



# FUTURE COMPUTER ARCHITECTURES

## NEUROMORPHIC COMPUTING

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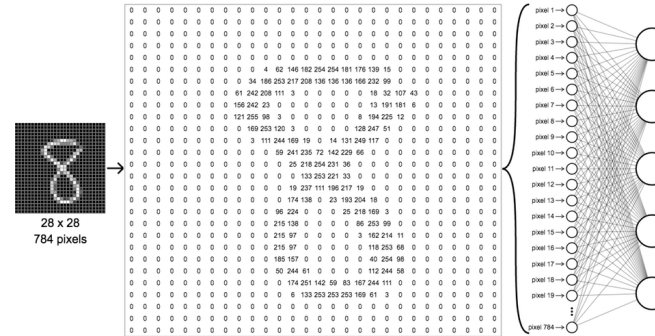
# MOTIVATION

## Bio-Inspired Computing

### Neuromorphic Computing

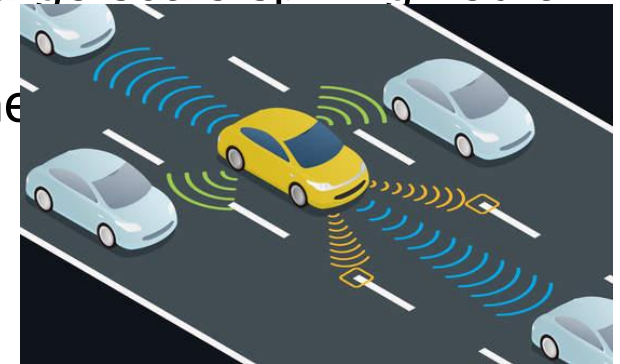
#### Cognitive Computing

- Pattern recognition
- Machine learning
- Deep learning
- Big data processing
- Error/noise robust computing
- Multisensory data processing



