b5/Neuron.svg/1280px-Neuron.svg.png>



Neuron Reconstruction



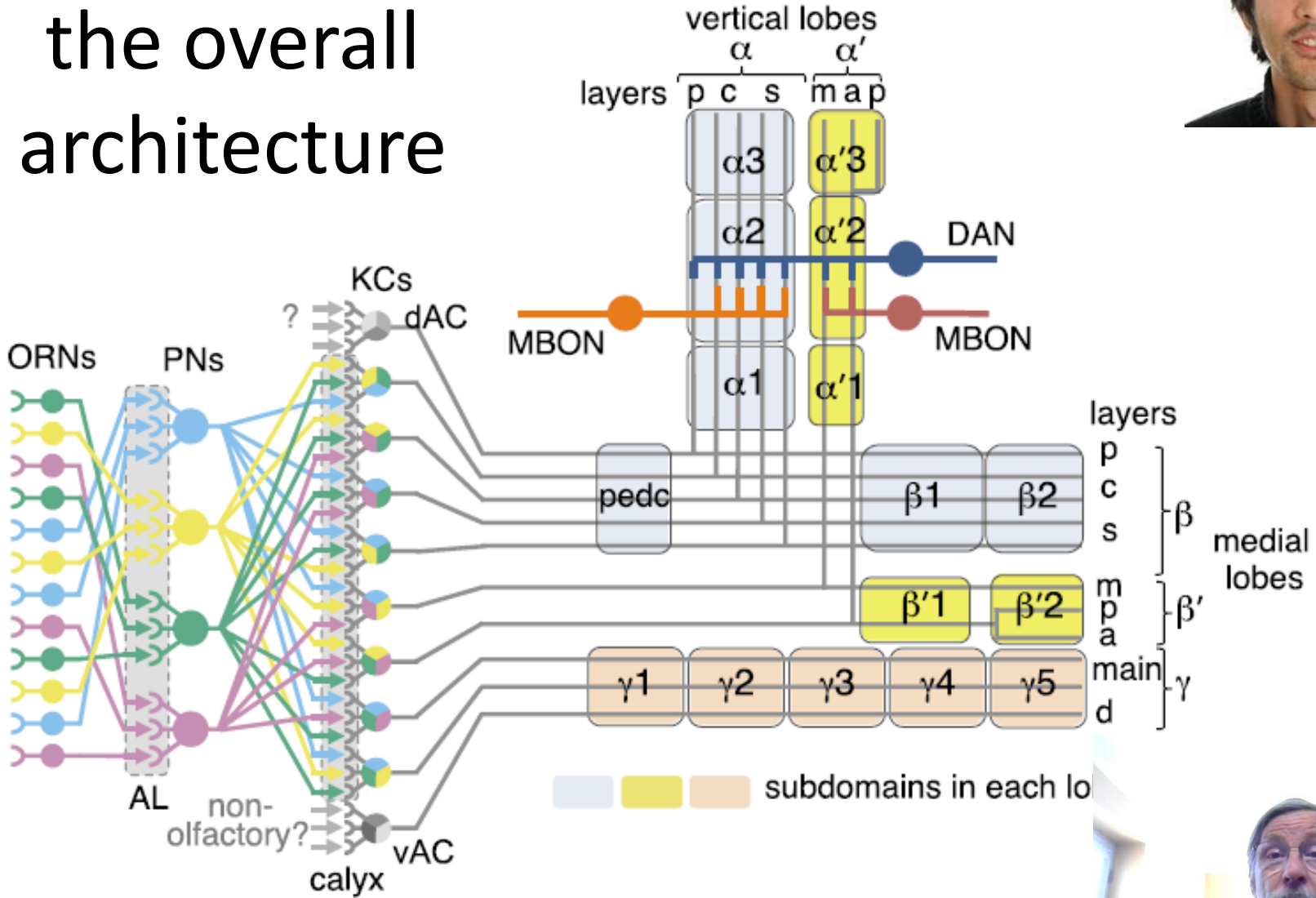
7 columns of the fruit fly medulla.

Each column is the second stage of processing behind each facet c

800 column
each side of

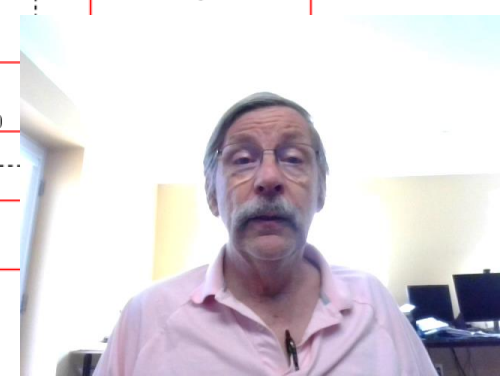


We know the overall architecture

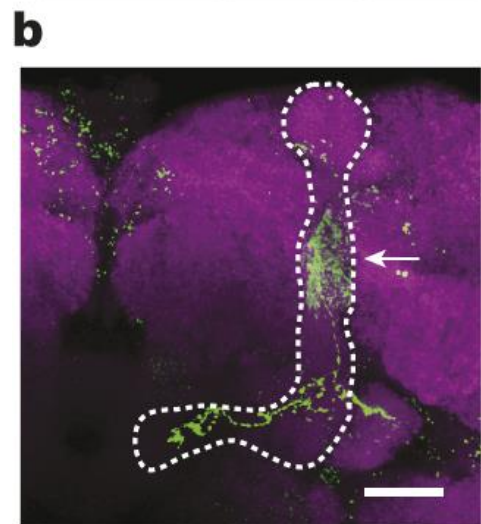
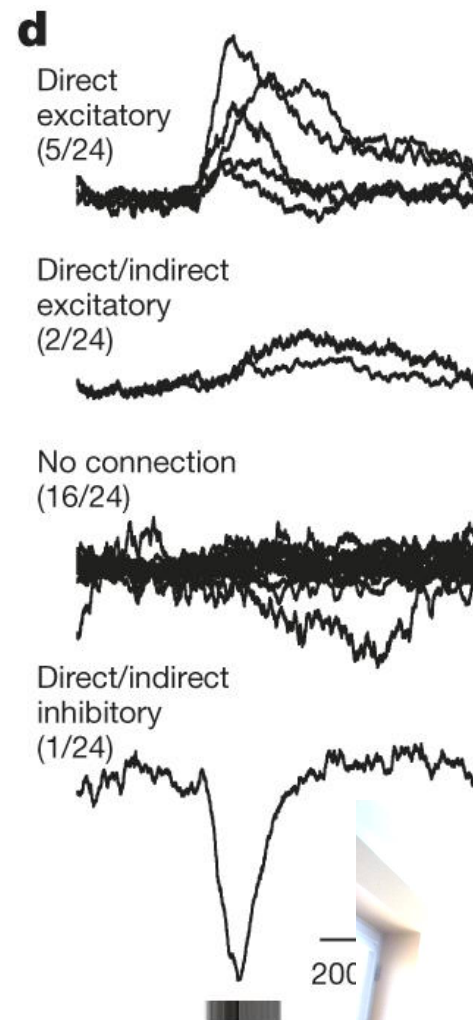
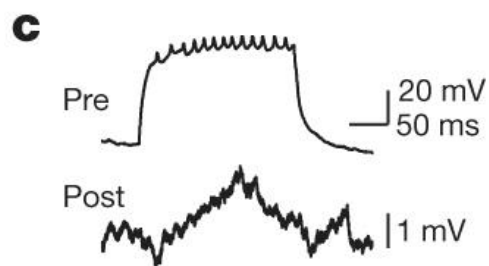
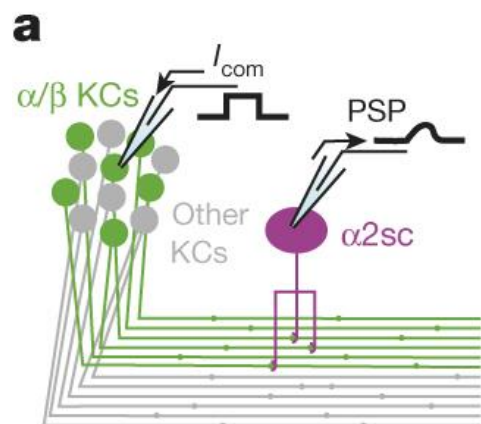


