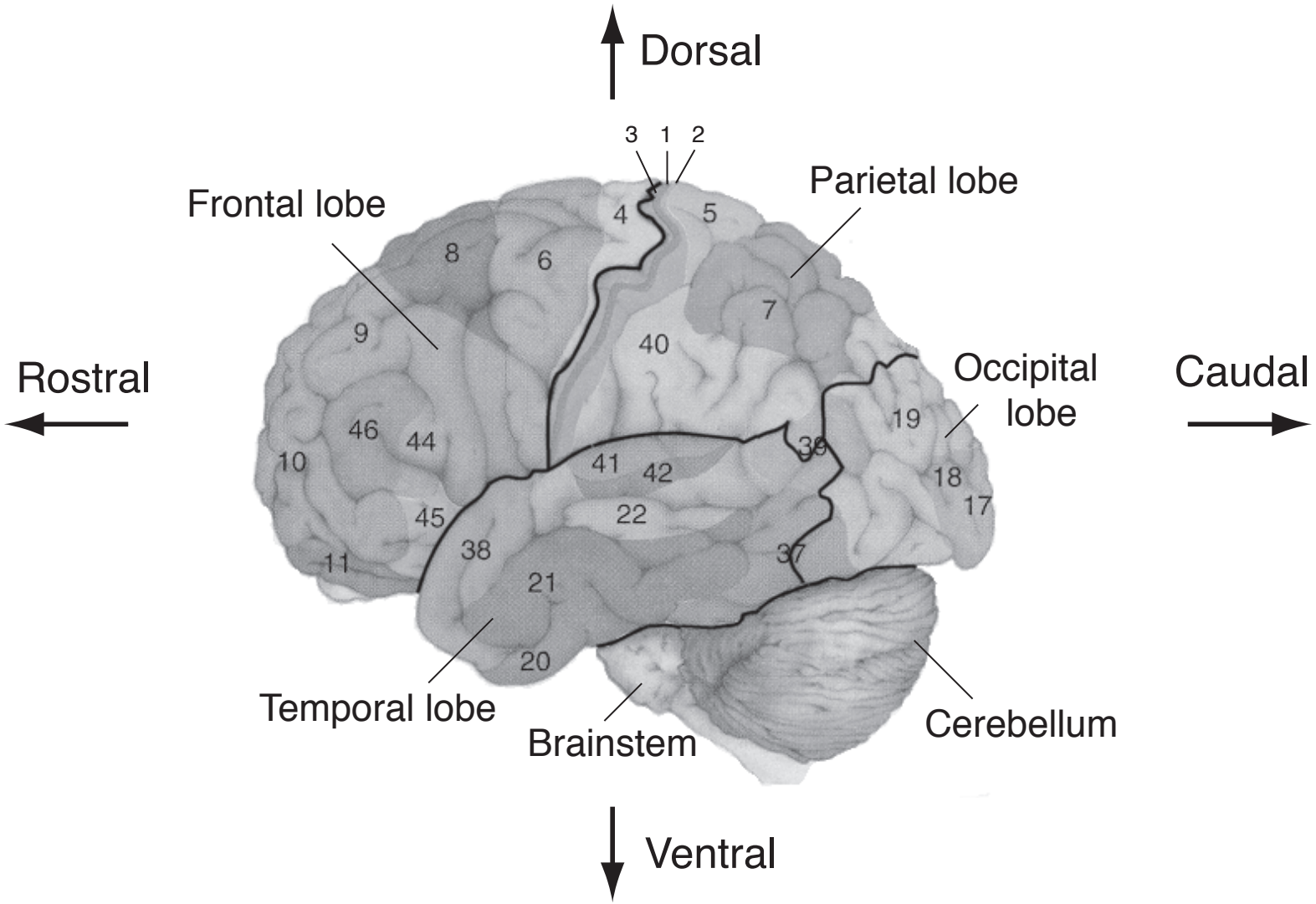
Neuroinformatics

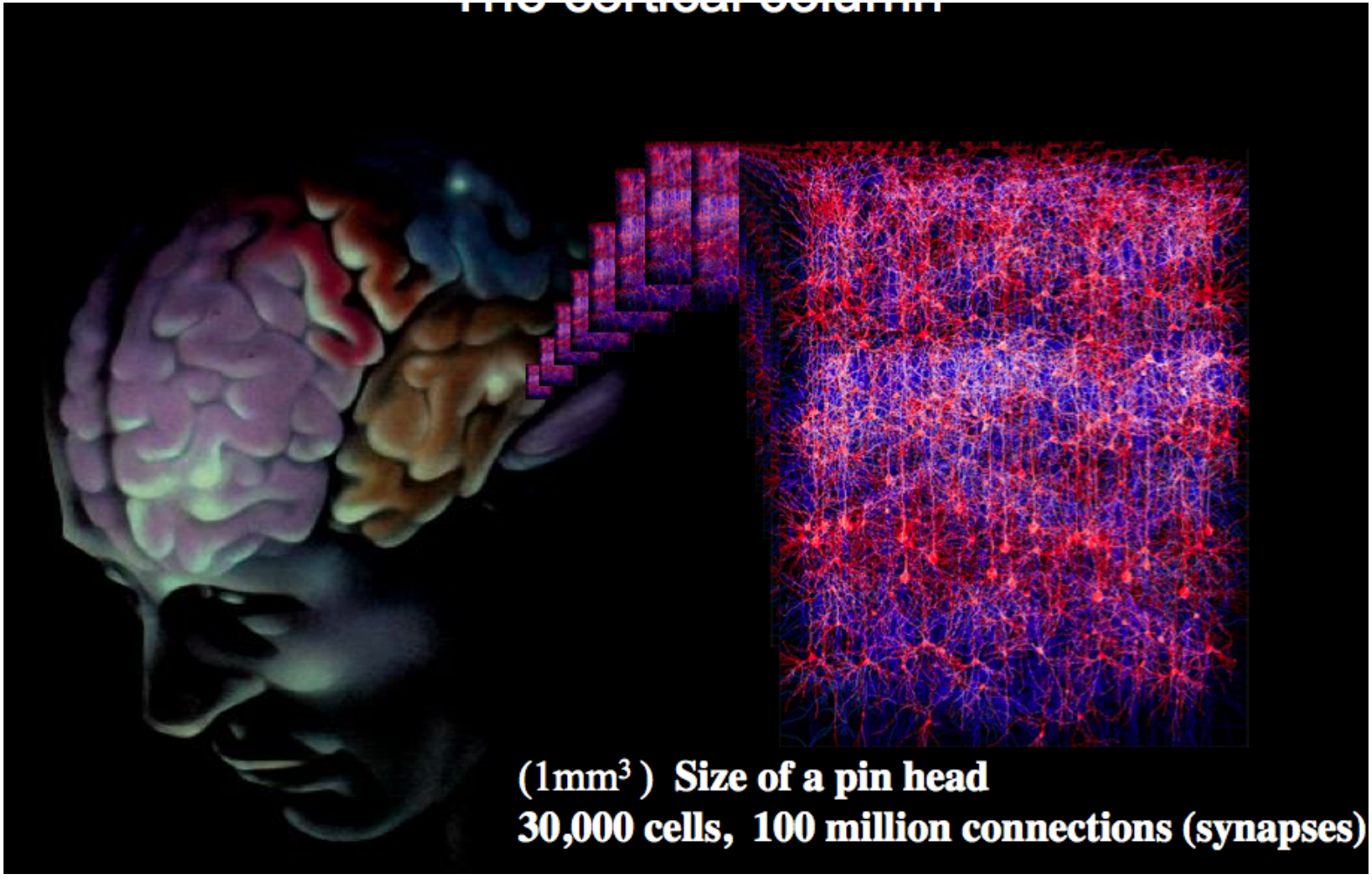
March 30, 2022

Lecture 7: Cortical organization & Random networks

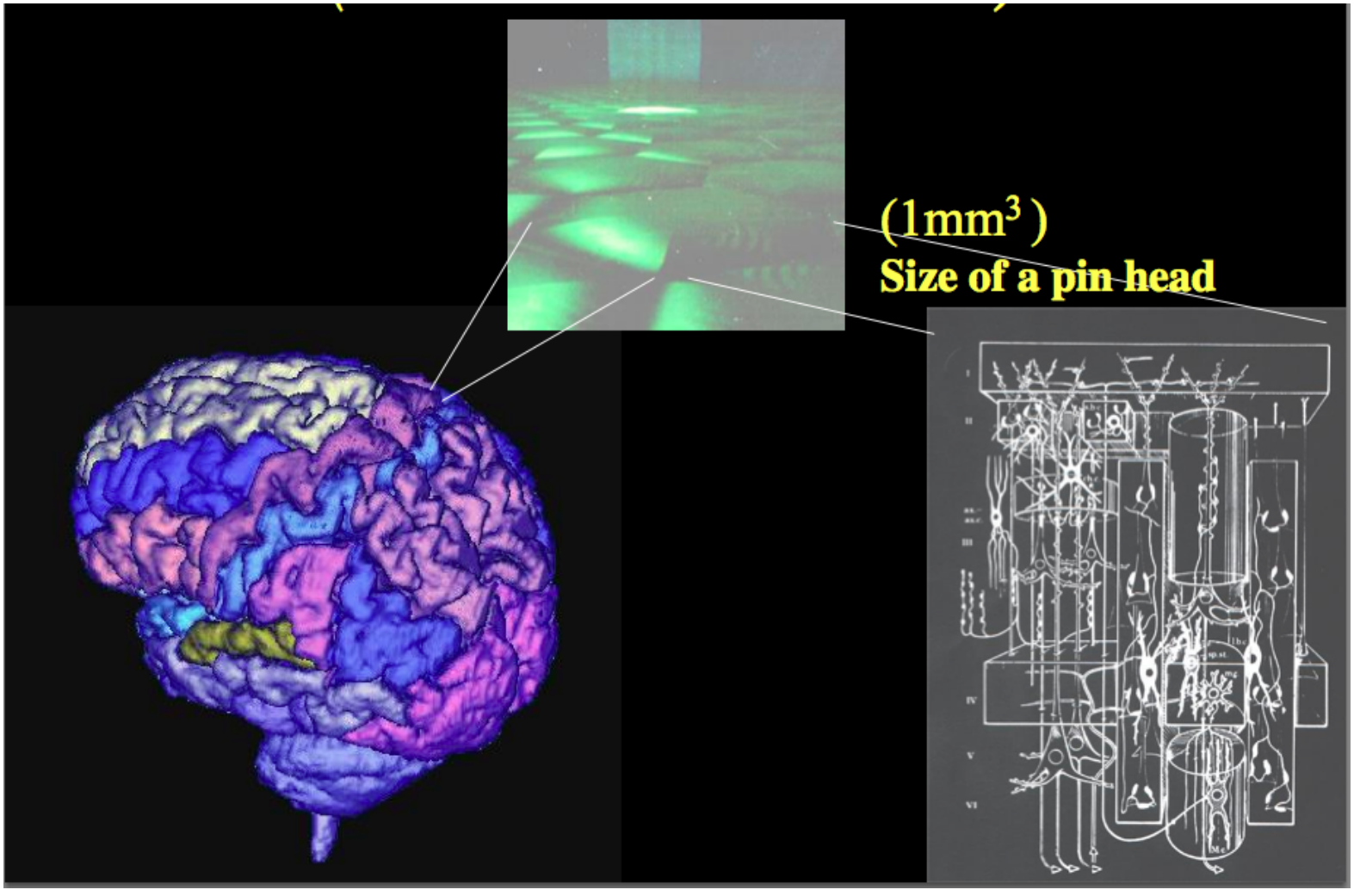
Brain areas - Broadmann classification



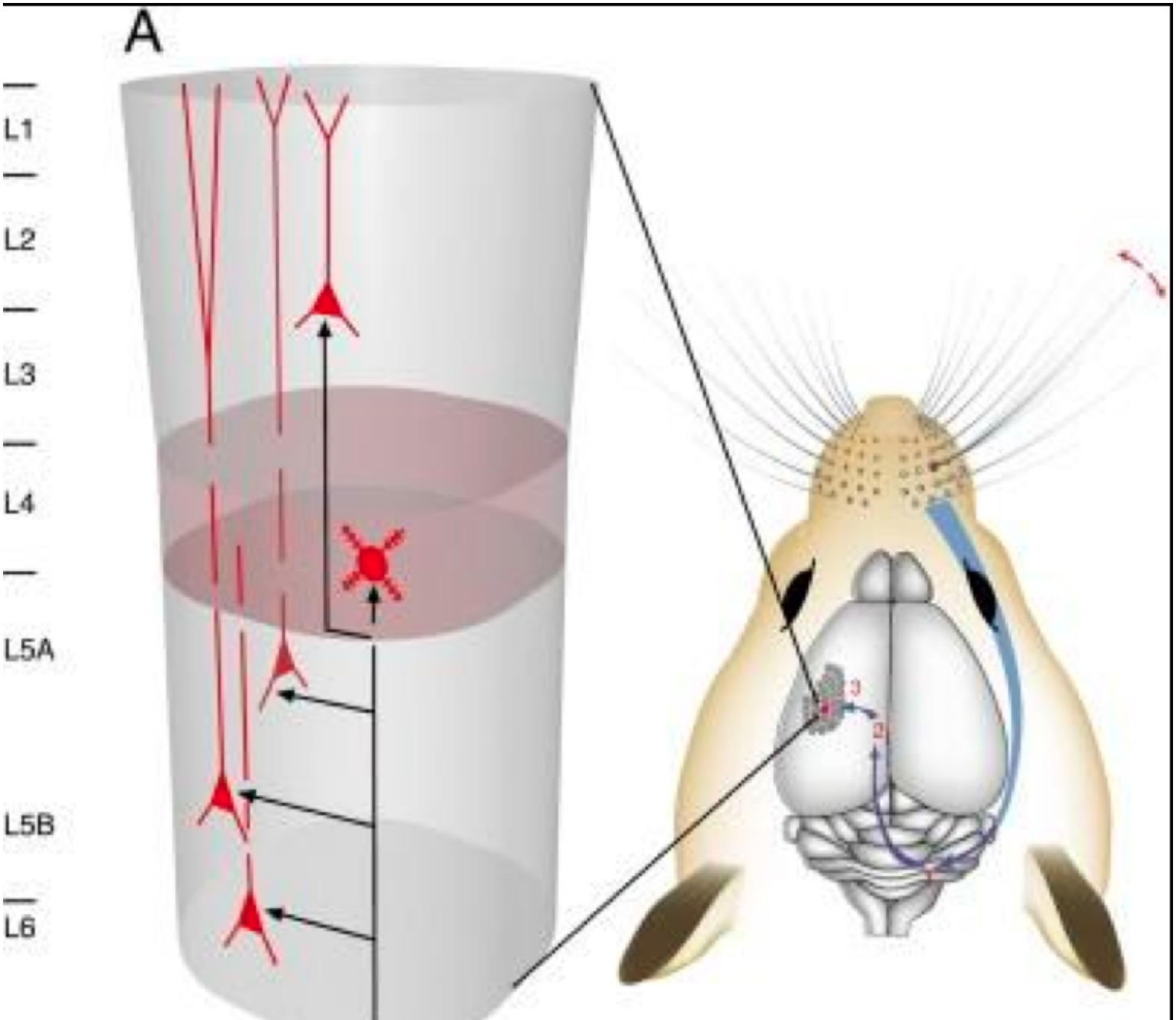
Cortical column - size



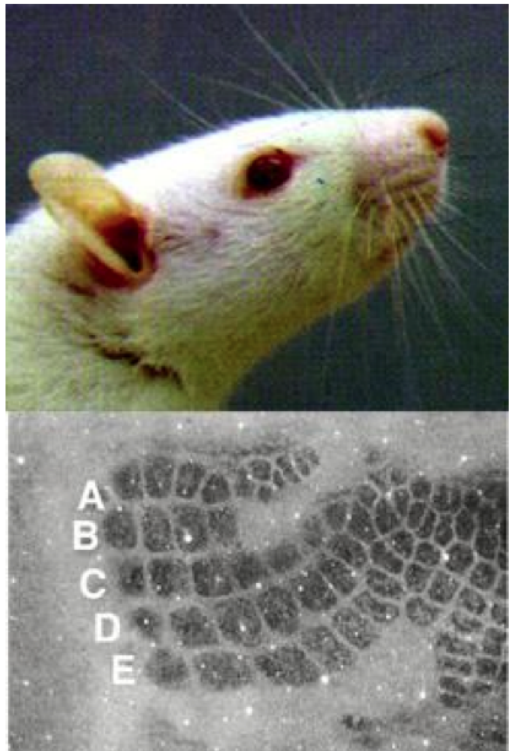
Cortical column - microcircuit

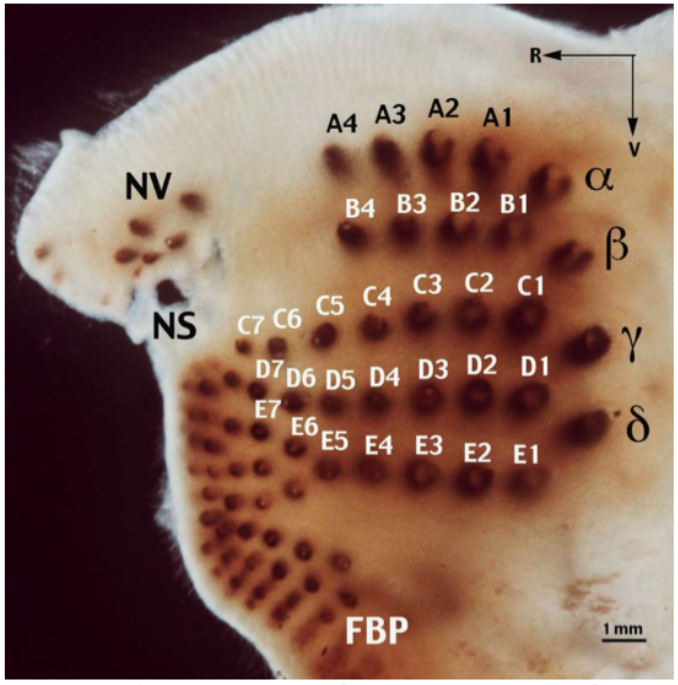


Mouse whisker and barrel cortex



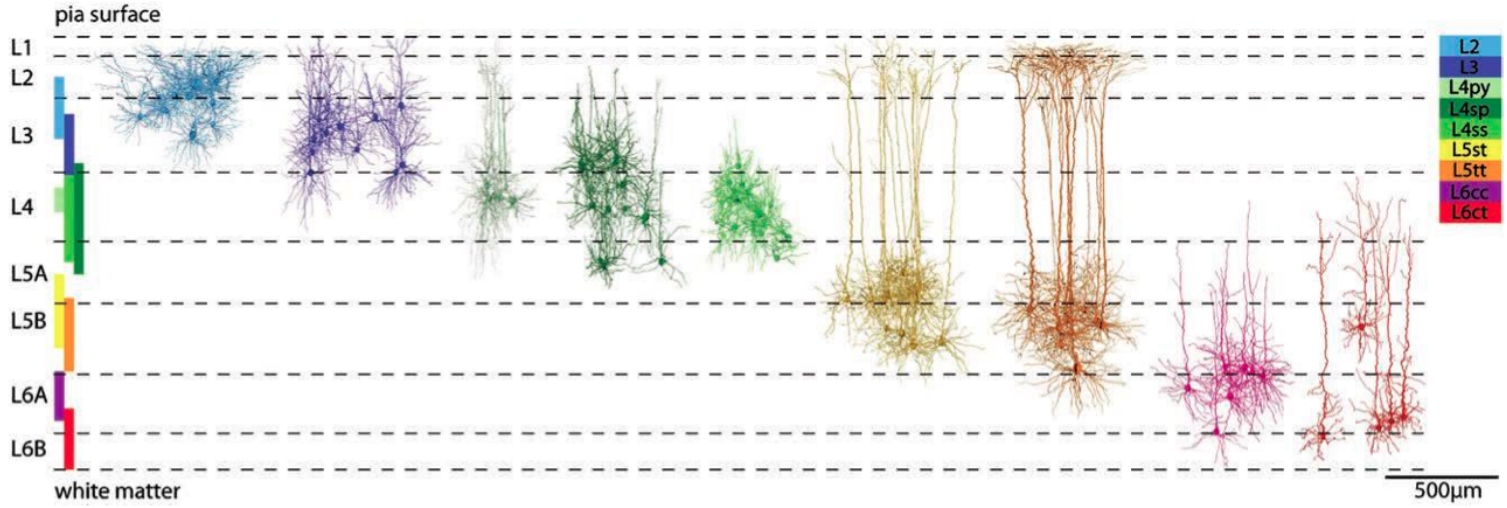
The excitatory cell types in the cortical column





Carol A. Himsel's, Peter Land , Sebastian Haidarliu & Ehud Ahissar.

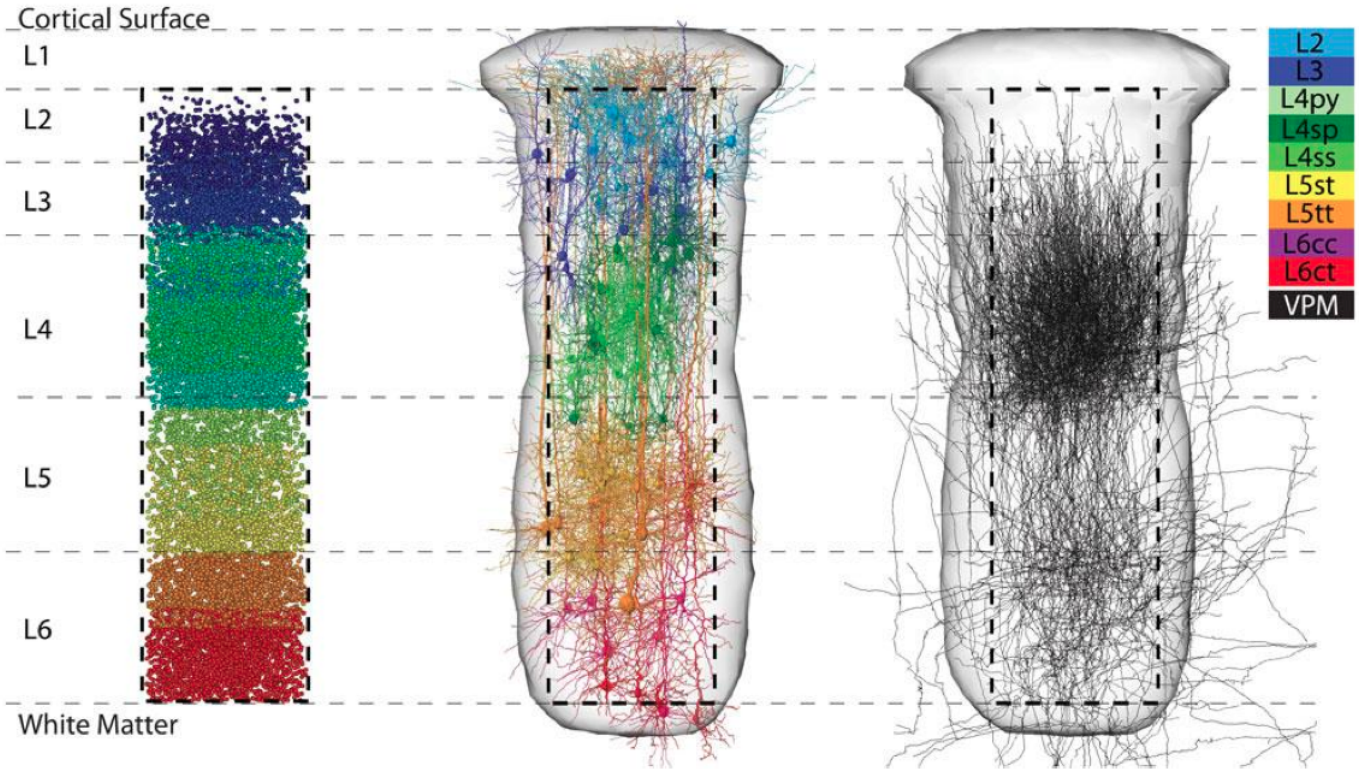
Excitatory cell types in the cortical column



Sakmann et al.,

- Bert Sakmann - Nobel prize in 1991

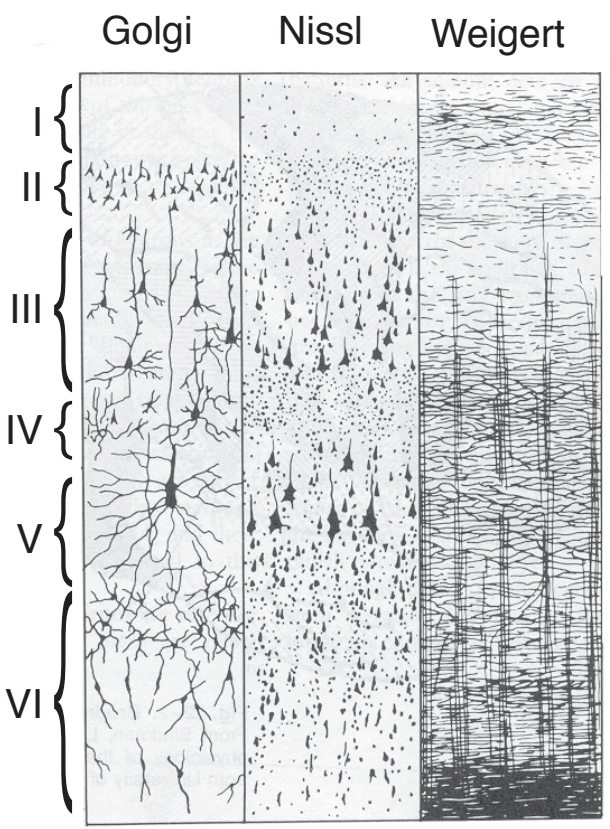
Input (axons) from the thalamus



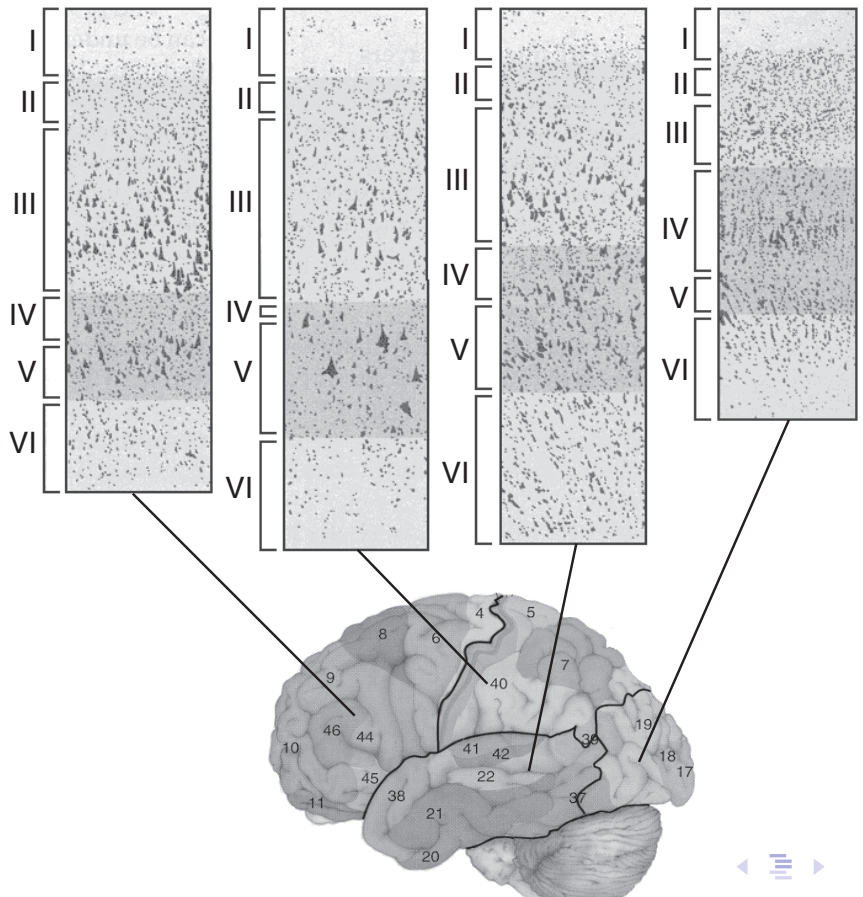
Cortex column

- neocortex-no horizontal anatomic segrregation, rat column: 6-10.000 neurons, 10 mil synapses
- 86 % synapses are excitatory, 14 % are inhibitatory