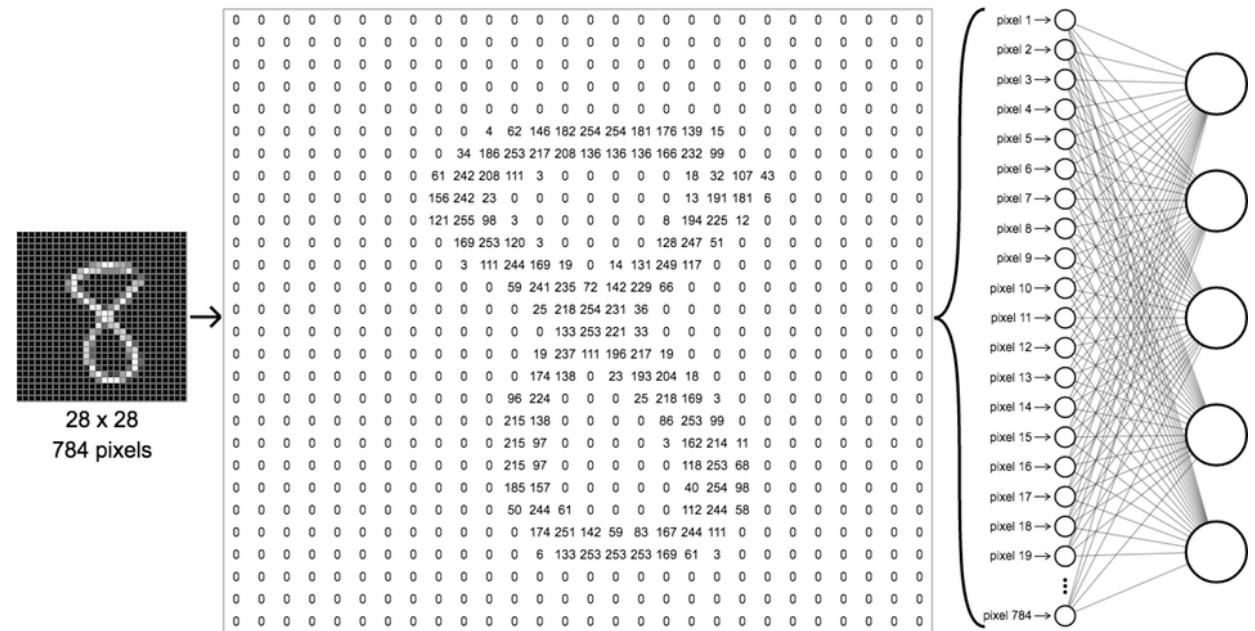
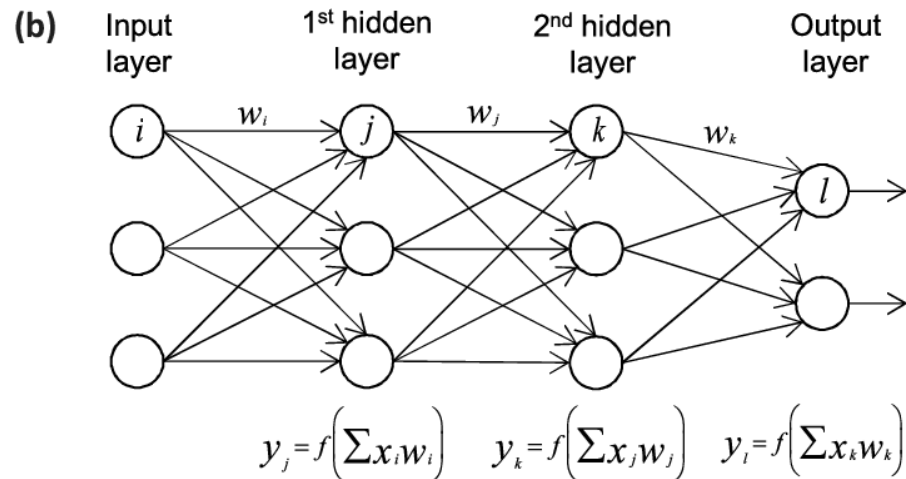
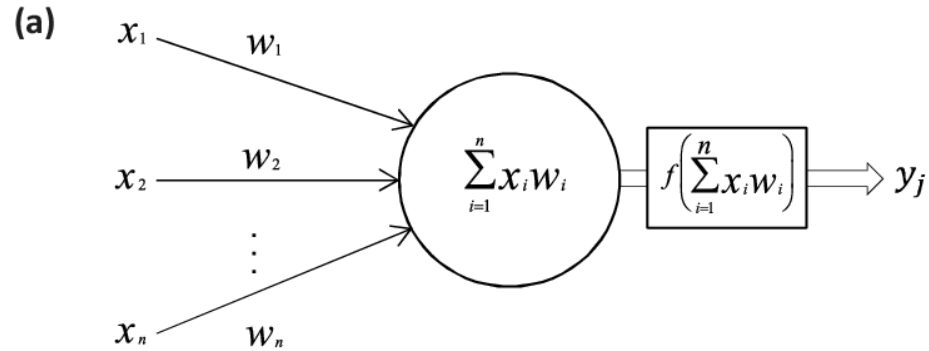
#### Artificial Neuroscience