Detailed circuit: 1100 neurons, 220K synapses

	KC-p(78)	KC-c(257)	KC-a(146)	KC-s(465)	KCs	PPL1-05-L MBONs	PPL1-05-R	PPL1-06-L	PPL1-06-R	MB-DPM Intrinsic	MB-APL	MBON-06 Feedforward	MBON-11-L	MBON-11-R
PPL1-06-L	42 x 1.50 55 x 2.27	240 x 3.05 216 x 2.37	143 x 3.42 129 x 2.42	415 x 2.71 373 x 2.03				1 8	7 6	26 36	7 4	1 5		6 6
PPL1-06-R	61 x 2.10 70 x 2.39	248 x 3.51 238 x 2.51	141 x 3.83 129 x 2.49	445 x 3.44 396 x 2.32										
MBON-14-A	77 x 6.39	257 x 11.49	145 x 13.78	465 x 16.35				244	293	28	7	106		65
MBON-14-B	78 x 8.92	257 x 11.57	145 x 13.10	465 x 16.72		2	2	202	280	30	3	95		64
α3														
PPL1-05-L	55 x 1.62 68 x 2.93	163 x 1.94 114 x 1.24	83 x 2.05 69 x 1.51	215 x 1.46 288 x 1.48		●				36	2	7	1	
PPL1-05-R	60 x 2.02 75 x 3.60	144 x 1.78 121 x 1.36	105 x 1.98 101 x 1.60	212 x 1.56 267 x 1.70			●			52	3	13	1	1
MBON-19-A	78 x 13.28	5 x 1.20	18 x 1.39	139 x 2.17		28	23			7		61	8	9
MBON-19-B	78 x 7.06	1 x 1.00	10 x 1.20	77 x 1.36		10	9			4		44	7	4
MBON-18	33 x 2.24	257 x 10.54	146 x 14.20	465 x 14.68 2 x 1.00		130	147	1	5	38	8	84	29	41
MBON-X	78 x 9.24	145 x 2.34	144 x 3.81	459 x 4.51		55	52			11		105	9	13
α2														
MB-APL	77 x 5.74 70 x 2.57	257 x 8.32 148 x 2.62	145 x 7.94 119 x 2.86	460 x 6.99 456 x 4.82		49	50	18	35	163	●	6	21	82
MB-DPM	78 x 8.63 70 x 2.70	185 x 3.79 149 x 1.70	146 x 6.34 127 x 2.49	465 x 7.77 423 x 2.60		58	61	32	36	●	29	13	2	5
Intrinsic														
MBON-11-L	2 x 1.50		1 x 1.00	19 x 1.00 5 x 1.00						1		1	●	
MBON-11-R	5 x 1.20		18 x 1.28	69 x 1.19 32 x 1.06				2		4				
MBON-06	19 x 1.68 10 x 1.20	11 x 1.00 8 x 1.00	12 x 1.08 12 x 1.33	166 x 1.48 156 x 1.27		1	1		3	67	60			
Feedforward														
MBON-07-A	12 x 1.33	194 x 1.90	116 x 2.12	344 x 2.20		1				17	8			
MBON-07-B	18 x 1.11	171 x 2.05	111 x 2.01	370 x 2.37						15	5			
α1														



Electrical measurements of circuit response



- Biology works differently than human-designed systems; we need to understand them.
- A sizeable number of theorists are working on exactly this



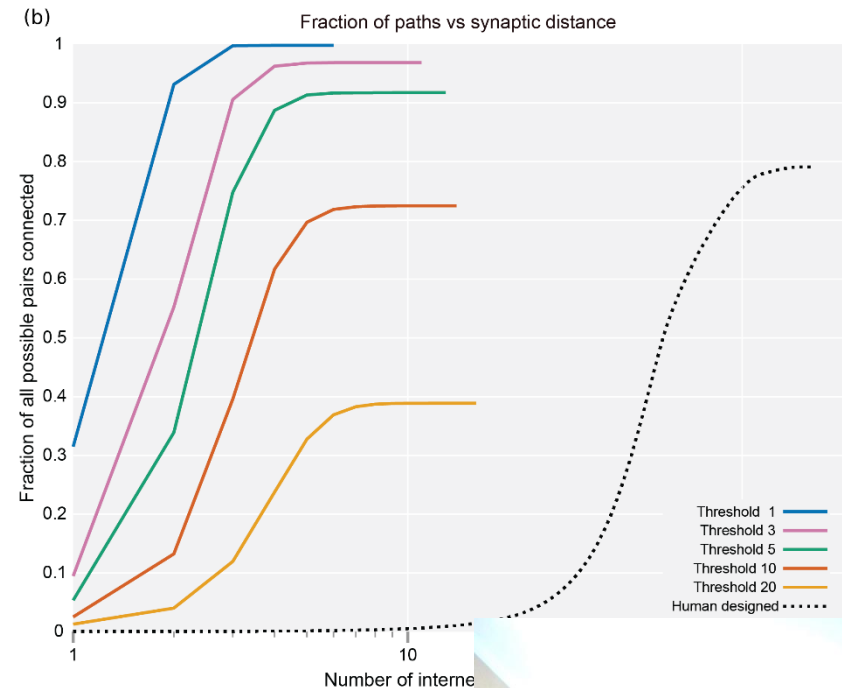
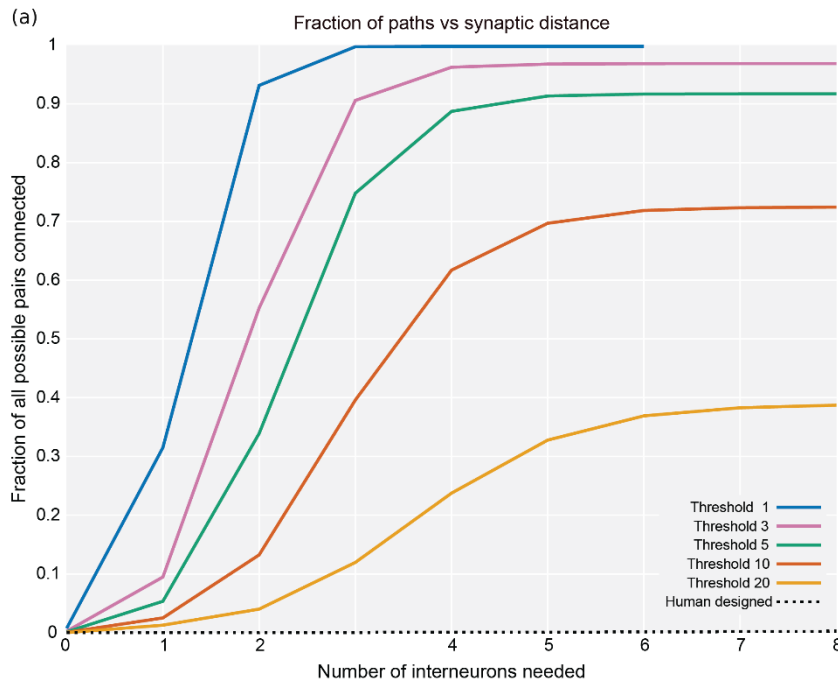
What do we know so far?