- $\frac{1}{3}$ excitatory synapses: (i) axon from the column, (ii) axons from neighboring columns, (iii) more distant regions, most inhibitatory connesction from the colums

A. Different staining techniques



B. Variation in cortex

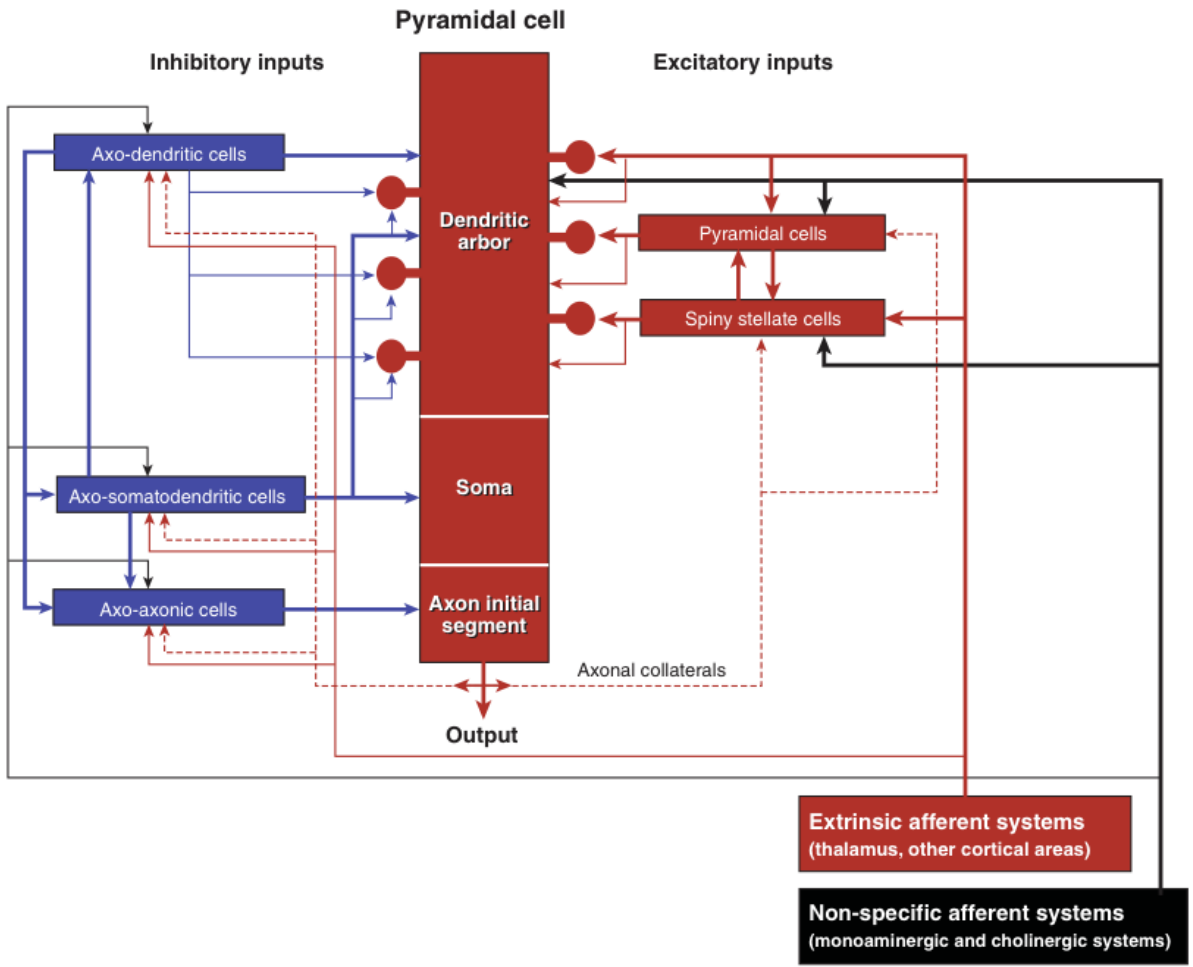


Cortical parameters

Variable	Value
Neuronal density	40,000/mm^3
Neuronal composition:	
Pyramidal	75%
Smooth stellate	15%
Spiny stellate	10%
Synaptic density	8 10^8/mm^3
Synapses per neuron	1000–20000
Distribution of synaptic types on pyramidal cell	
Inhibitory synapses	10%
Excitatory synapses from remote sources	45%
Excitatory synapses from local sources	45%
Asynchronous gain (relative synaptic efficiency)	0.003–0.2
Time duration of spike	$\sim$ 1 ms
Velocity of spike (myelinated axon of 0.02 mm diameter)	120 m/s
Length of axon	few mm to $\sim$ 1 m
Synaptic cleft	20 nm
Synaptic transmission delay due to diffusion	0.6 ms

Basic cortical microcurcuit-general

- 70-80 % - pyramidal cell,
- spiny nonpyramidal cells (short-axon cells)
- 15-30 % Aspiny nonpyramidal cells (short-axon cells without dendritic spines)
- red: glutamatergic (excitatory) , blue: GABAergic (inhibitory), black: others