- Differences from human chips:
 - One component type, the neuron, implements logic, wiring, and memory.
 - High fanout and short paths
 - Low voltage operation
 - Non-local signaling
 - Networks are recurrent
 - Asynchronous with no high speed clocks or scan chains
- Similarities
 - Placement/partitioning has similar objectives
 - Timing analysis is similar



High fanout, very short paths

- Average fanout in fly brain is 143 (also fan-in)

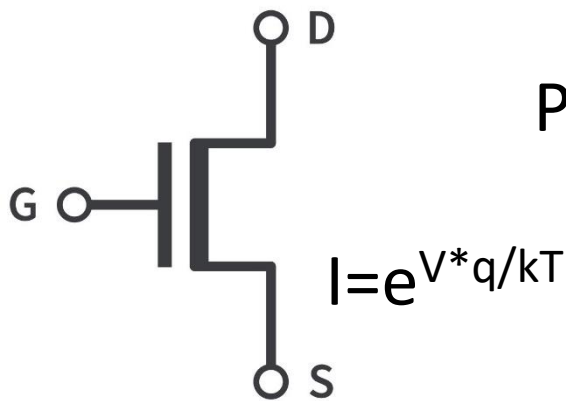


- Path lengths are extremely short

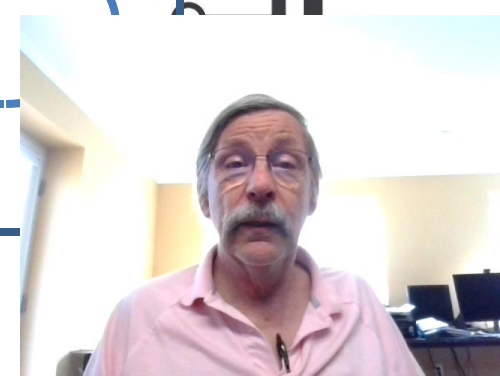


Low voltage operation

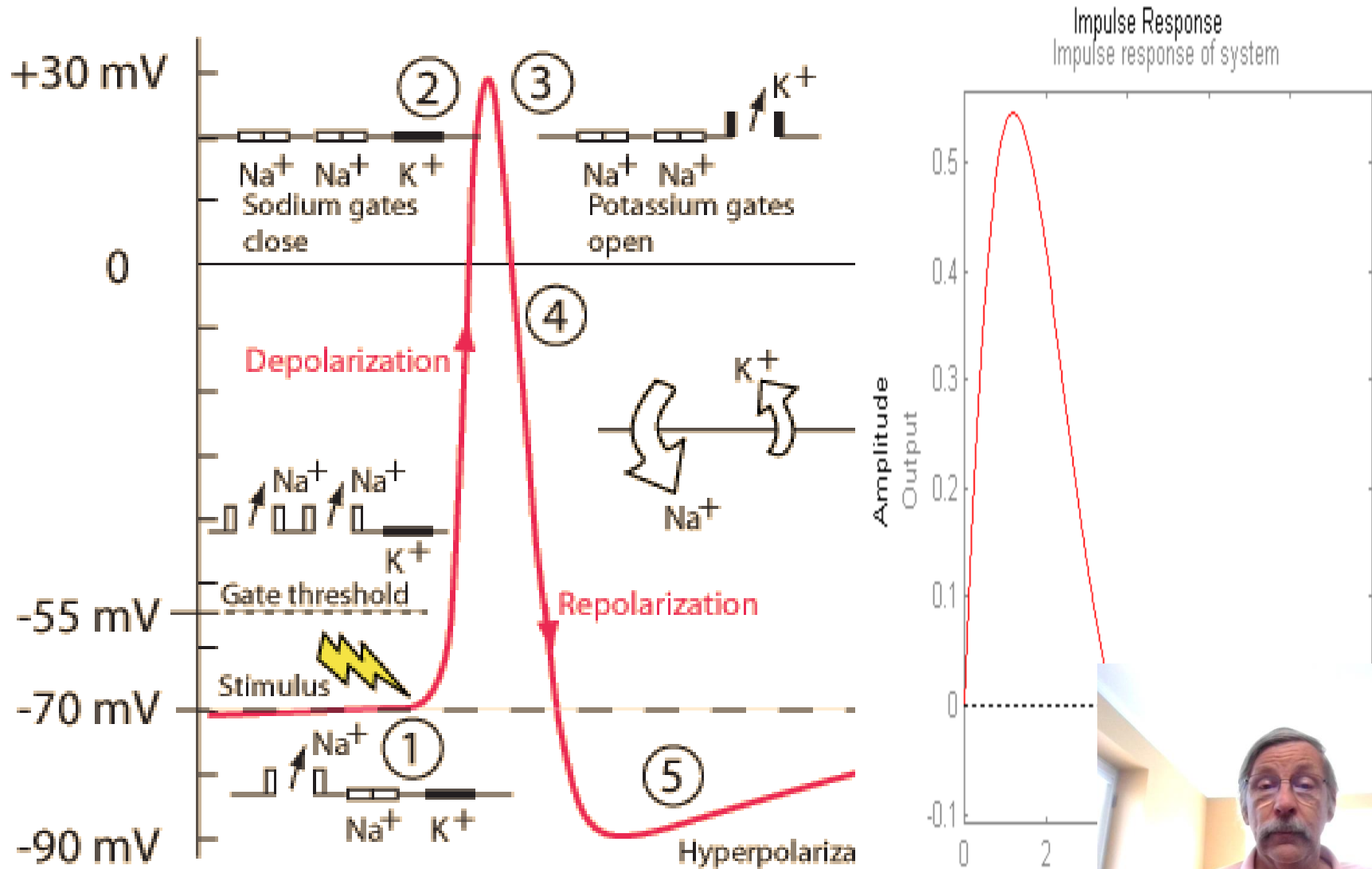
- CMOS is limited to ≥ 800 mV
 - Otherwise off currents get too high
- But biology runs on ~ 80 mV swings
- Since power goes as V^2 , about 100x savings
- How does biology do it?



$$P(\text{on} | V) = e^{V \cdot q / kT}$$

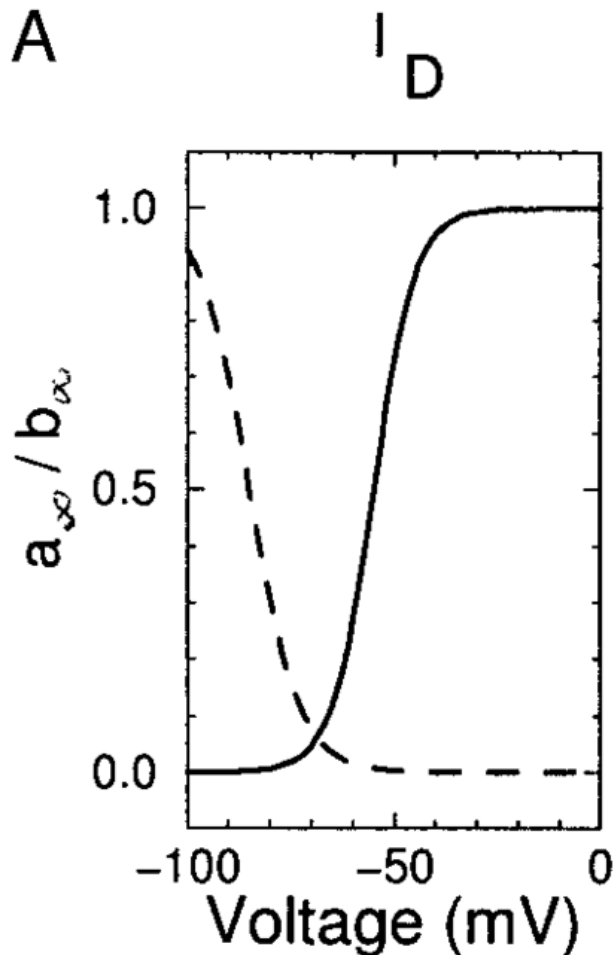


Biology explainable in EE terms

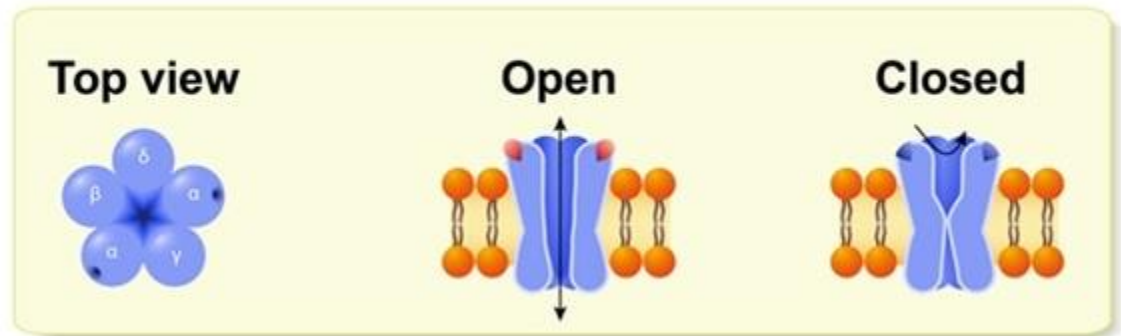


Sharp thresholds; cost is decreased speed

- Voltage gated channels are like FETs



ION CHANNEL



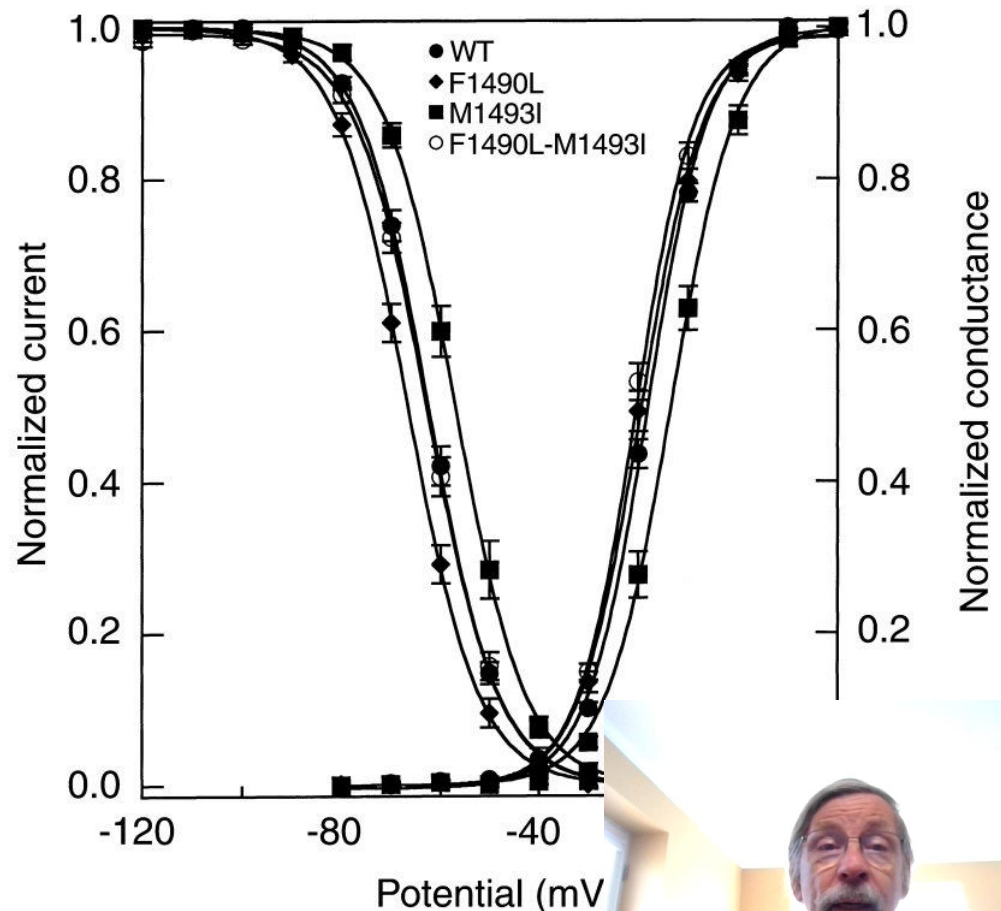
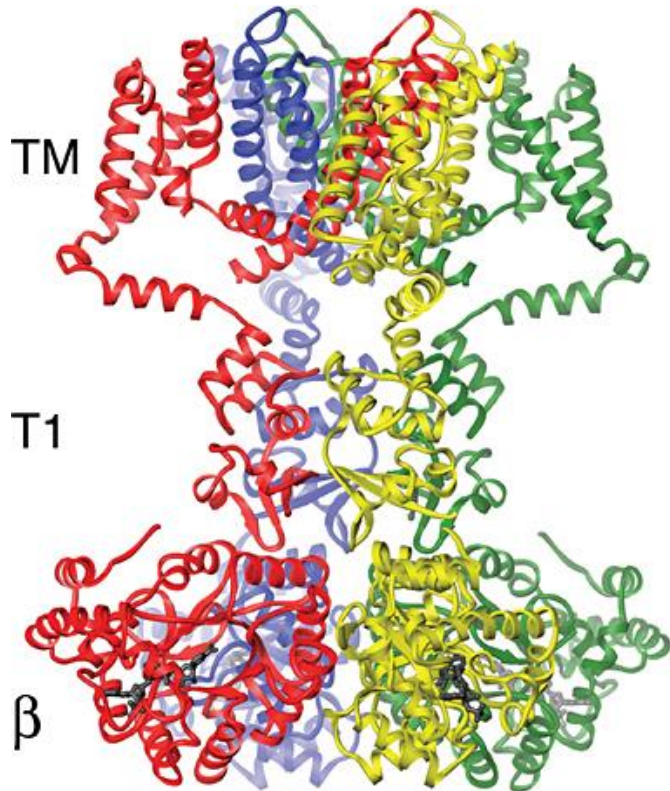
<https://www.news-medical.net/health/Types-of-Ion-Channels-in-the-Body.aspx>

[Bursting in Inhibitory Interneuronal Networks: A Role for Gap-Junctional Coupling](#)