Basic cortical microcurcuit-cats and monkeys

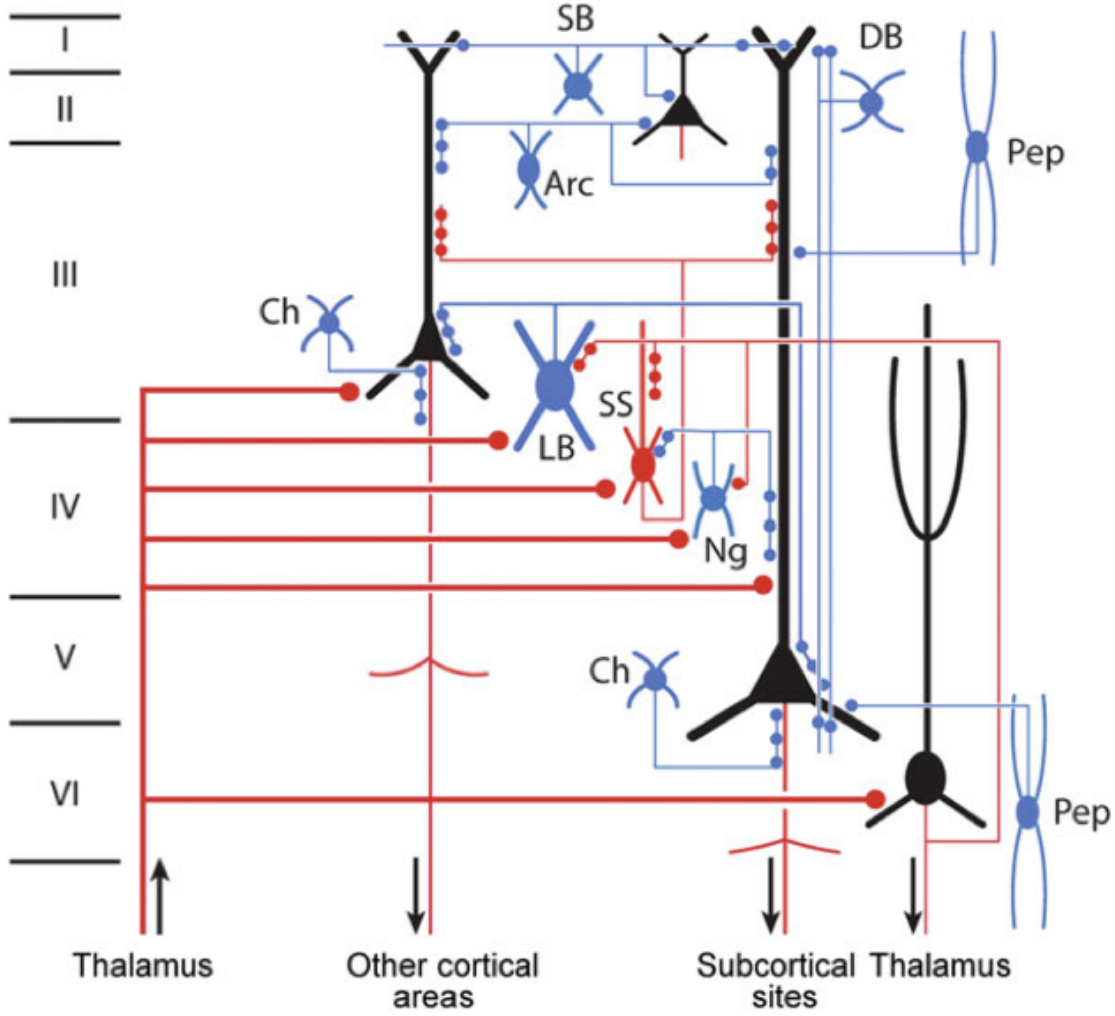


FIGURE 1–2. A schematic circuit based upon the known cortical cells upon which thalamic afferent fibers terminate in cats and monkeys. The GABAergic smooth intereneurons (blue) are identified by the names that they have received in these species. Arc, neuron with arciform axon; Ch, chandelier cell; DB, double bouquet cell; LB, large basket cell; Ng, neurogliaform cell; Pep, peptidergic neuron. Excitatory neurons (red) include pyramidal cells of layers II–VI and the spiny stellate cells (SS) of layer IV. (Based on Jones, 2007)

Presynaptic and postsynaptic AP

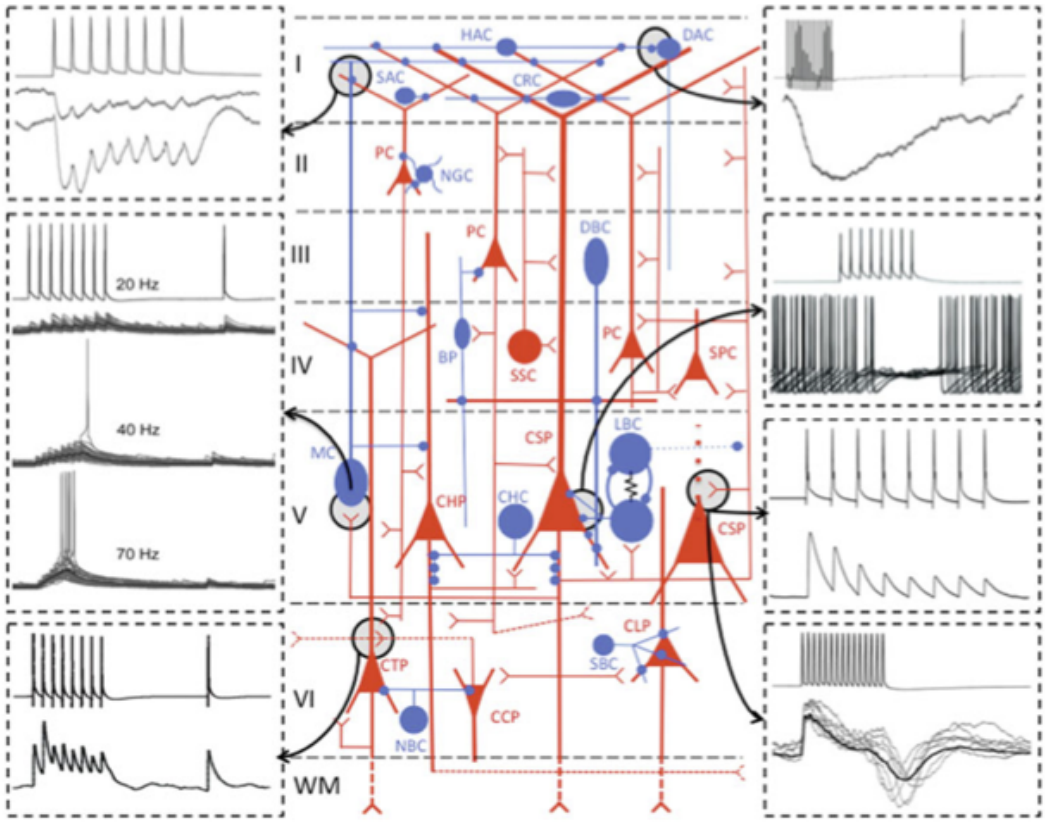


FIGURE 3–1. Simplified schematic representation of the neocortical microcircuitry. Red indicates excitatory neurons, dendrites, and axons; blue indicates inhibitory neurons, dendrites, and axons. Inhibitory synapses are marked in blue dots, and excitatory synapses are marked in red forks. From the top left and down, the insert illustrates a synaptic response from an MC onto a PC, a PC onto an MC, and a CCP onto a CTP. From top right and down, the inserts illustrate synaptic responses from an HAC on a VAC, an LBC on a PC, a PC response on a PC, and a disynaptic PC response on a PC via an MC. In all cases the presynaptic action potentials are above and the postsynaptic responses are below. Layers are indicated in roman numerals. Axons projecting beyond the neocortical dimensions are indicated by dotted lines. For the PCs, axons are thin lines relative to the dendrites; for the inhibitory neurons, only axons are schematized. Black arrows from grayed background circles indicate the synaptic locations for the inserted illustrated responses. BP, bipolar cell; CCP, cortico-cortical pyramid; CHC, chandelier cell; CHP, cortico-hemispheric pyramid; CLP, cortico-claustral pyramid; CRC, Cajal-Retzius cell; CSP, cortico-spinal pyramidal; CTP, cortico-thalamic pyramid; DBC, double bouquet cell; HAC, horizontal axon cell; LBC, large basket cell; MC, Martinotti cell; NBC, nest basket cell; NGC, neurogliaform cell; PC, pyramidal cell; SBC, small basket cell; SPC, star pyramidal cell; SSC, spiny stellate cell; DAC, descending axon cell; SAC, short axon cell; WM, white matter.

Example - visual system

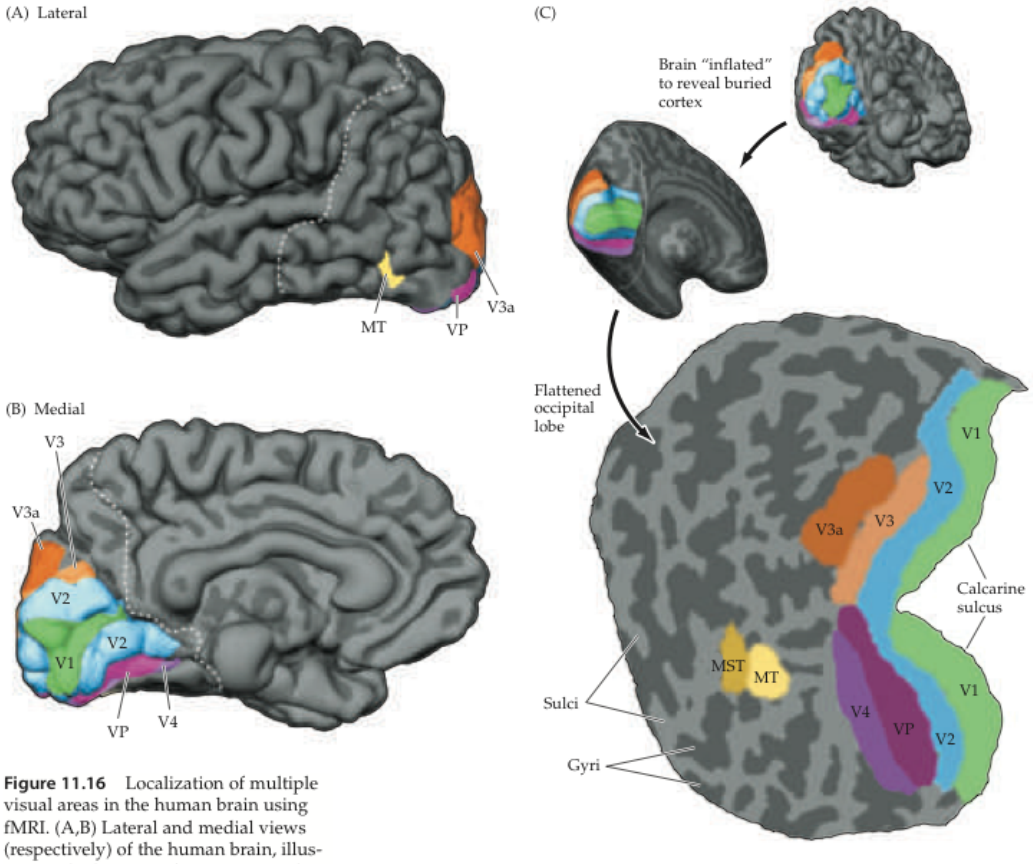
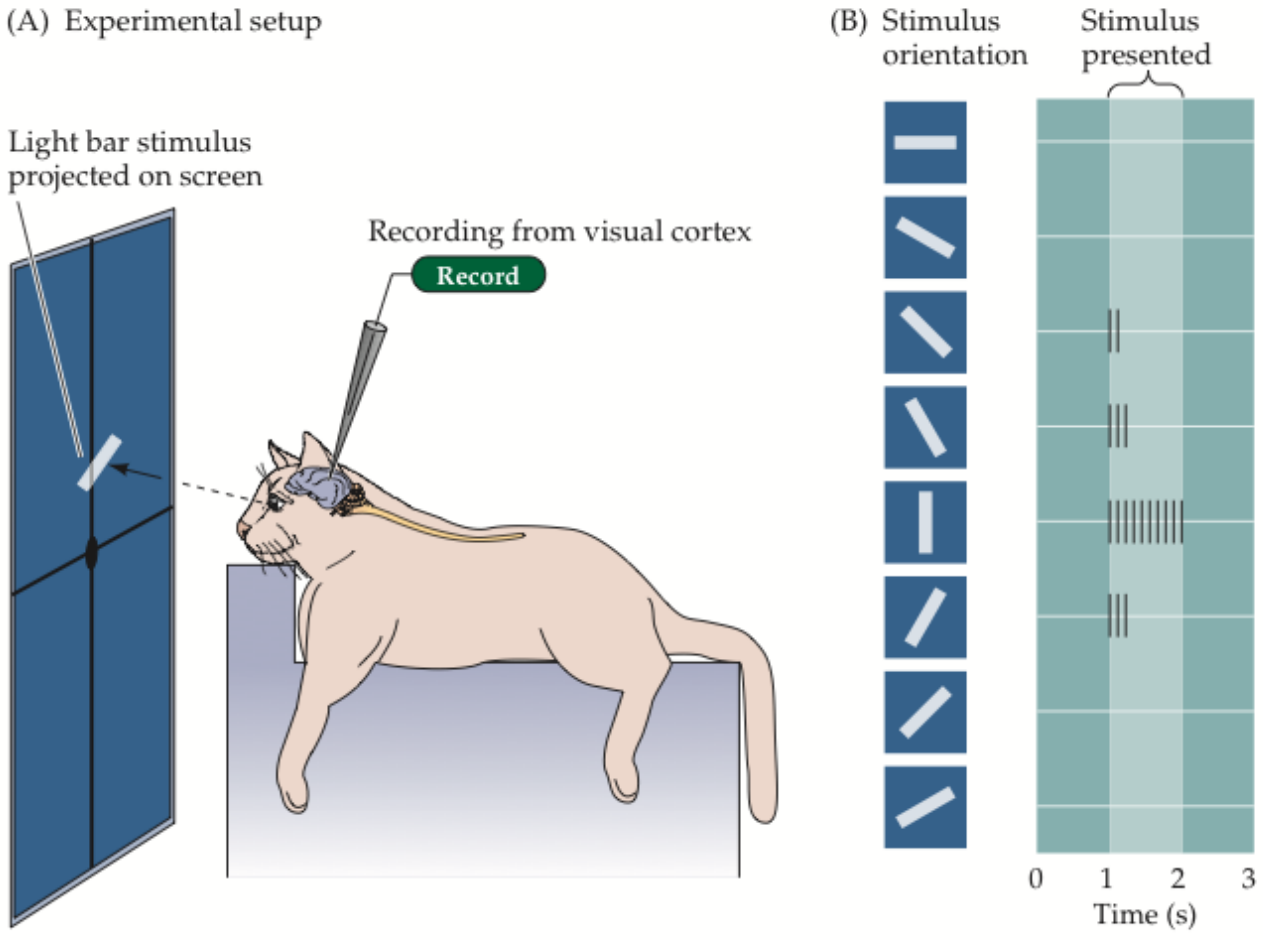
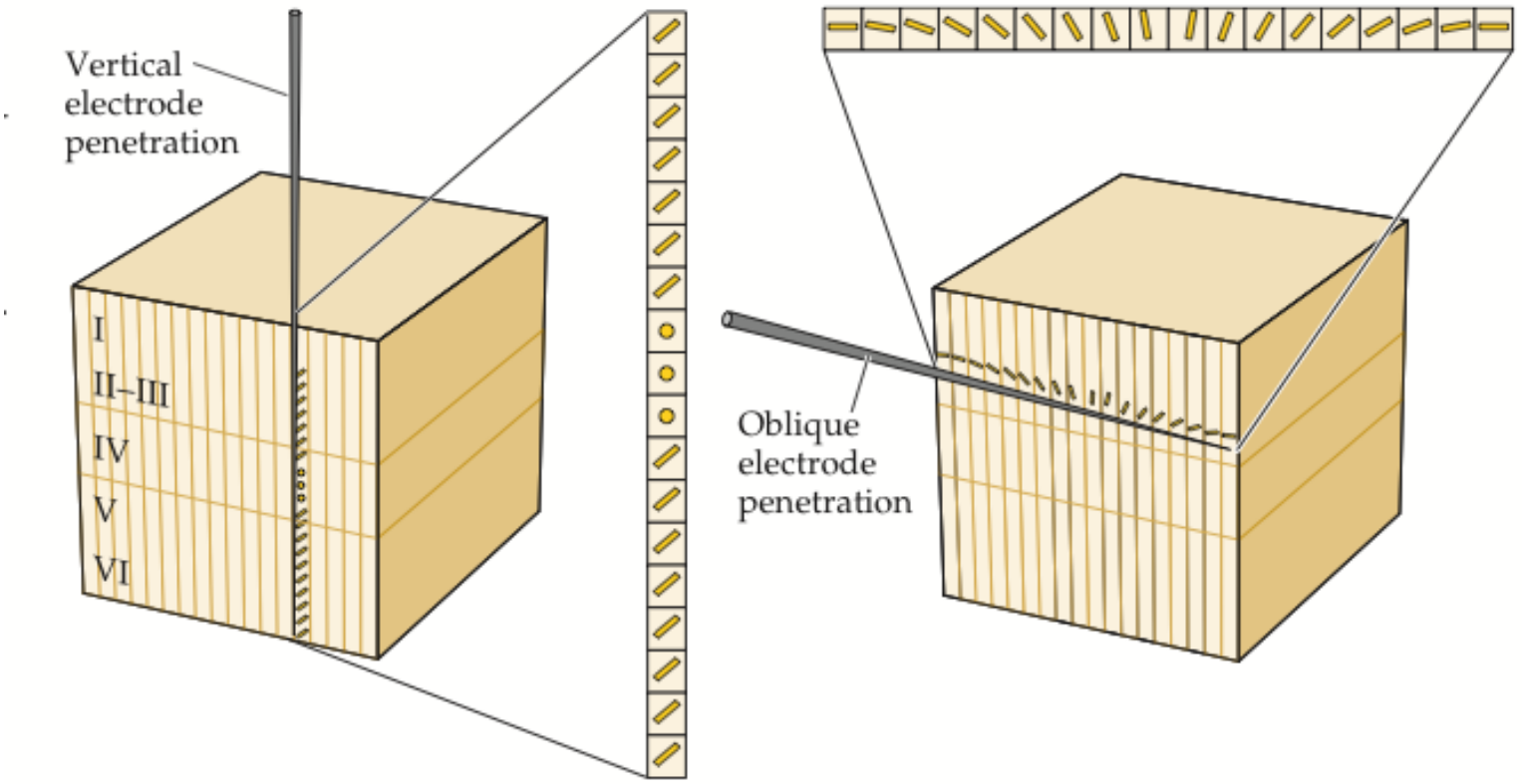


Figure 11.16 Localization of multiple visual areas in the human brain using fMRI. (A,B) Lateral and medial views (respectively) of the human brain, illus-