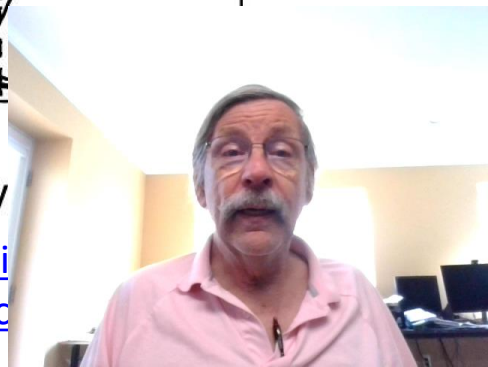
No across-chip threshold variation

- Thresholds are defined by chemistry

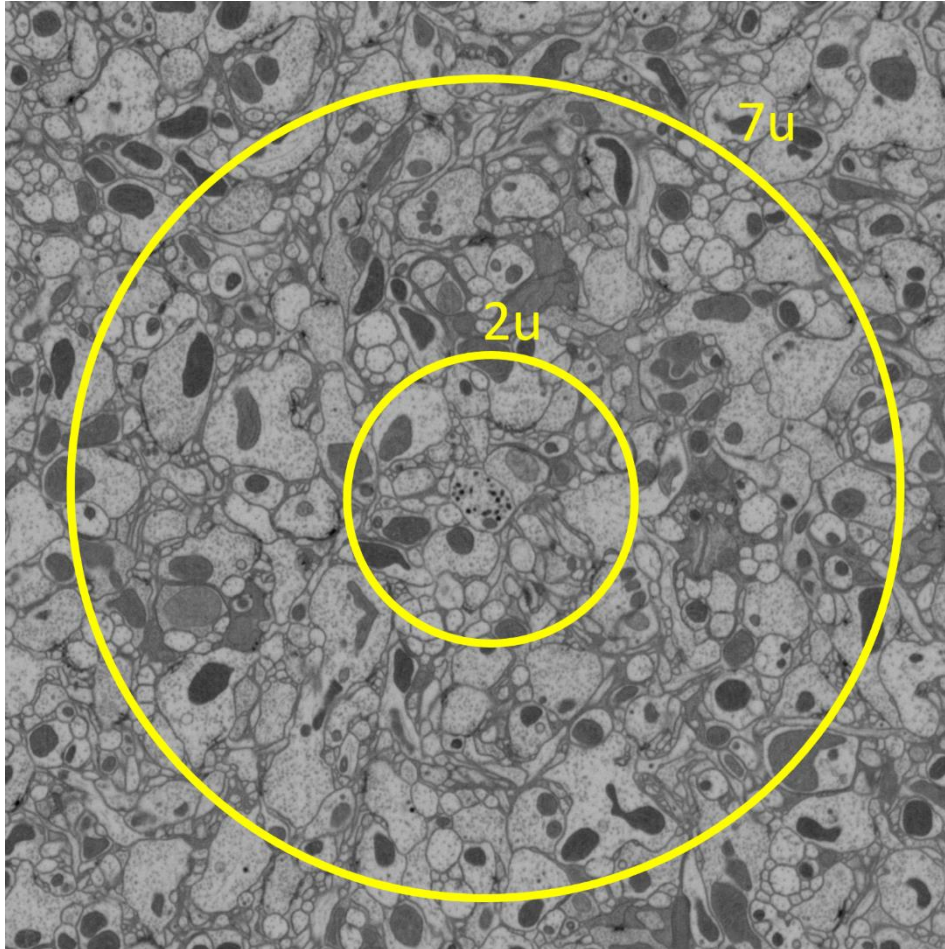


<https://www.hhmi.org/news/structure-biological-transistor-detailed-higher-organisms>

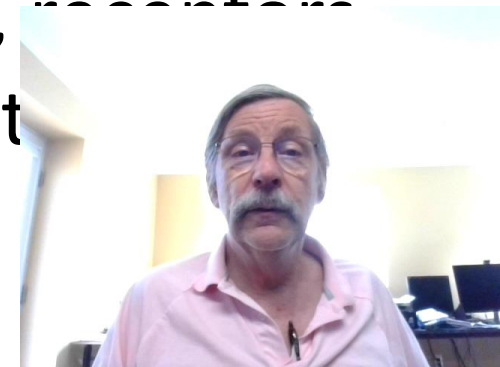
[A double mutation in families with defines new aspects of sodium c](#)



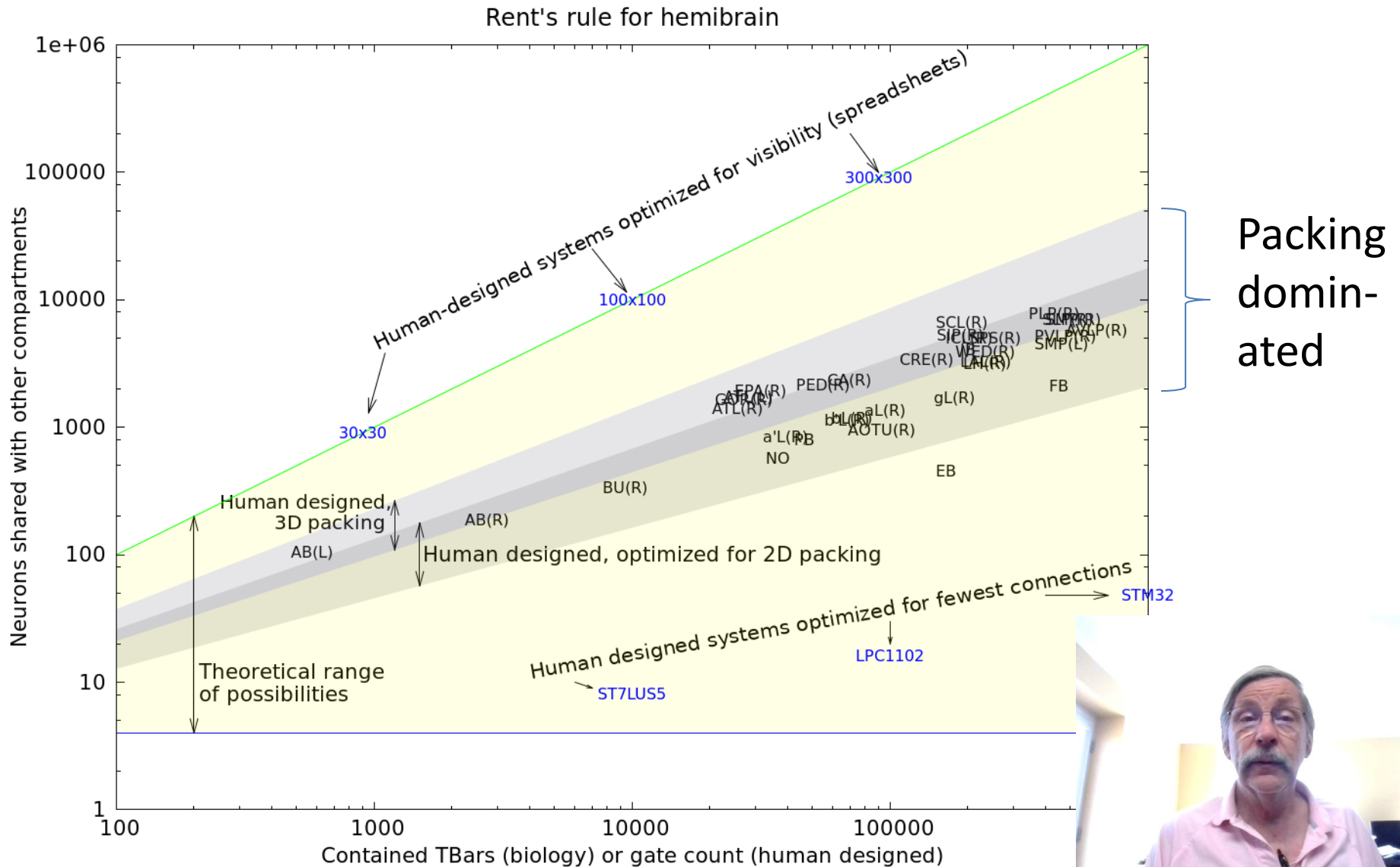
Biology uses non-local signals



- Range shown for dopamine diffusion for two sensitivities
- Others are more extreme – for SIFamide, 4 cells express, receptors all over t



Global connections are similar

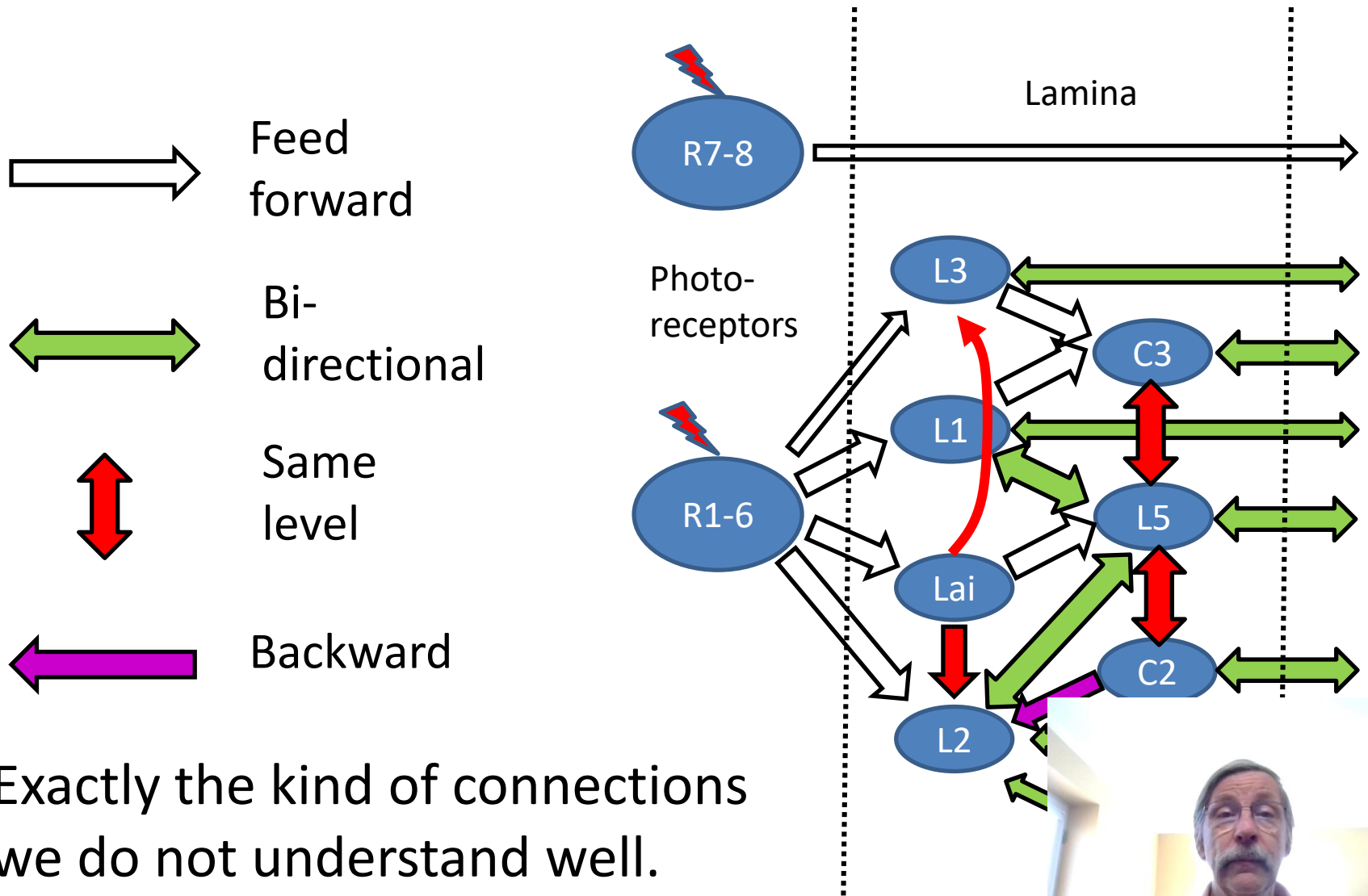


No high speed clocks in biology

- Also no scan chains
- Power supplies are very different



Biological networks are recurrent

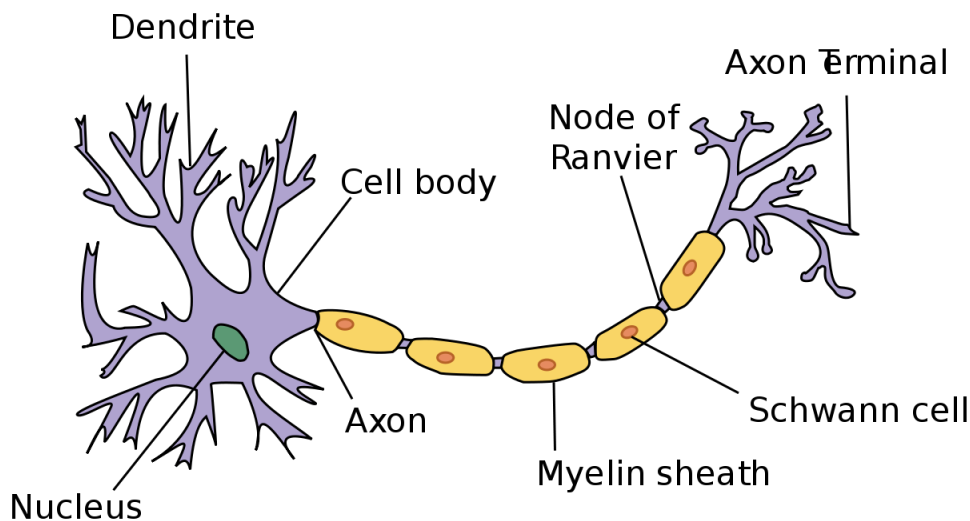


Exactly the kind of connections we do not understand well.

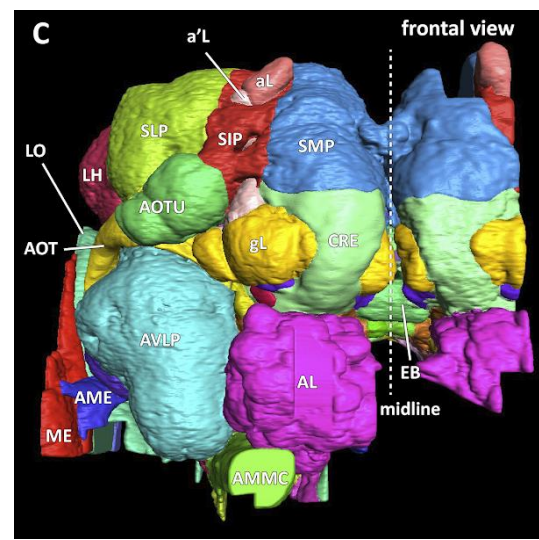
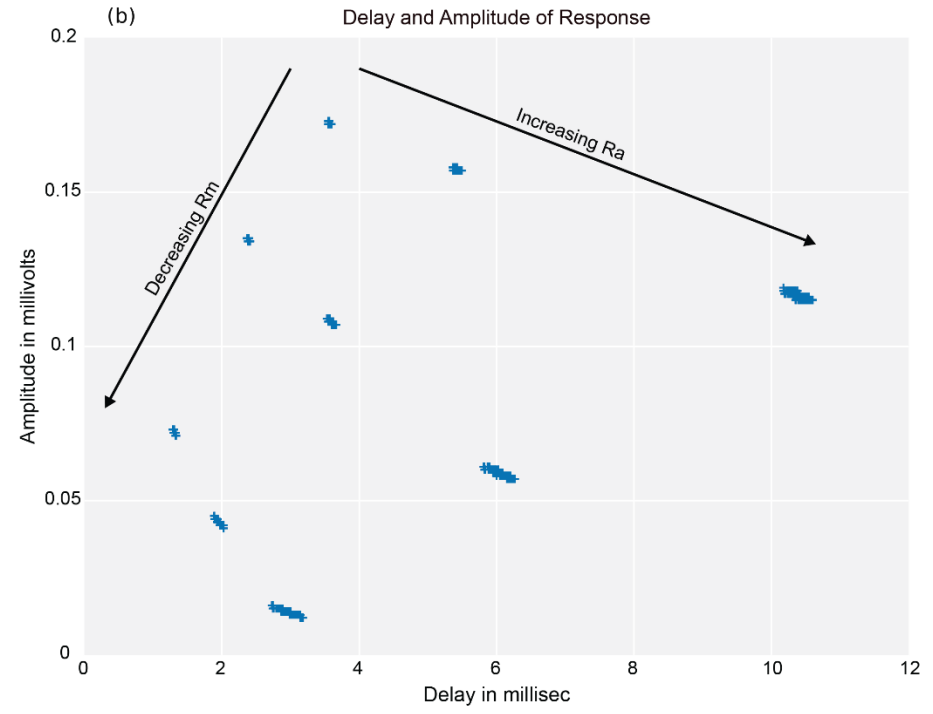
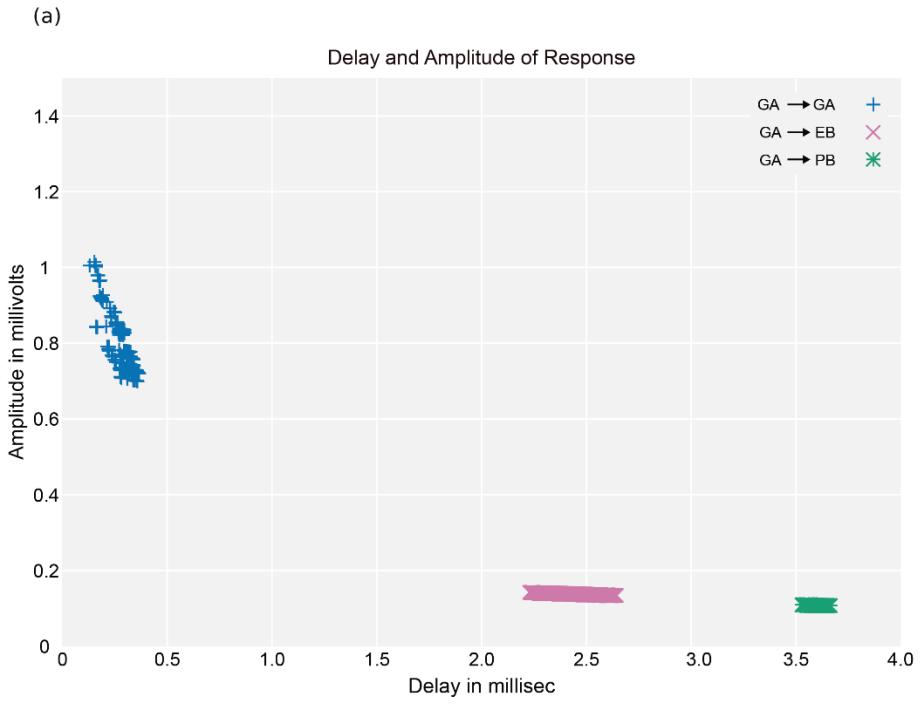