Cat's famous experimnet - Hubel, Wiesel

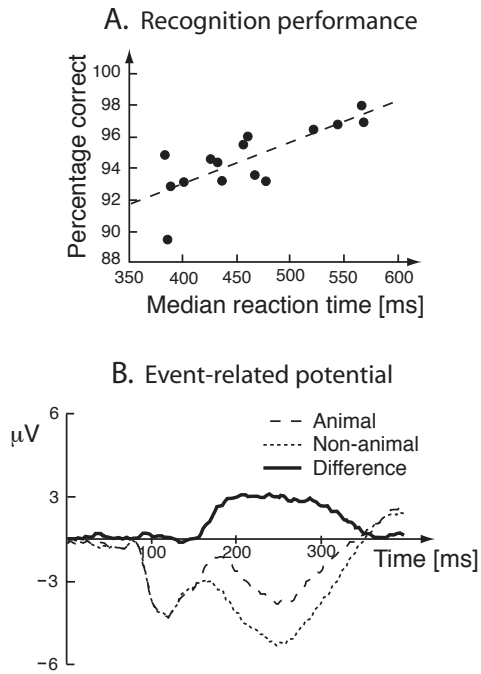


Columnar organization



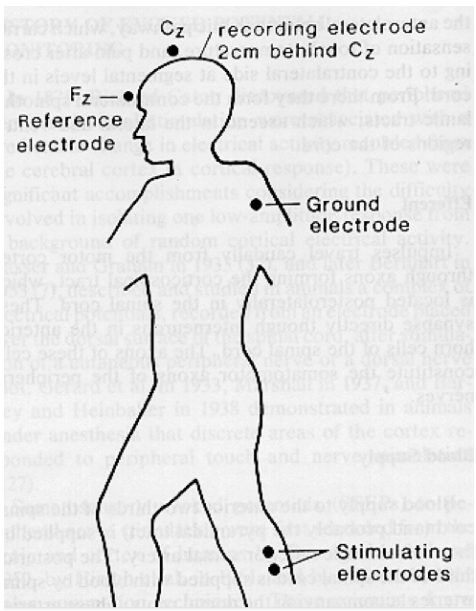
Rapid transmission in brain

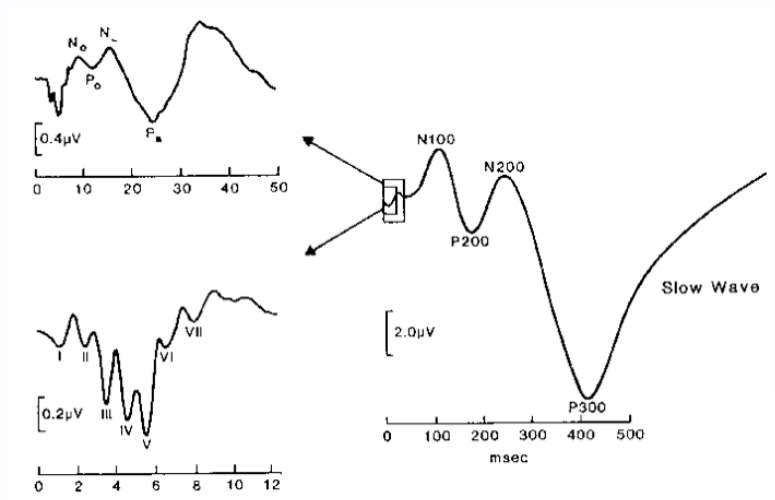
- Object recognition is fast - 20 ms: experiments of Simon Thorpe
- Presence of animals in visual scenes presented by short time - 20ms $\rightarrow$ subject released button when animal was present
- Evoked potentials by surface EEG $\rightarrow$ frontal cortex indicates correct answer after 150 ms!
- Each neuron in hierarchical level process and pass on information of the order of 10-20ms!



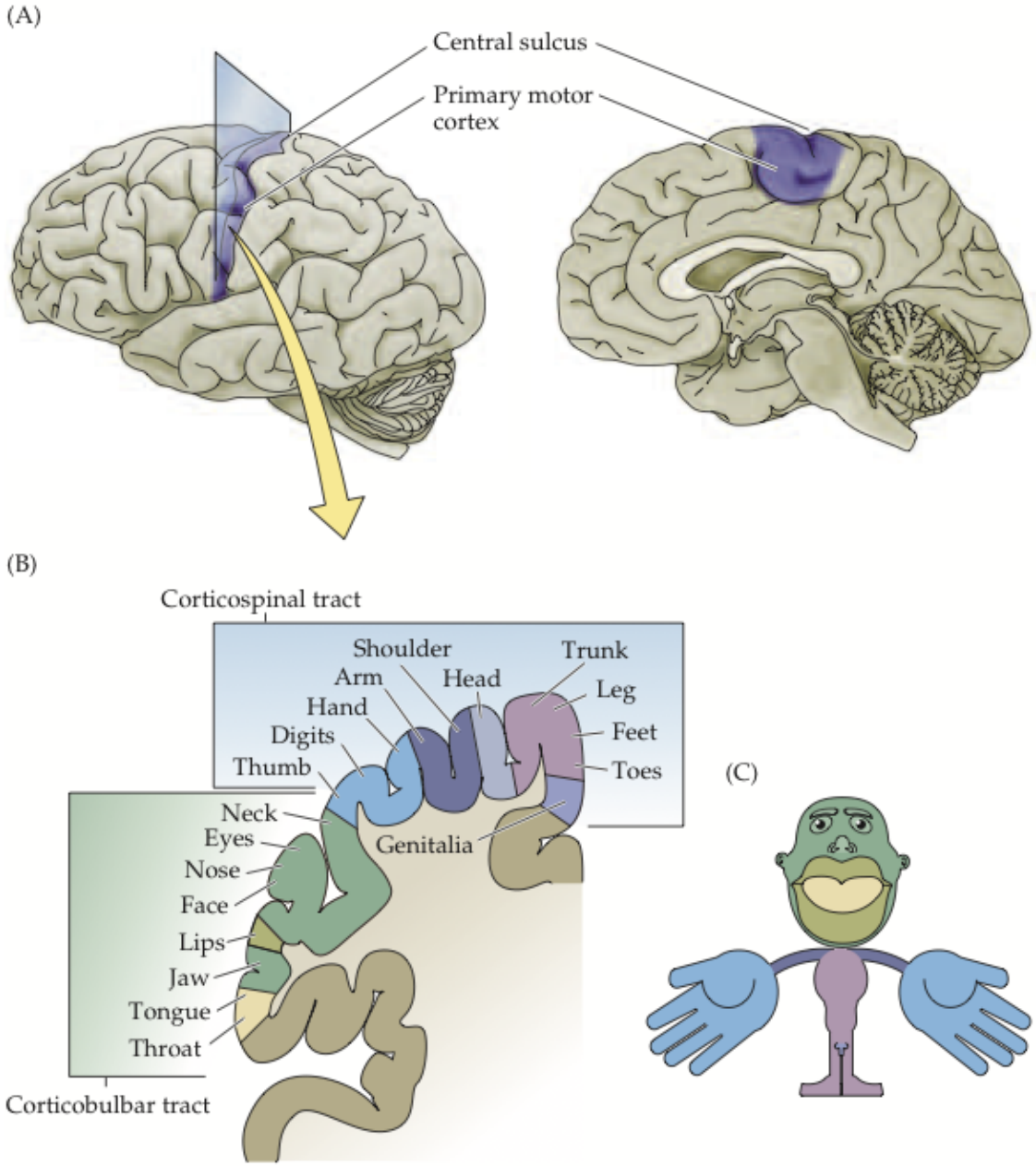
Evoked potentials - EEG averaging (100-1000)

- EEG surgace or Macroelectodes recording (contribution of thousands neuron cells)
- low amplitudes $\rightarrow$ low signal-to-noise ration (SNR)
- averaging is used (noise is random) $\rightarrow$ signal is time-locked to stimulus $\rightarrow$ over 100-1000 trials
- Above example is somatosensory evoked potentials (SSEP), compared to visual EP (VEP)

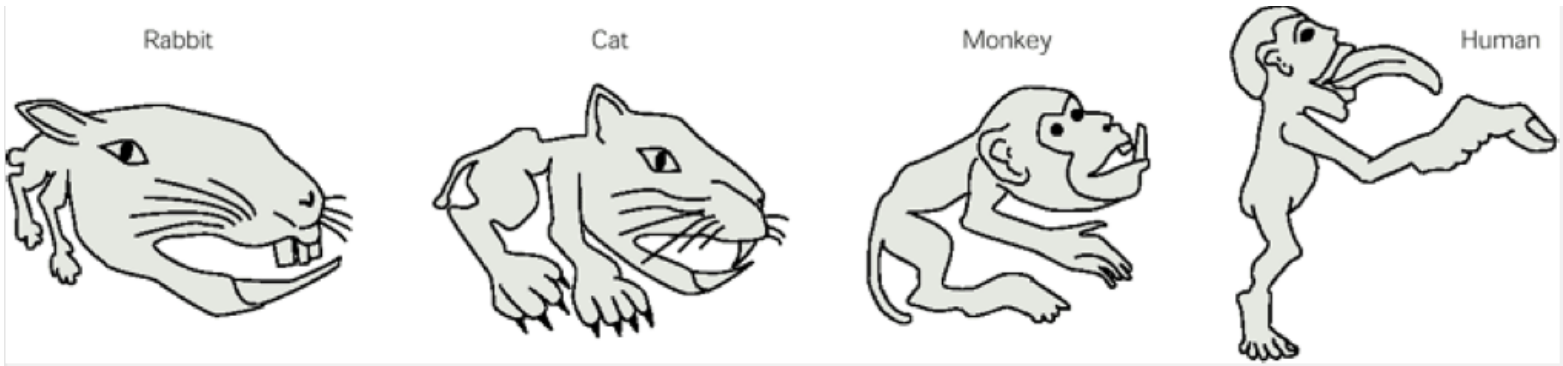




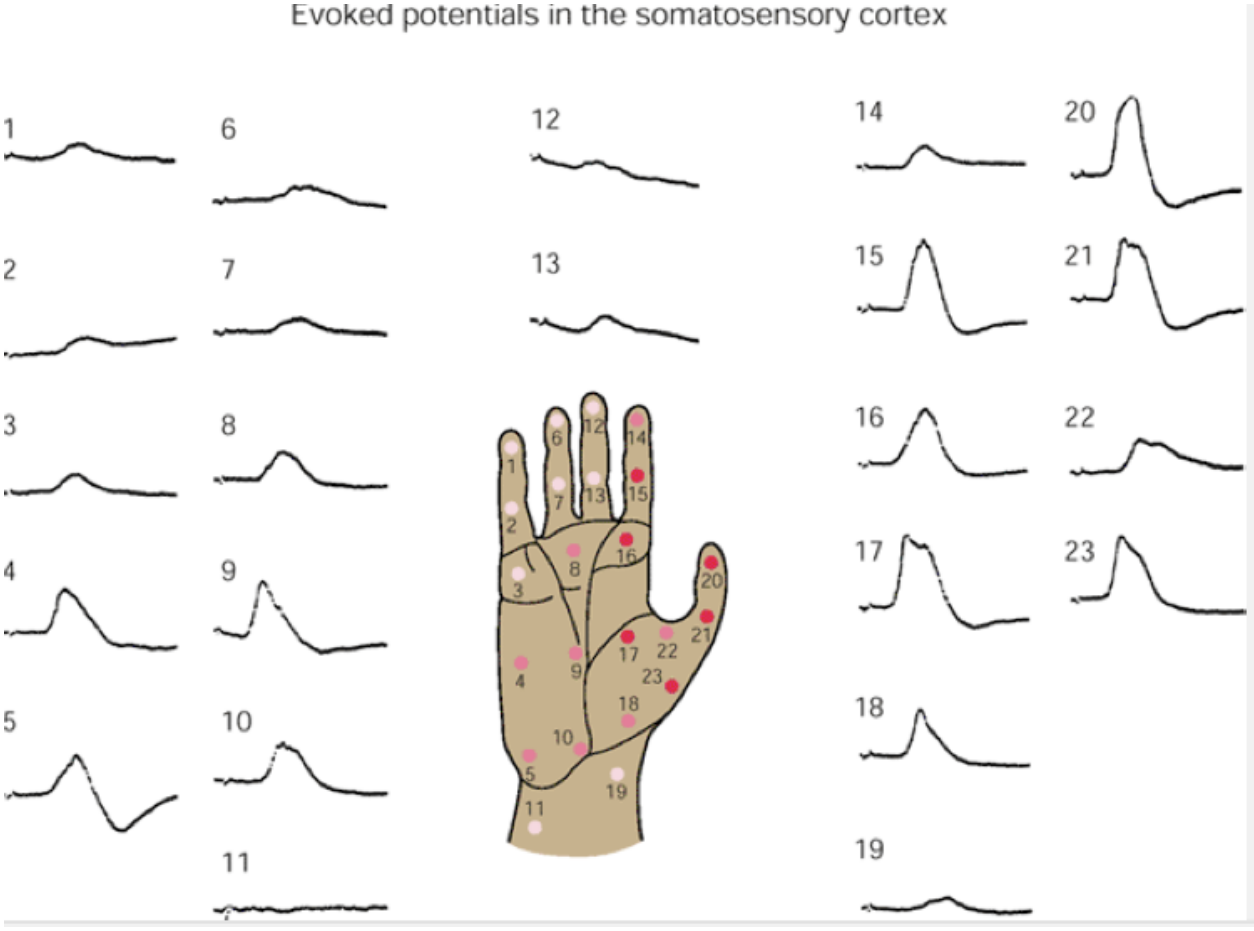
How do we measure cortical maps - Evoked potentials



Adaptive sematosensory information

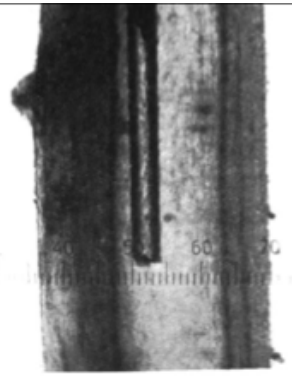


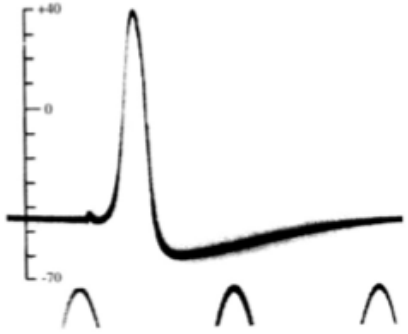
Topographical sematosensory maps



Simulation - neurons modellling

Sir Alan Lloyd Hodgkin





Sir Andrew Fielding Huxley

$$I = C_m \dot{V} + g_{Na}\, h\, m^3\, (V - V_{Na}) + g_K\, n^4\, (V - V_k) + G_L\, (V - V_L) \qquad (1)$$

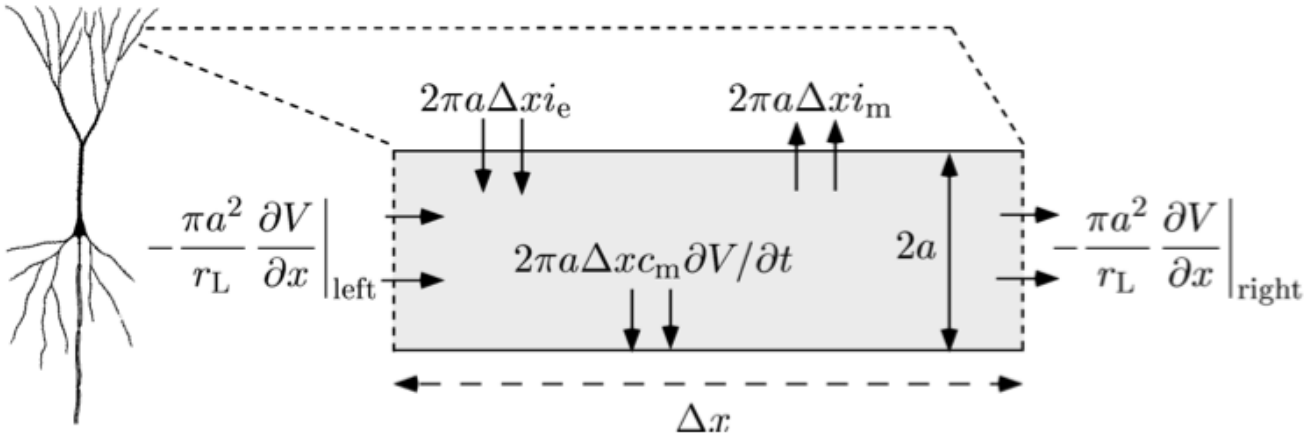
$$\frac{d}{dt} m = \alpha_m (V)\ (1 - m) - \beta_m (V)\ m \qquad (2)$$

$$\frac{d}{dt} n = \alpha_n (V)\ (1 - n) - \beta_n (V)\ n \qquad (3)$$

$$\frac{d}{dt} h = \alpha_h (V)\ (1 - h) - \beta_h (V)\ h \qquad (4)$$

Cable Theory

Passive cable equation



$$\frac{r_m}{r_i} \div \frac{{}^2V(x,t)}{x^2} \quad r_m c_m \frac{V(x,t)}{t} \quad V(x,t) = 0$$

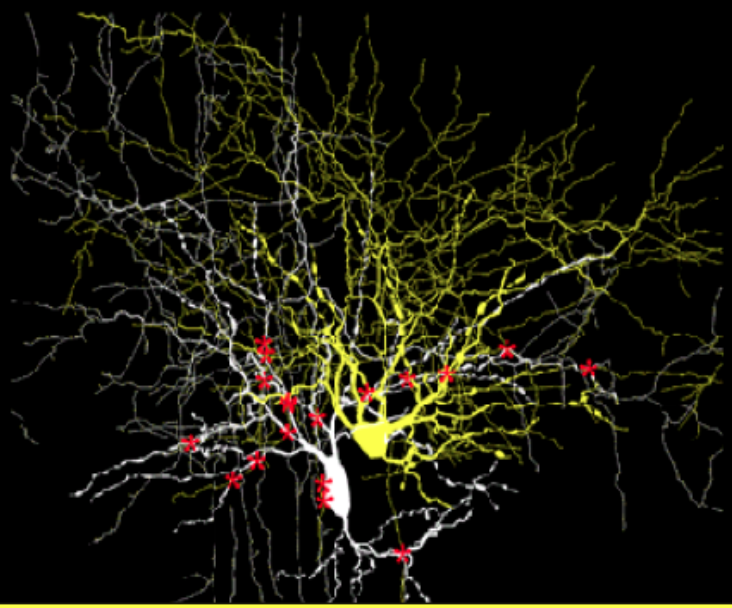
$$\frac{{}^2V}{X^2} = \frac{V}{T} + V(X,T)$$