Timing analysis is more complicated, but basically familiar

- Point to point delays need to be augmented with point-to-point amplitudes
- Larger neurons (as in mammal neuron below) are more complex
- Circuit delays and logic delays are comparable



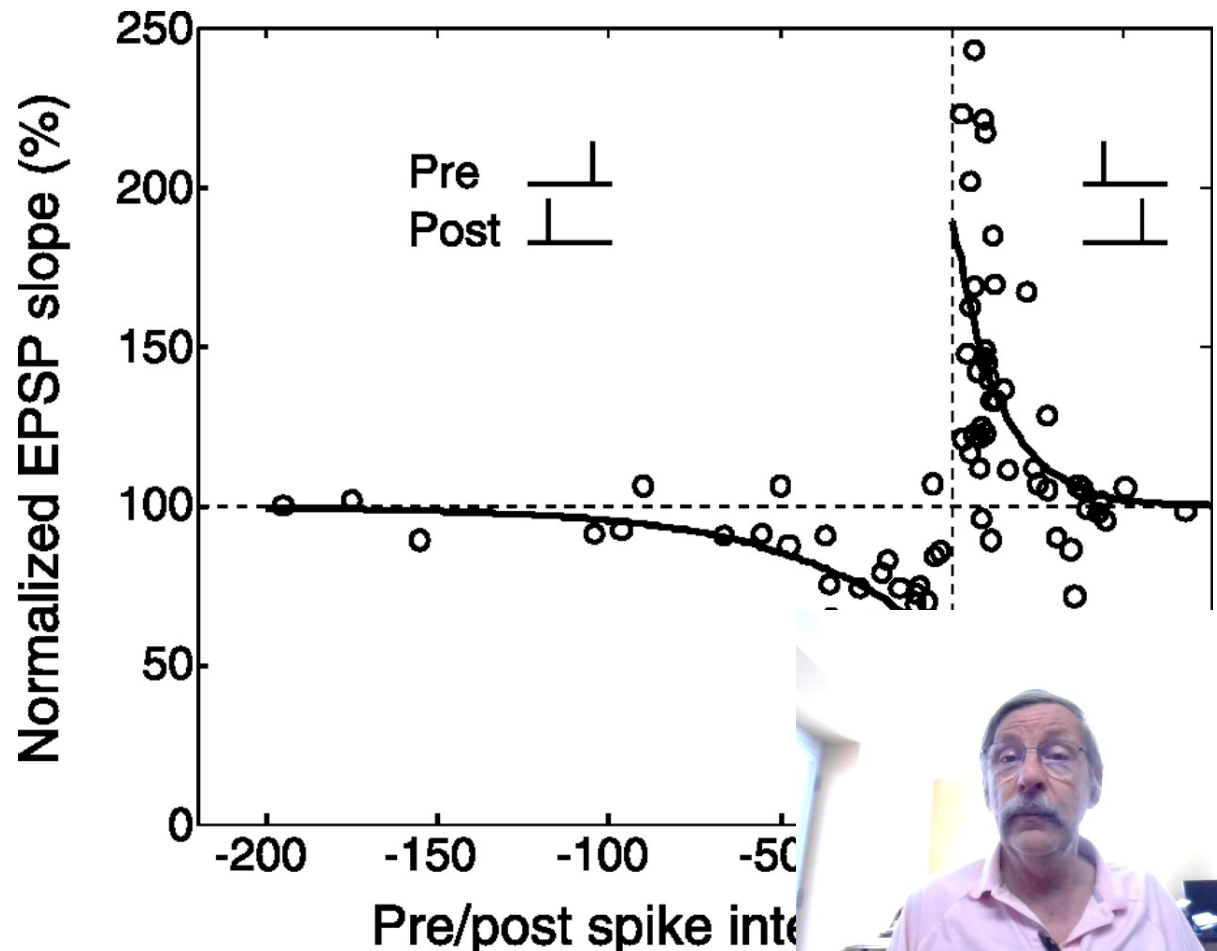
Example of timing and amplitude



Spike Timing Dependent Plasticity

- Brain is not a von Neuman architecture
- Adjustable synapses throughout circuit(s)

Synaptic modification induced by repetitively paired pre- and postsynaptic spikes in layer 2/3 of visual cortical slices from the rat.

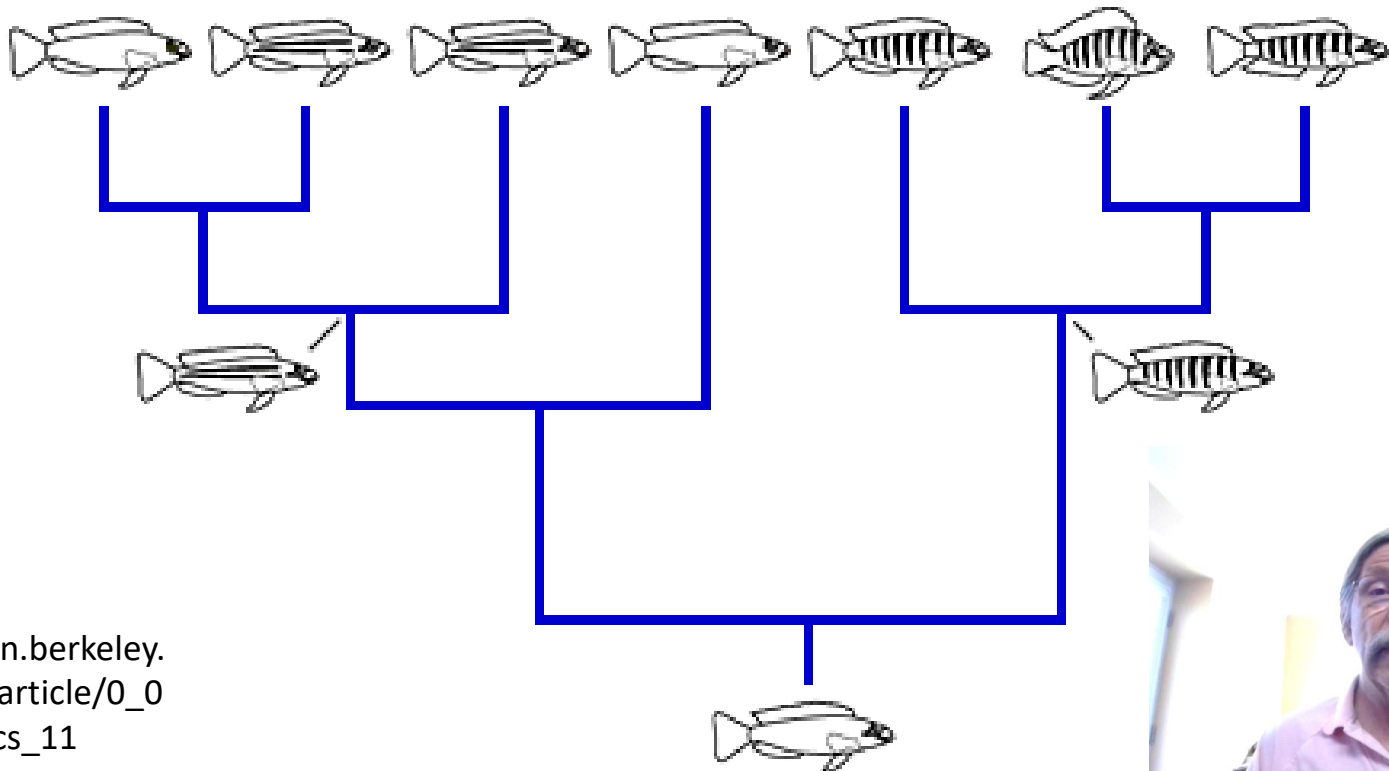


With permission of Yang Dan

Yang Dan, and Mu-Ming Poo *Physiol Rev* 2006;86:1033-1048

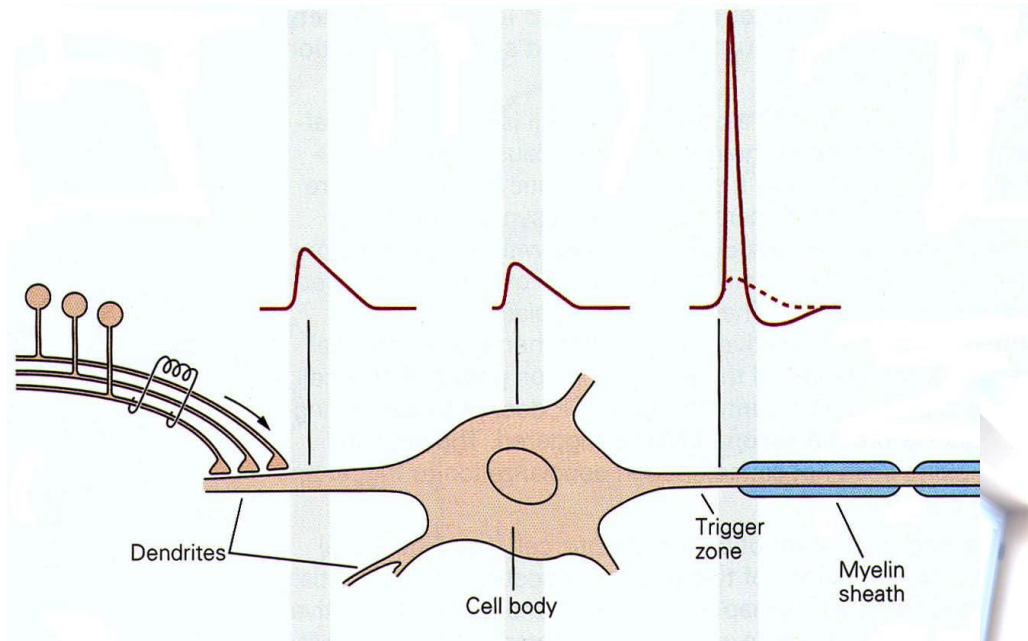
Biology always works in ECO mode

- Each version must be competitive with best so far
- Typically works by duplicate then diversify
- Could be far from global optimum



Once we decipher biology, can we get it into our phones, computers, and cars?

- It is not clear if neuron-like architectures are needed, or just used by biology for convenience, or out of necessity



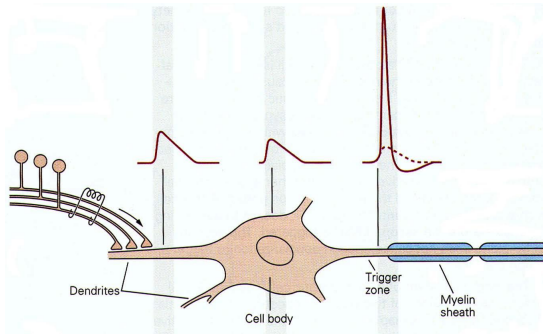
My opinion



- 10x faster



- 10x faster



?

<https://www.flickr.com/photos>

<https://www.flickr.com>

<https://pixabay.com/en/ross>

- 1



Related fields

- Chemists and physicists can work on reliable low-voltage switches
- Device physicists can work on memristors and other devices for timing dependent plasticity
- Interconnect could go non-local (light?)
- Logic synthesis
 - High fanout devices
 - Threshold logic
 - Asynchronous circuits
 - Non-feedforward networks
 - Mixed logic/memory/wiring



Can biology help in physical design?

- Placement and partitioning get no new insight
 - By Rent's rule, biology systems are similar
 - Timing driven design likely similar
- No insights into low skew clocks or scan test.
- Gate level isotropic 3D construction
- P&R algorithms that can cope with large fanouts and combined P&R and logic
- Physical design using non-local interconnect

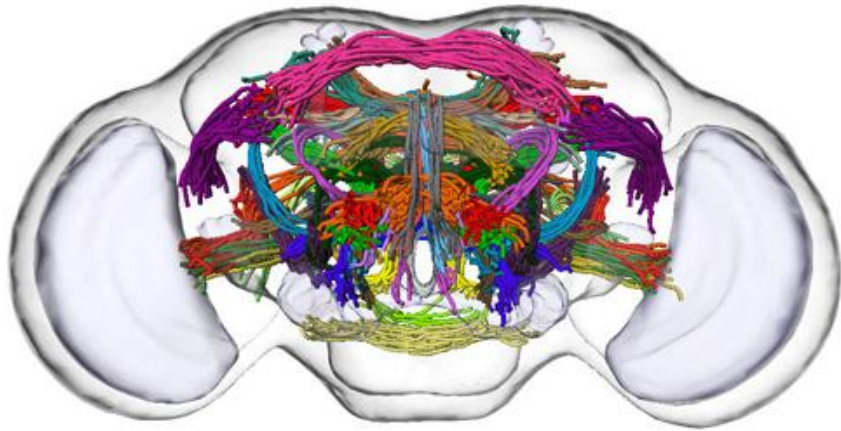


Who should study the brain?

- Biologists of course, but also engineers and computer scientists
- Golden age of neuroscience
 - Tools are becoming equal to the task
 - The field is ripe for breakthroughs

https://upload.wikimedia.org/wikipedia/commons/8/88/1933_Nobel_Peace_Prize_awarded_to_Norman_Angell.JPG





STUDY THE BRAIN