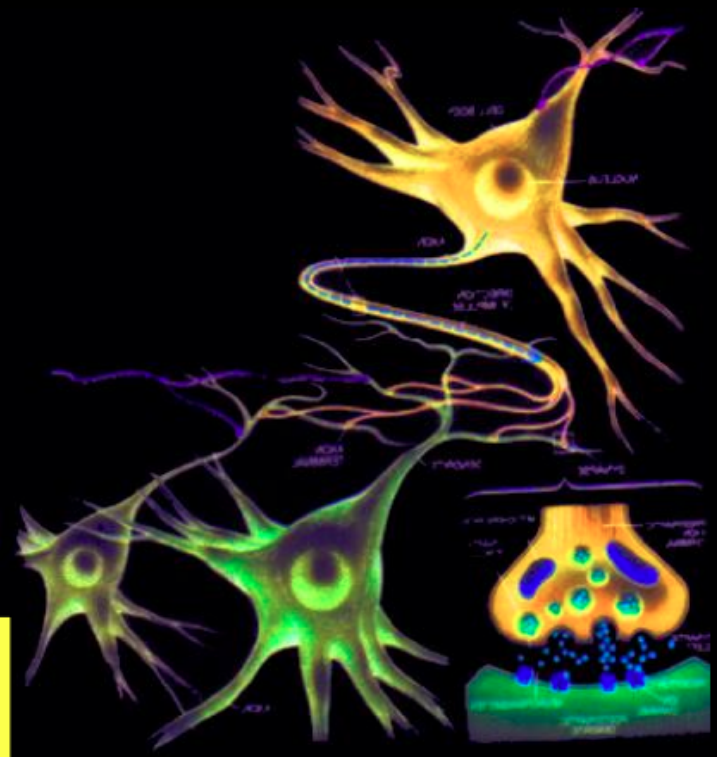
$X = x/\lambda$

$T = t/\tau_m$

Learning - plasticity

Modeling synapses (PSP's) as R-C circuits and as plastic device

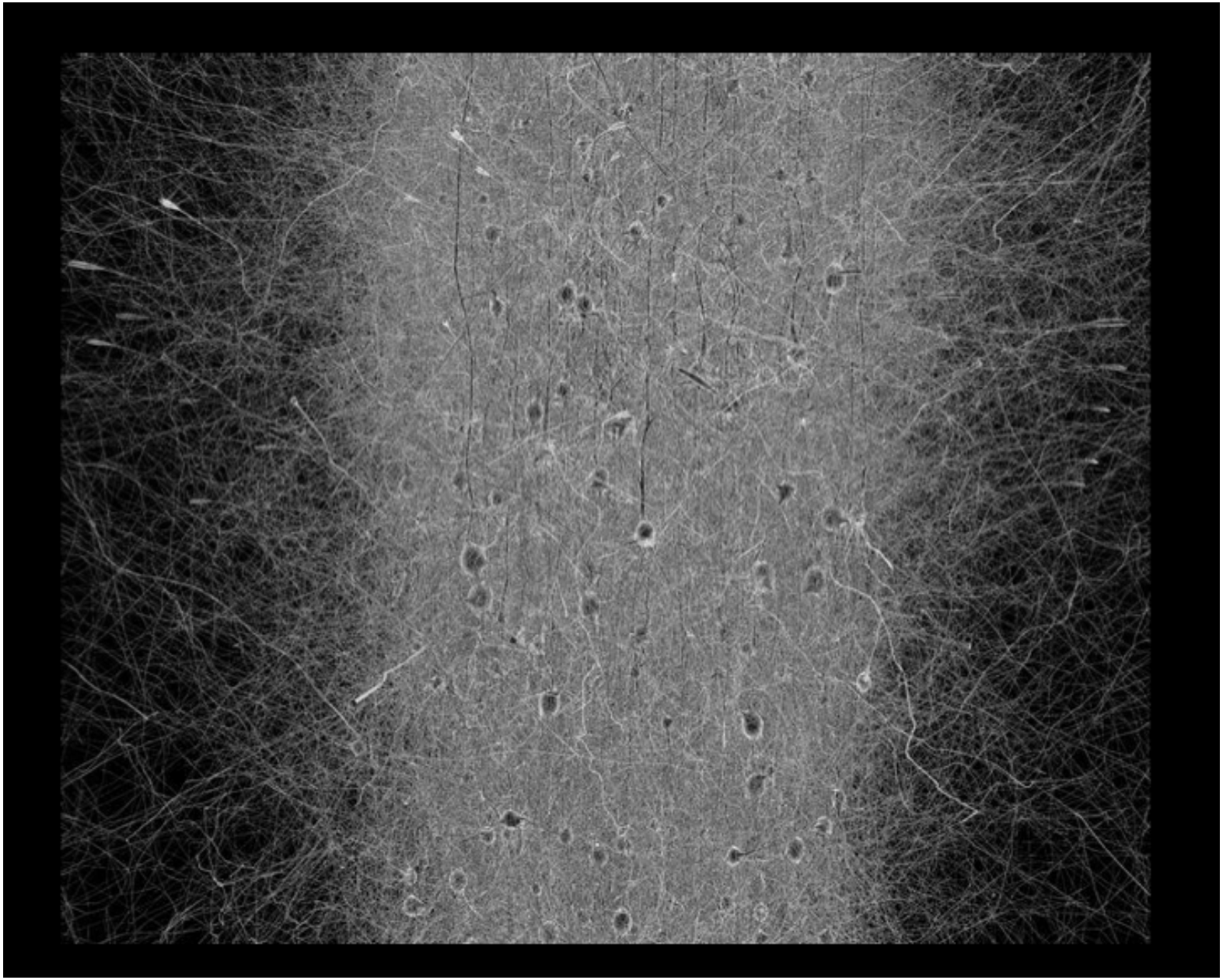




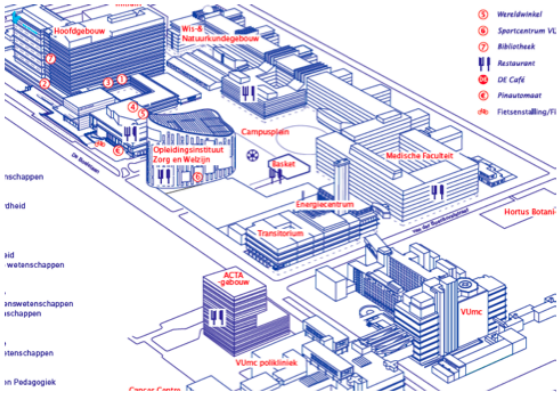
$$\Delta w_+ = A_+ e^{\frac{-(t_{post}-t_{pre})}{\tau_+}} \quad when\left(t_{post} > t_{pre}\right)$$

$$\Delta w_- = A_- e^{\frac{-(t_{post}-t_{pre})}{\tau_-}} \quad when\left(t_{pre} > t_{post}\right)$$

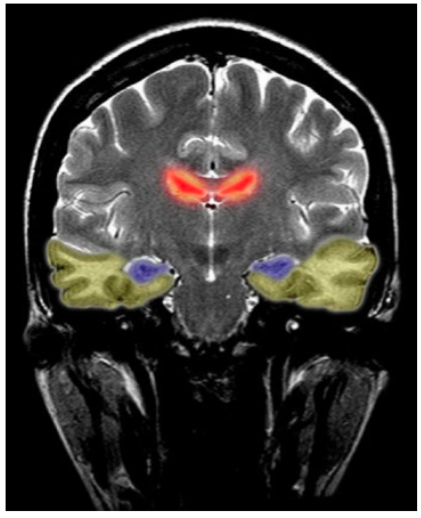
Blue Brain Project

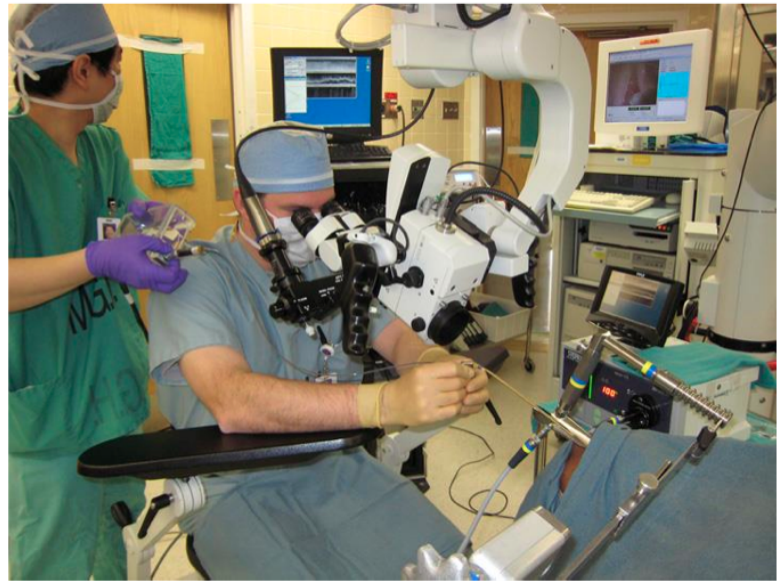


Towards Human Brain project



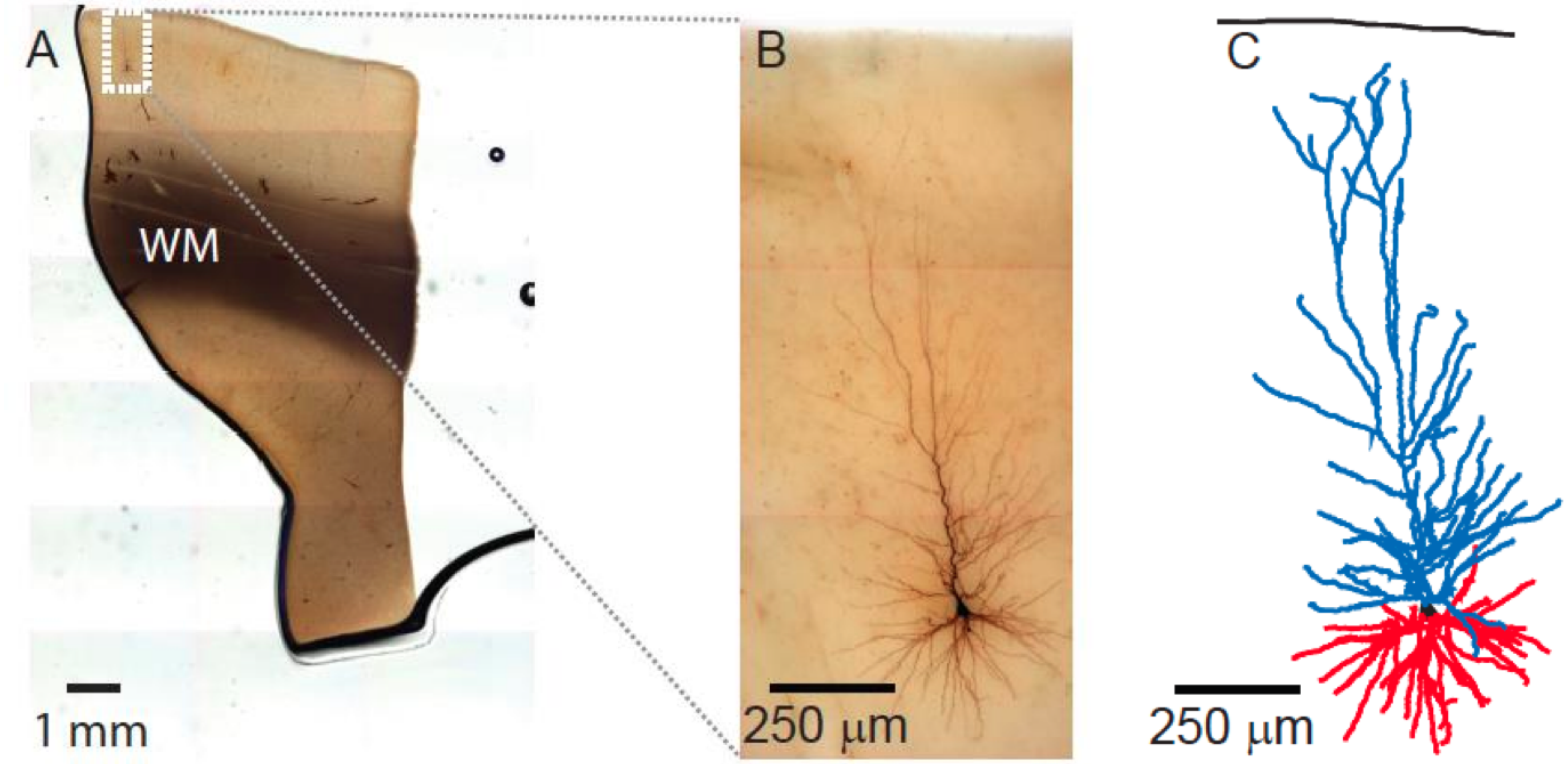
Neuroscience Campus Amsterdam





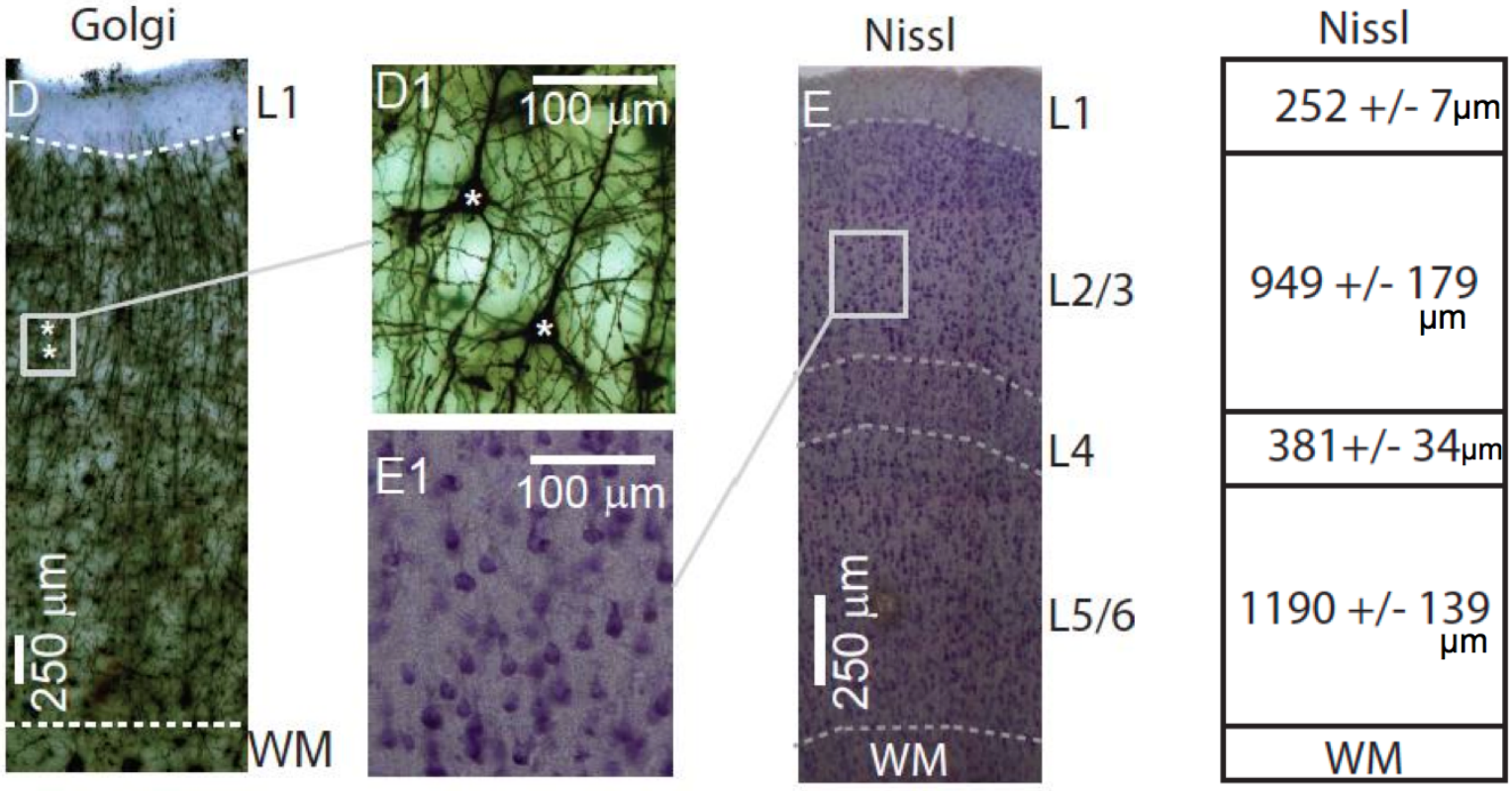
Hans Baayen, MD
Neurosurgeon
VUmc Amsterdam

Recording and reconstructing Human Neurons

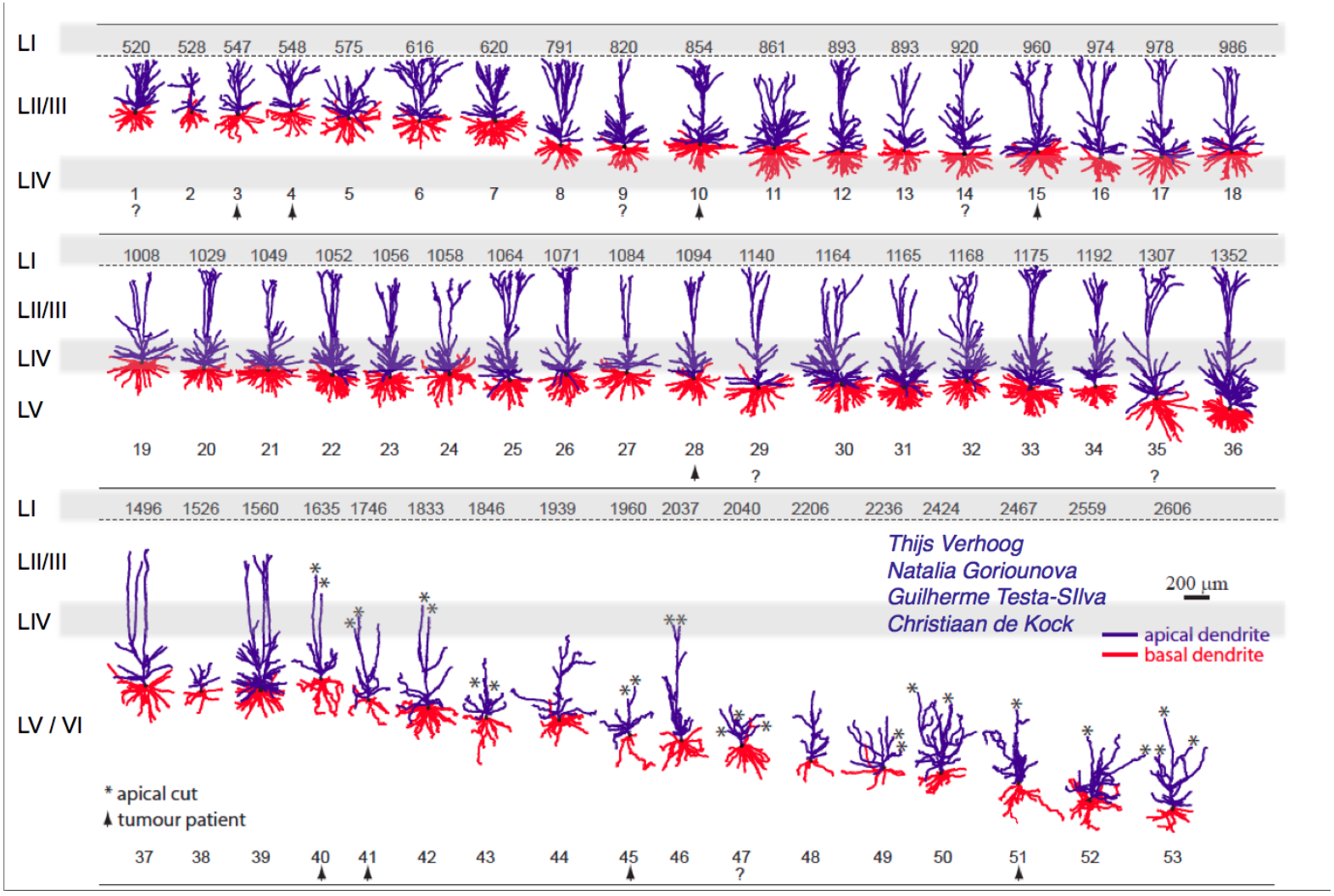


Thijs Verhoog
Natalia Goriounova
Guilherme Testa-Silva
Christiaan de Kock

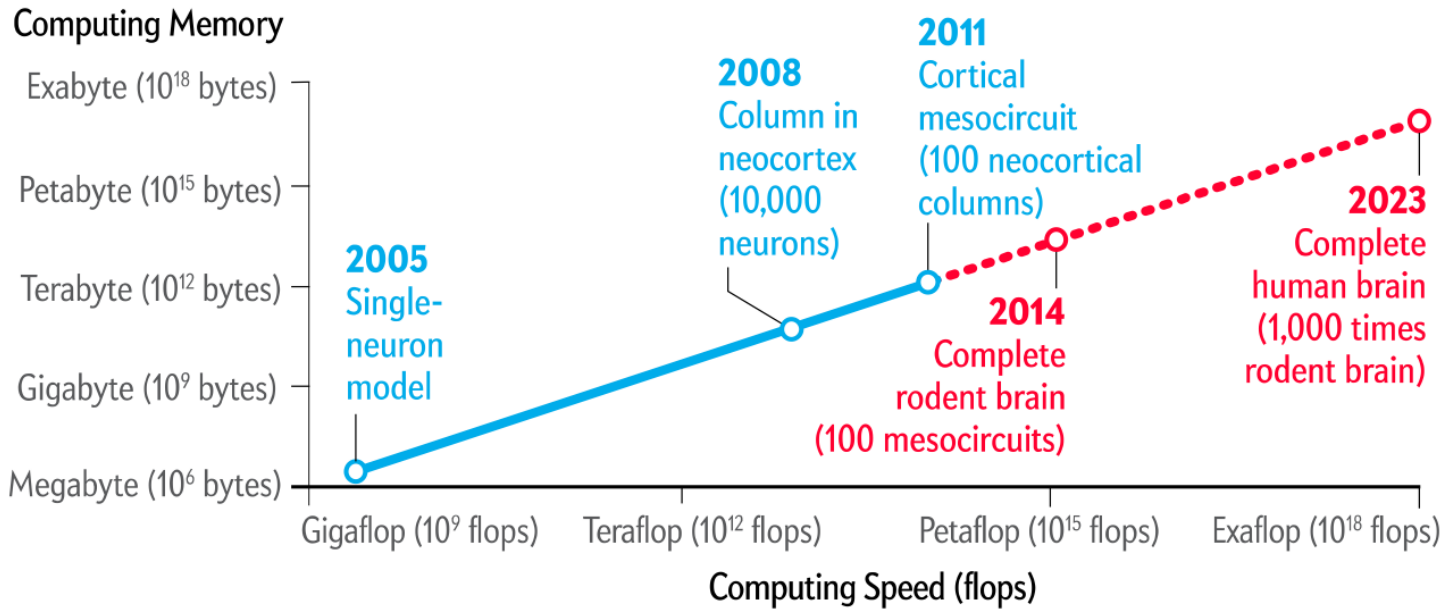
Histological characterization



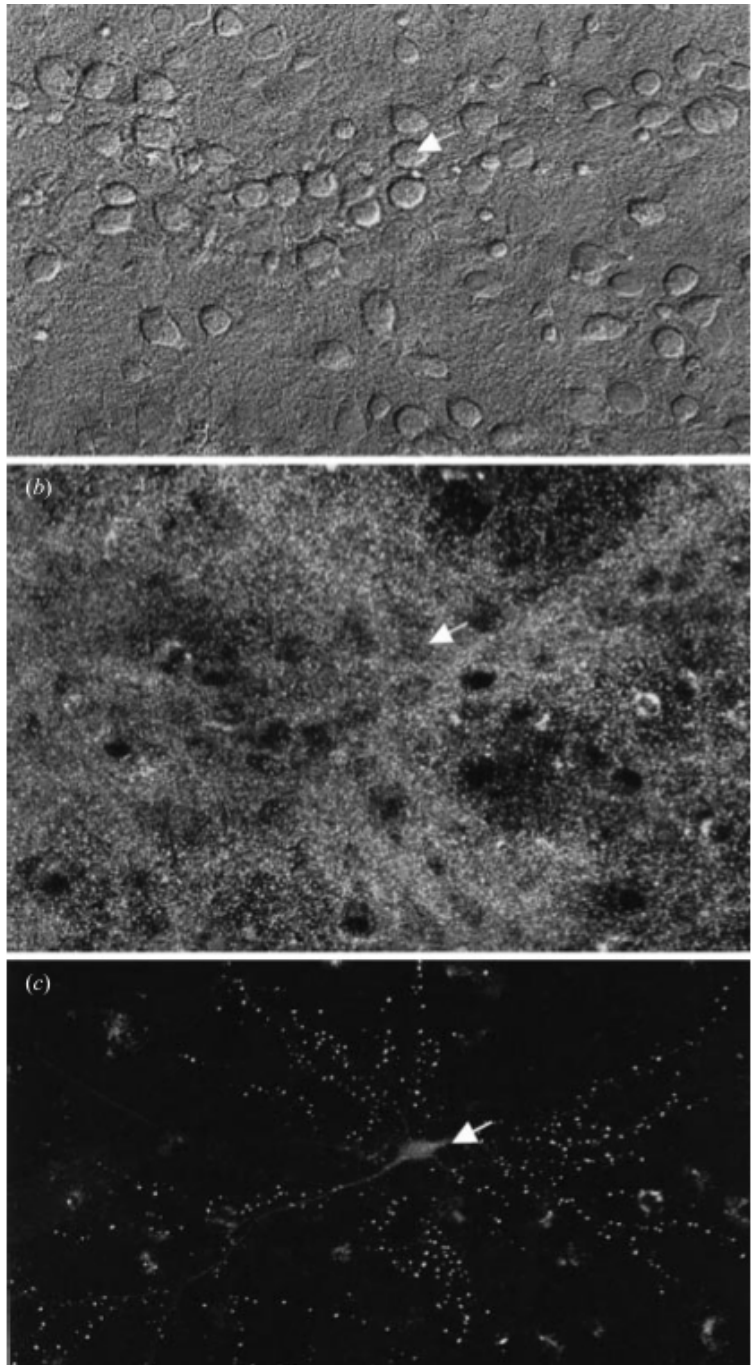
Human pyramidal neurons across cortical layers



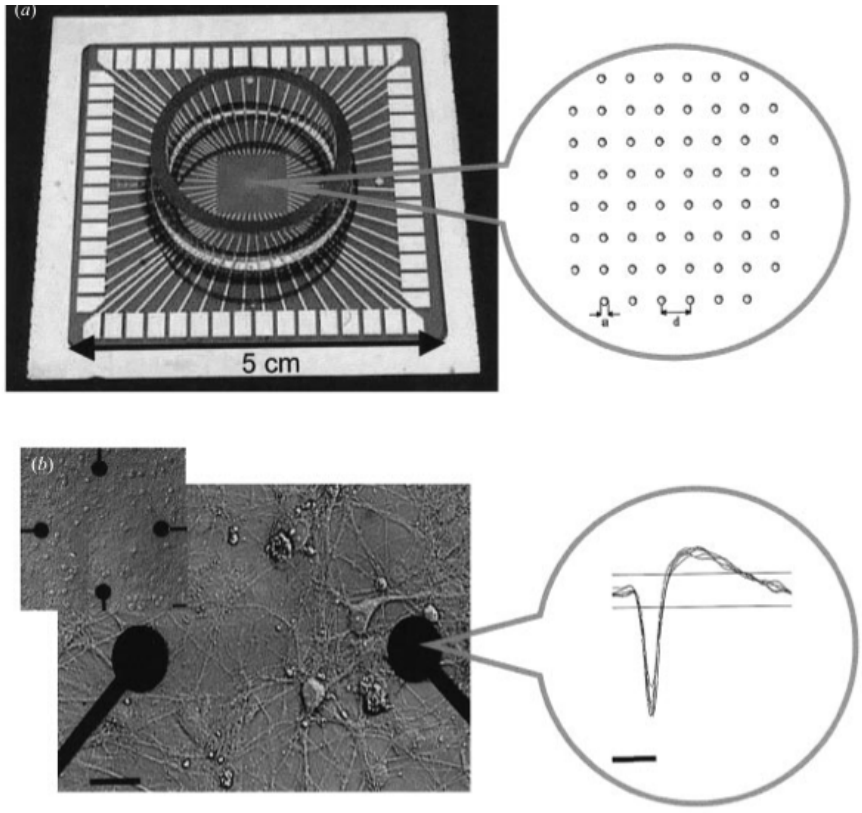
Expected growth in computational power



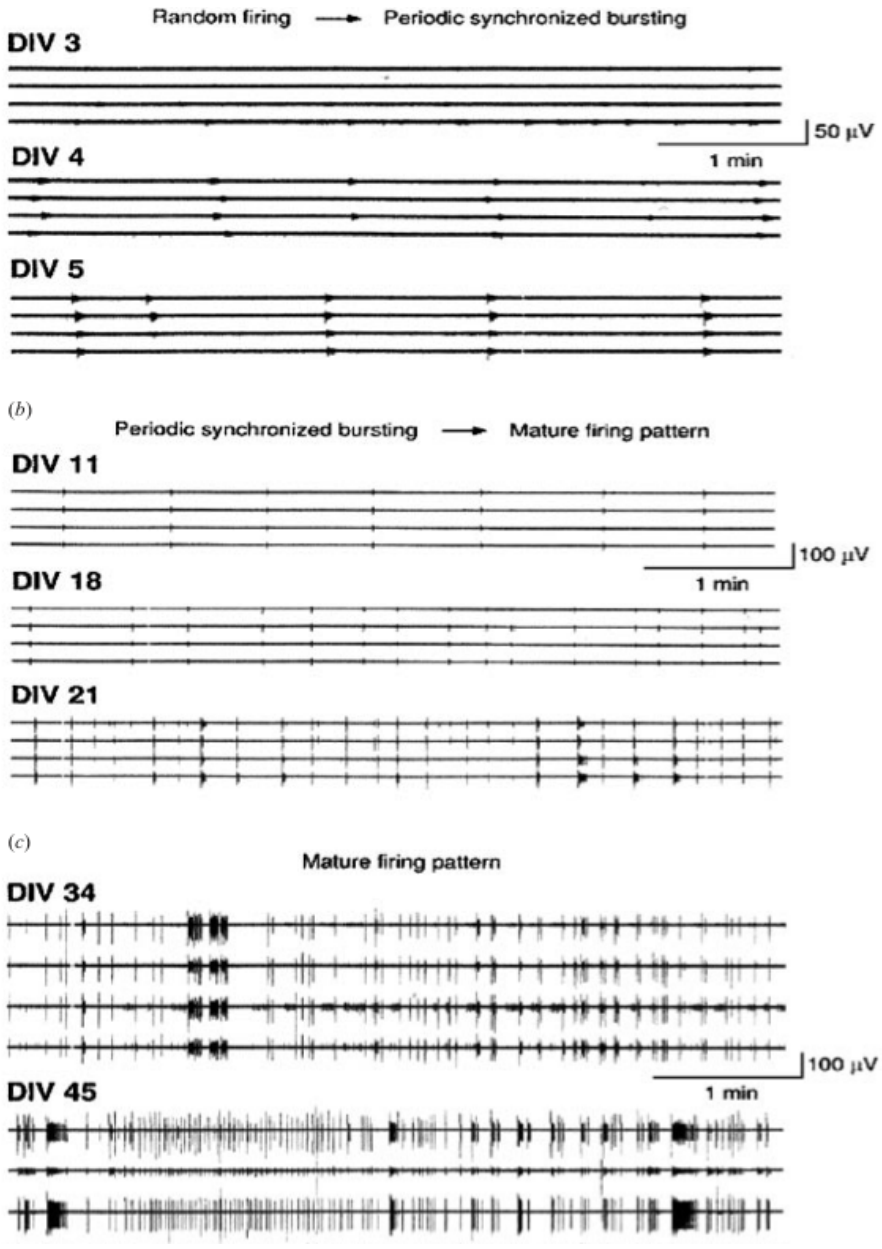
Random networks - ex vivo



Random networks - microelectrode array

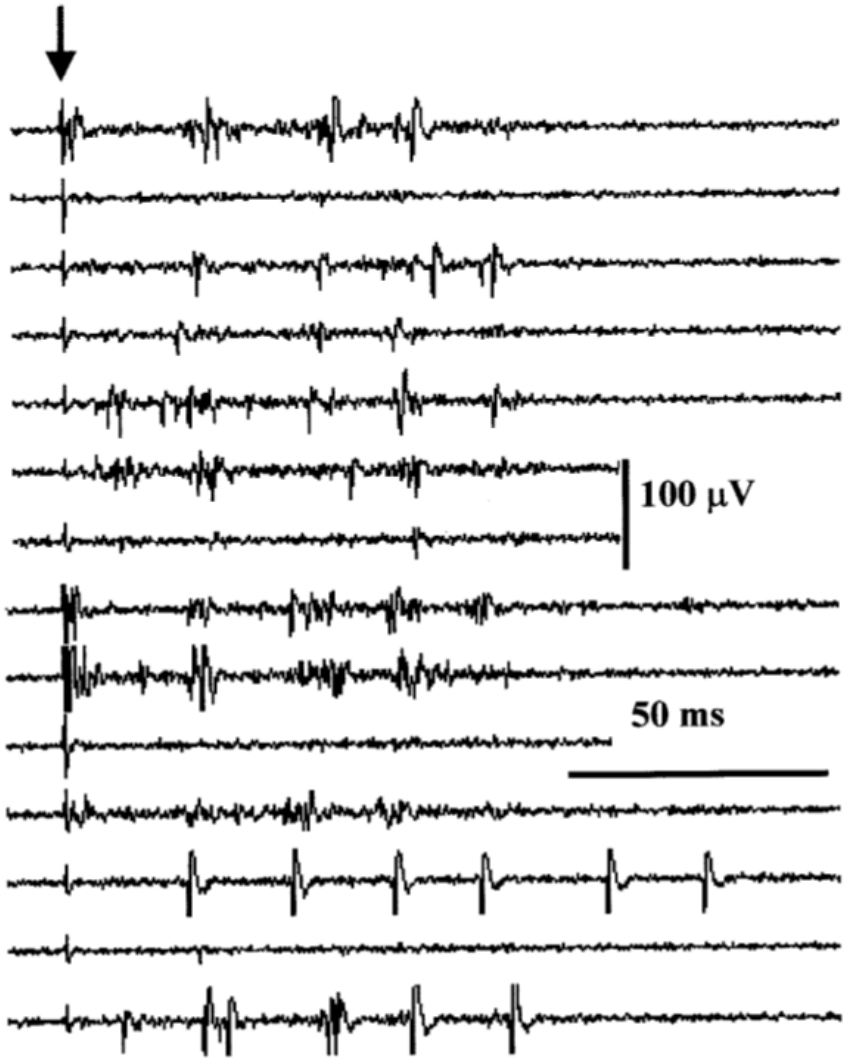


Random networks - Development changes in neocortical activity



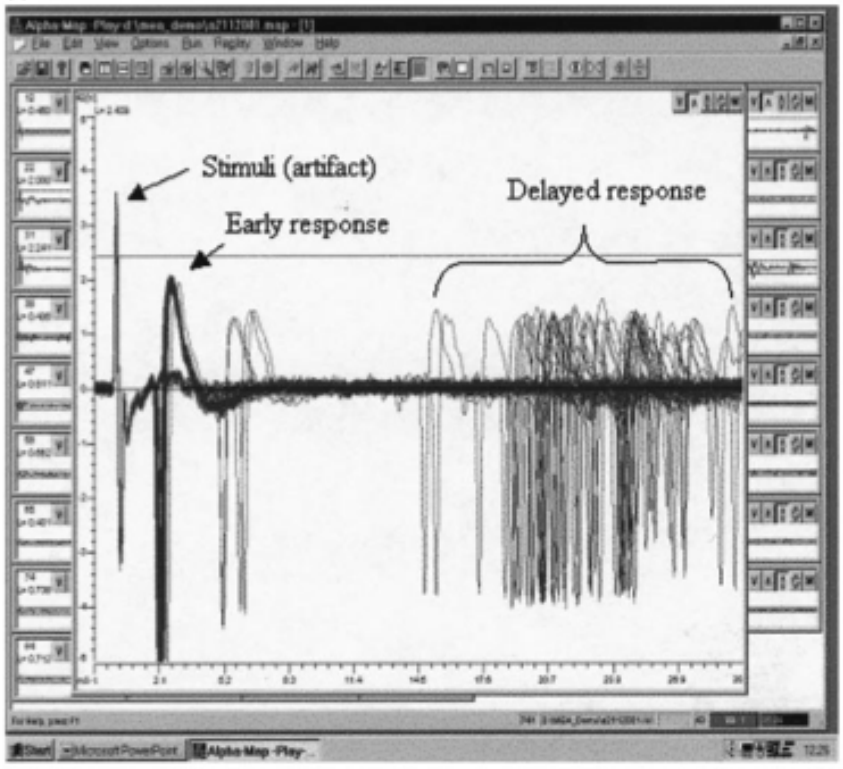
Random networks - stimulation

- $50\mu A$ stimulust lasting $420\mu s$
- three responses: (i) early componet, (ii) refractory period (iii) late component

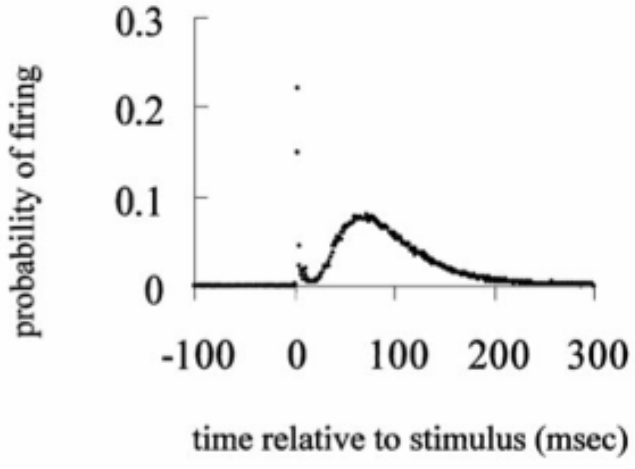


Random networks - response to stimulation: 3 components

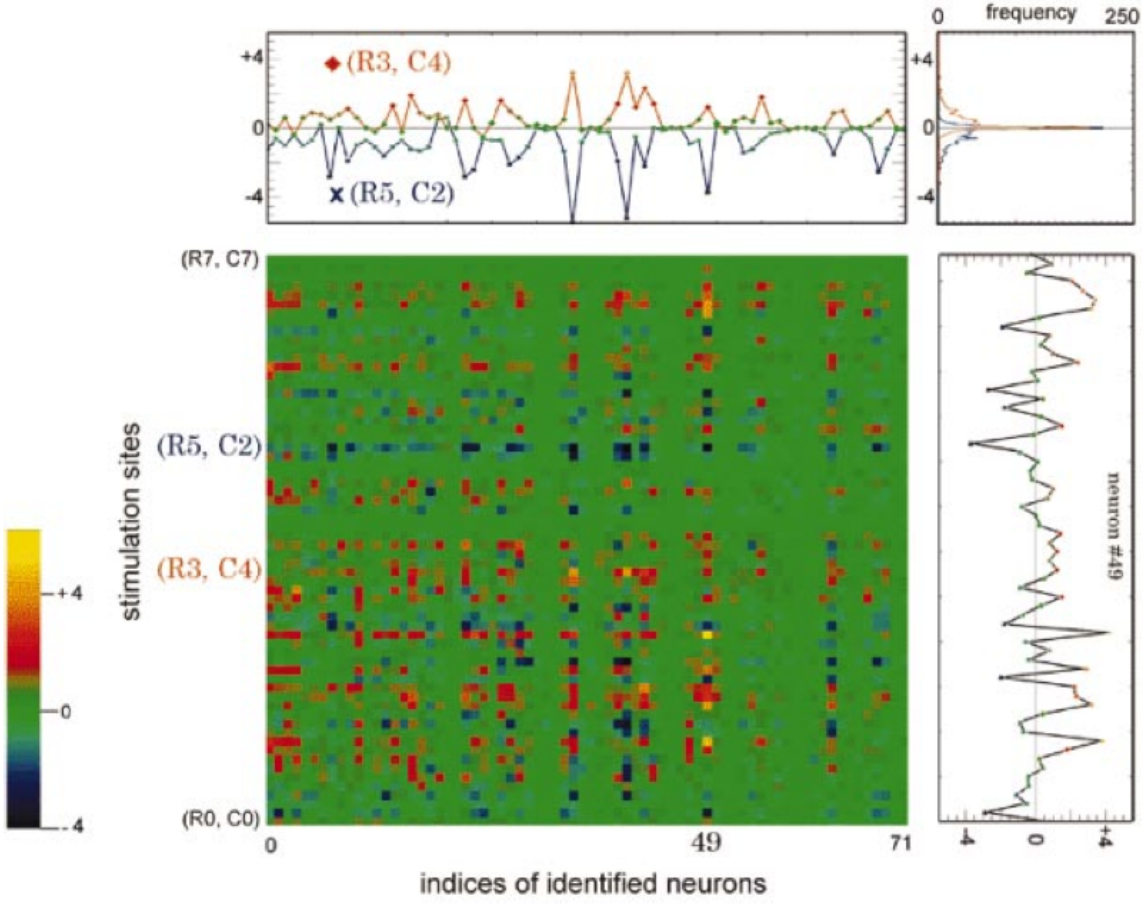
(a)



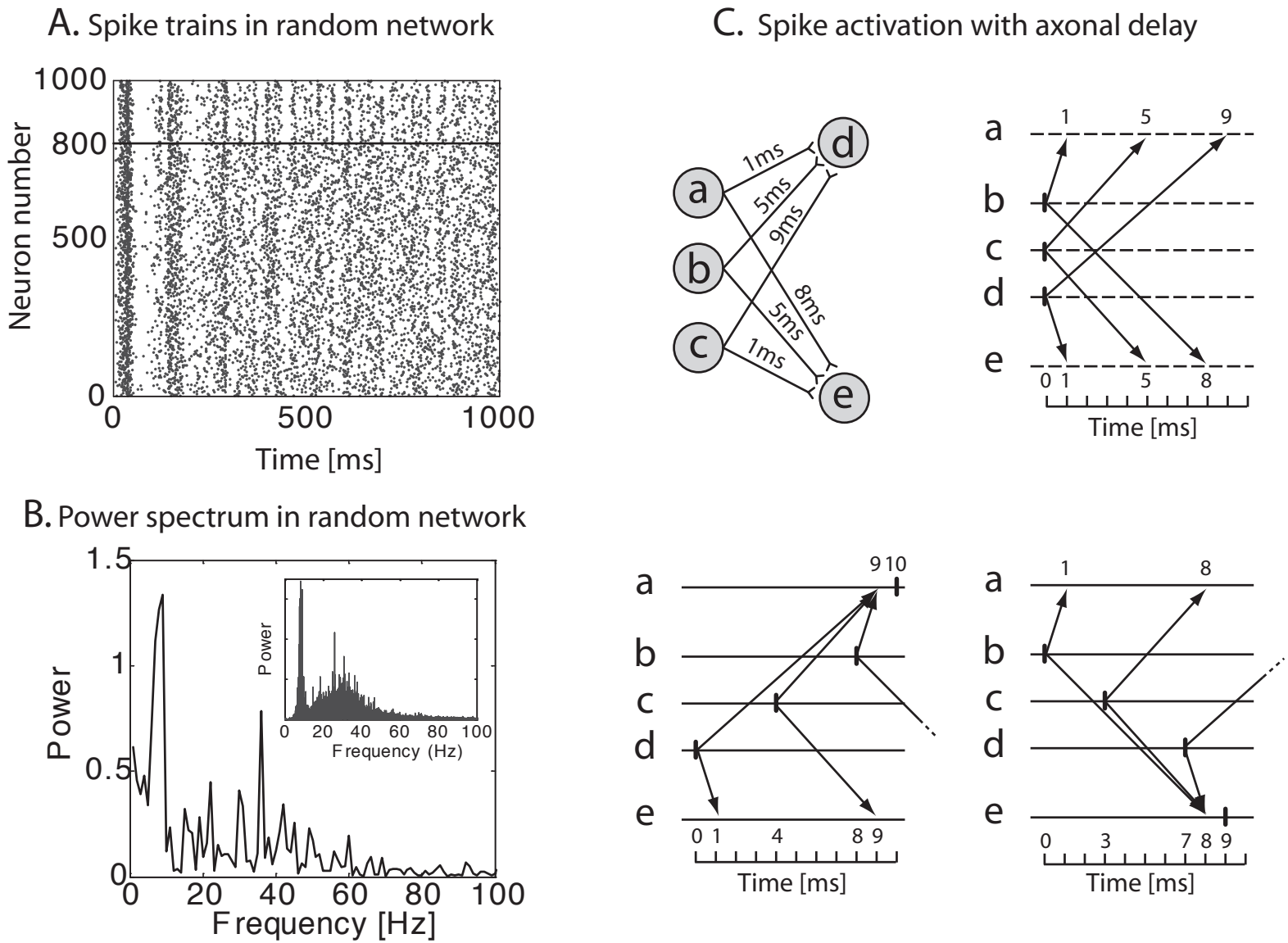
(b)



Random networks - response to stimulation: Hebb's rule



Random networks with axonal delay



from Izhikevich 2003/2006

Polychronization

- two groups: i) (d,c,b,a) firing spike time pattern (0,4,8,10) ms / ii) (b,c,d,e) firing spike time pattern (0,3,7,9) ms
- firing is not synchronous but time-locked, poly $\rightarrow$ many, chronous $\rightarrow$ time/clock
- reproducible time locking pattern
- spike-timing-dependent plasticity (STDP) can spontaneously organize neurons into such groups
- main result:he number of coexisting polychronous groups could be far greater than the number of neurons in the network, sometimes even greater than the number of synapses
- Each neuron is part of many groups, firing with one group at one time and with another group at another time.
- Simultion on 1000 neurons with STDP and conduction delays
- mamalian cortex $\rightarrow$ neuron distribution:excitatory (80%) and inhibitory (20%), 0.1 probability of connection between any two neurons

STDP rule

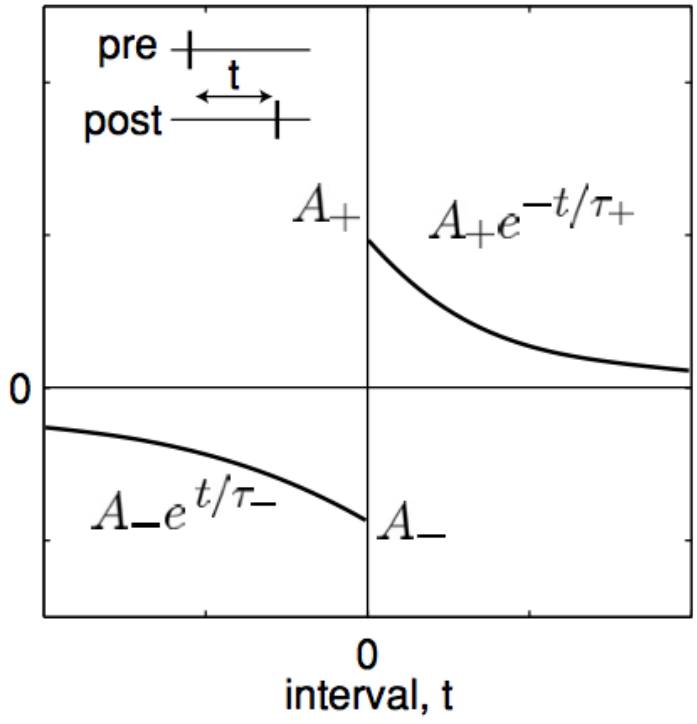
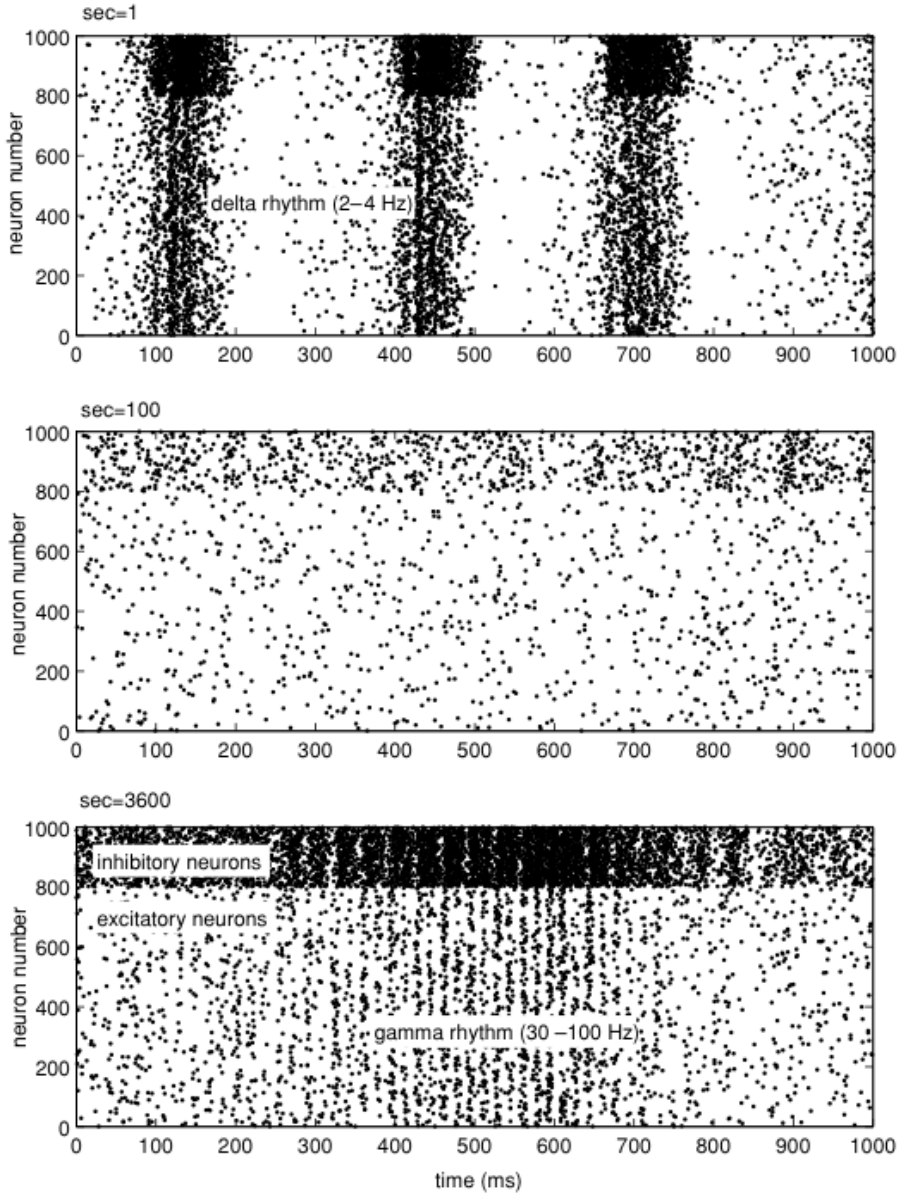


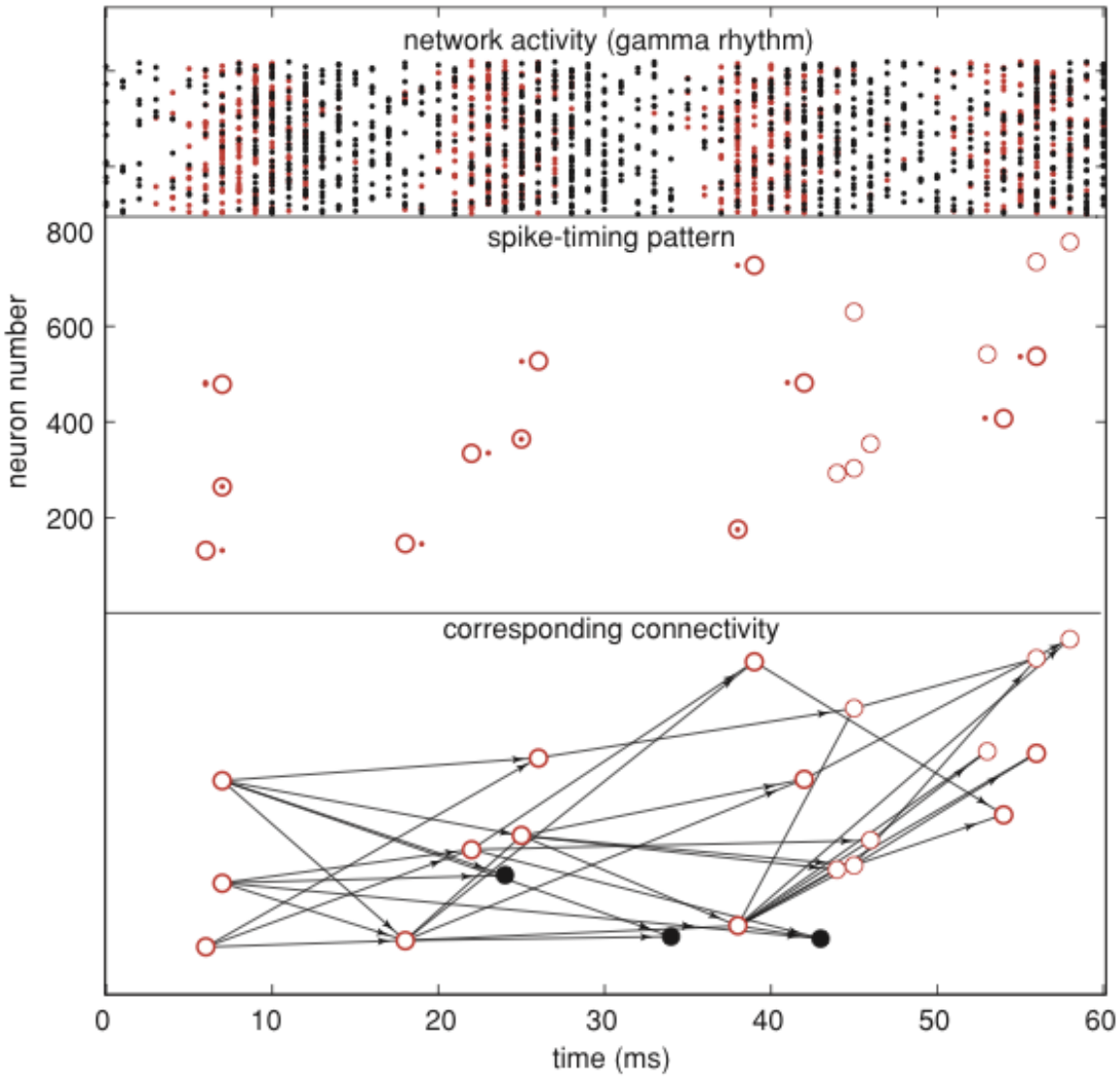
Figure 4: STDP rule (spike-timing-dependent plasticity, or Hebbian temporally asymmetric synaptic plasticity): The weight of synaptic connection from pre- to postsynaptic neuron is increased if the postneuron fired after the presynaptic spike, that is, the interspike interval $t > 0$. The magnitude of change decreases as A_+e^{-t/τ_+}. Reverse order results in a decrease of the synaptic weight with magnitude A_-e^{t/τ_-}. Parameters used: $\tau_+ = \tau_- = 20\,\text{ms}$, $A_+ = 0.1$, and $A_- = 0.12$.

Rhythmic activity of the spiking model



from Izhikevich 2003/2006

Polychronous group activation



from Izhikevich 2003/2006

Example of polychronous group

- Although spiking of excitatory neurons looks random and uncorrelated, there are certain persistent spike-timing patterns that emerge and reoccur with millisecond precision
- Pattern denoted by circles in the middle of the figure repeats itself a few times per hour with 1 ms spike jitter.
- activation of the group is locked to the gamma oscillation; that is, the first three neurons fire at the first gamma cycle, their spikes travel 10 to 20 ms and arrive at the next four neurons in the next gamma cycle, and so on, resulting in precise stereotypical activity.

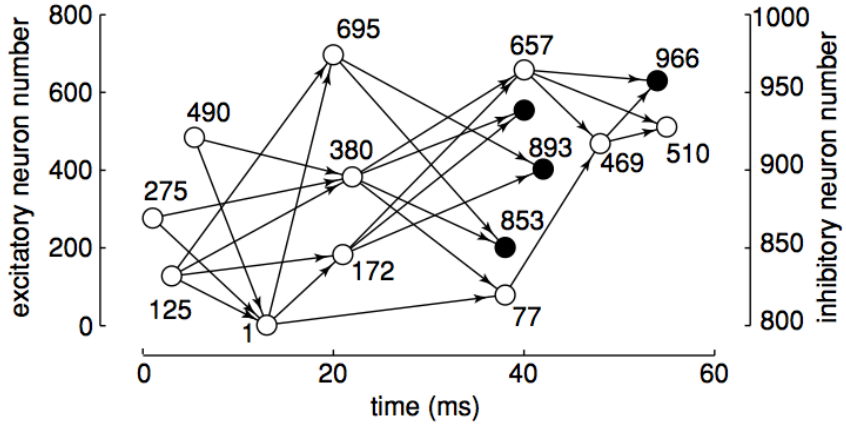
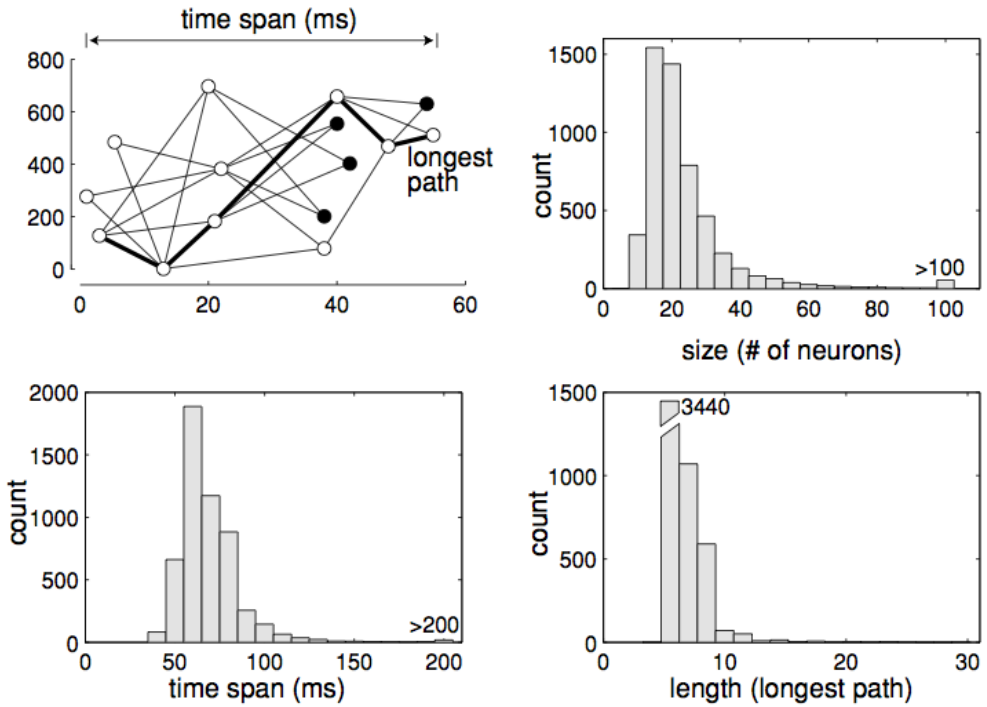


Figure 7: Example of a polychronous group: Firing of neurons (125, 275, 490) with the timing pattern (0, 3, 7) ms results in spikes arriving simultaneously at neuron 1, then at neurons 172, 695, and 380. This multitiming (polychronous) activity propagates farther along the network and terminates at neuron 510.

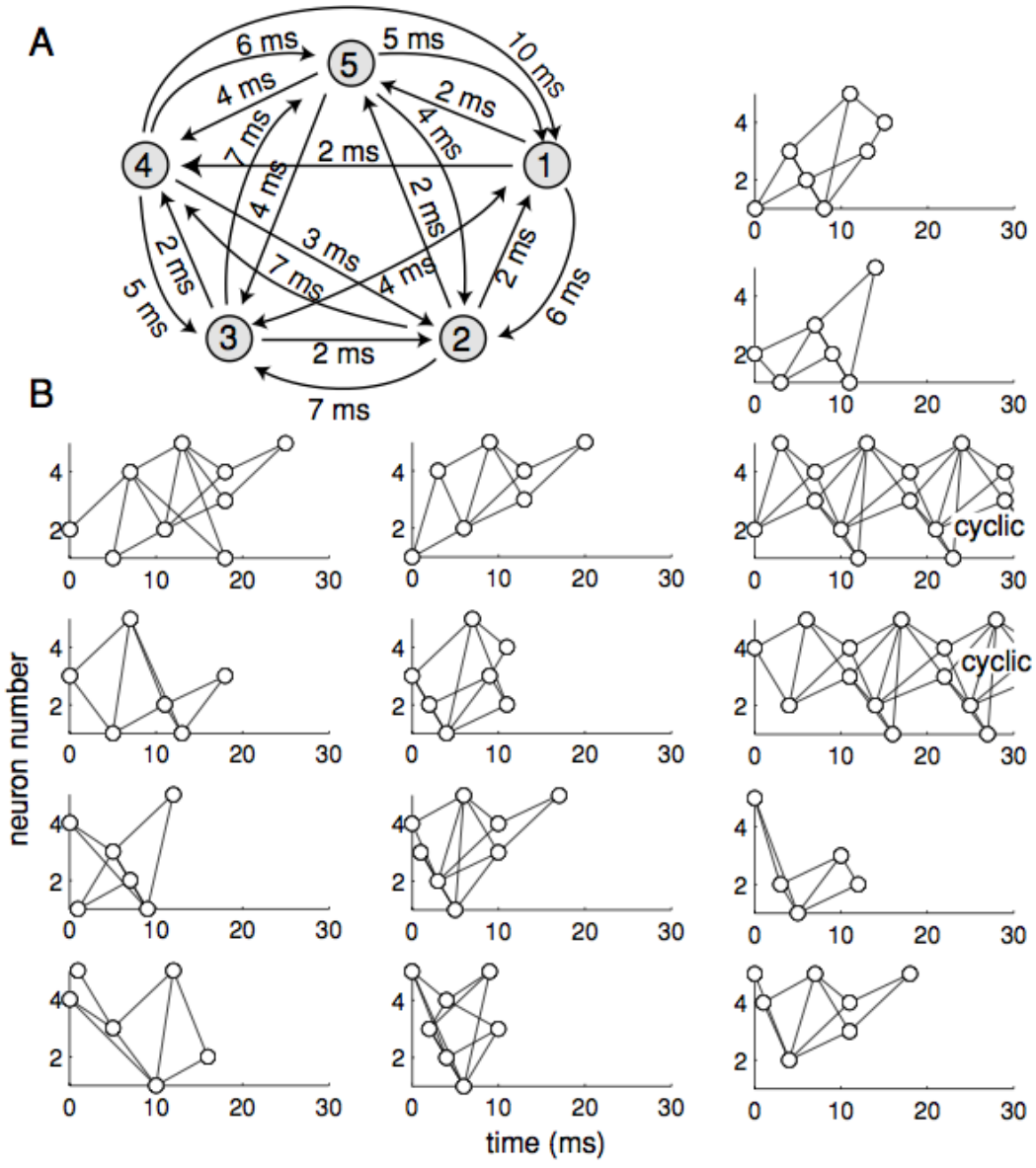
Group emergence

- 1000 neurons: 5000 groups, The groups did not exist at the beginning of simulation but appear as a result of STDP acting on random spiking
- groups constantly appear and disappear; their total number fluctuates between 5000 and 6000
- a core of 471 groups that appeared and survived the entire duration of 24 hour simulation



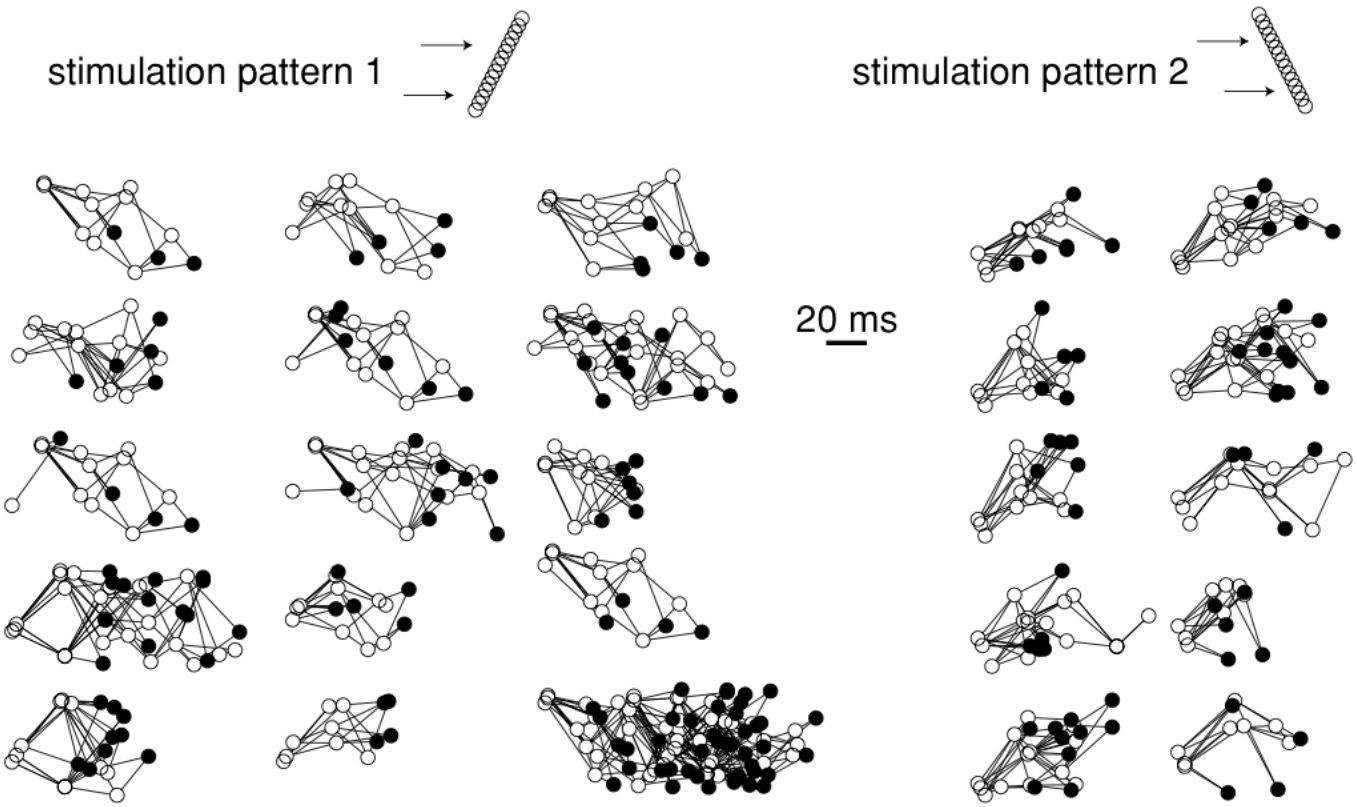
More groups than synapses

- 5 neurons: 14 groups, 6 neurons, 42 groups $>$ synapses !



Representation: Significance of polychronous group?

- Representation of memories and experience
- no coherent external input to the system was present,random groups emerge; that is, the network generates random memories not related to any previous experience
- Stimulation Every second during a 20-minute period, we stimulate 40 neurons, 1, 21, 41, 61, . . . , 781, either with the pattern (1,2,...,40) ms or with the inverse pattern (40,...,2,1) ms
- after 20 minutes of simulation 25 new groups emerged



Conclusion

- minimal model: spiking neurons, axonal conduction delays, and STDP: well-established properties of the real brain
- Polychronous groups are representations of possible inputs to the network, so that each input selects groups from the repertoire.
- Learning of a new input consists of selecting and reinforcing an appropriate group (or groups) that resonates with the input, persistent stimuli may create new groups
- FeedForward:The anatomy of the spiking networks that we consider is not feedforward but reentrant. Thus, the network does not “wait” for stimulus to come but exhibits an autonomous activity.
- Spiking networks with delays have more groups than neurons. The system has potentially enormous memory capacity and will never run out of groups, which could explain how networks of mere 10^11*neurons* (the size of the human neocortex) could have such a diversity of behavior.

```
% Created by Eugene M. Izhikevich, February 25, 2003
% Excitatory neurons   Inhibitory neurons
Ne=800;                Ni=200;
re=rand(Ne,1);         ri=rand(Ni,1);
a=[0.02*ones(Ne,1);    0.02+0.08*ri];
b=[0.2*ones(Ne,1);     0.25-0.05*ri];
c=[-65+15*re.^2;      -65*ones(Ni,1)];
d=[8-6*re.^2;          2*ones(Ni,1)];
S=[0.5*rand(Ne+Ni,Ne),-rand(Ne+Ni,Ni)];

v=-65*ones(Ne+Ni,1);  % Initial values of v
u=b.*v;               % Initial values of u
firings=[];           % spike timings

for t=1:1000          % simulation of 1000 ms
   I=[5*randn(Ne,1);2*randn(Ni,1)]; % thalamic input
   fired=find(v>=30); % indices of spikes
   if ~isempty(fired)
      firings=[firings; t+0*fired, fired];
      v(fired)=c(fired);
      u(fired)=u(fired)+d(fired);
      I=I+sum(S(:,fired),2);
   end;
   v=v+0.5*(0.04*v.^2+5*v+140-u+I);
   v=v+0.5*(0.04*v.^2+5*v+140-u+I);
   u=u+a.*(b.*v-u);
end;
plot(firings(:,1),firings(:,2),'.');
```

Further Readings

Edward L. White (1989) **Cortical circuits**, Birkhäuser

Moshe Abeles (1991) **Corticonics: Neural circuits of the cerebral cortex**, Cambridge University Press