large scale spiking neural



# MODERN A.I.

## Artificial Neural Networks

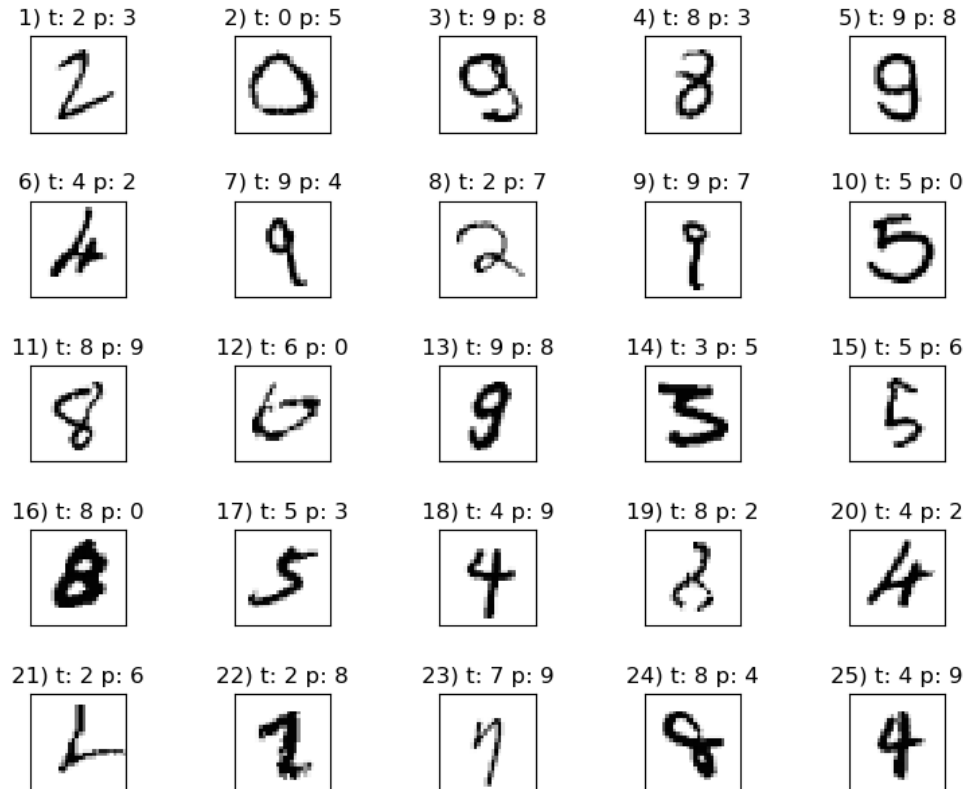




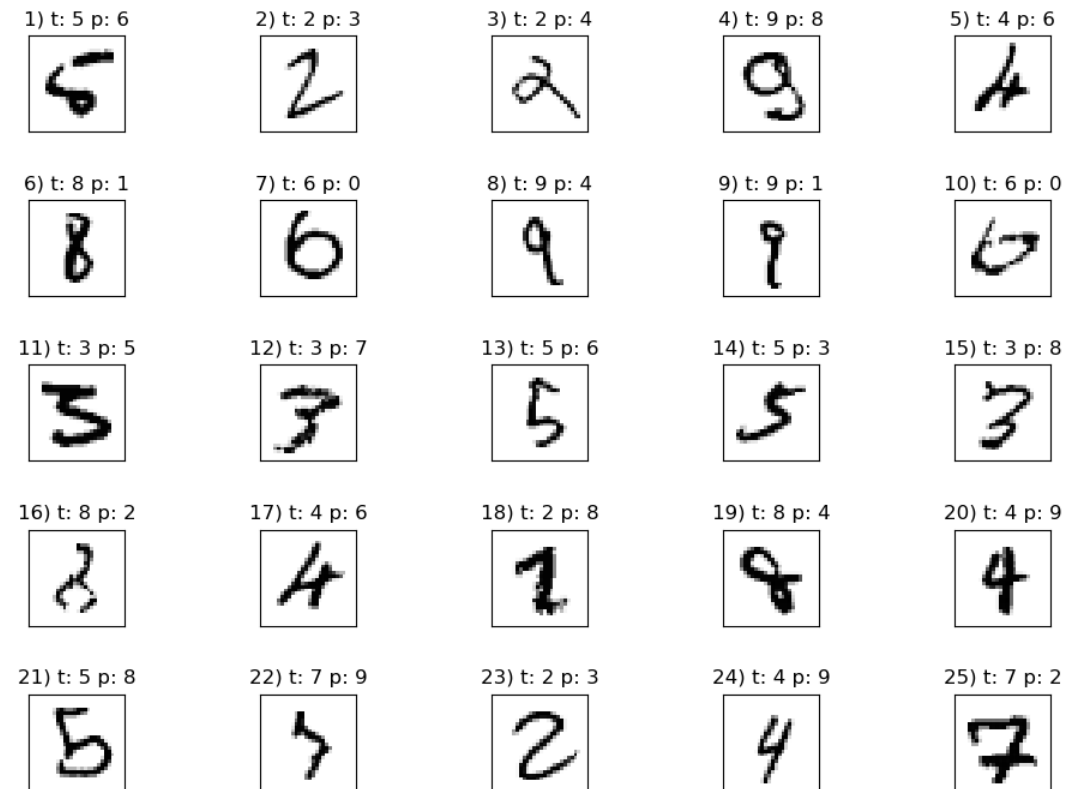
# MODERN A.I.

## Artificial Neural Networks

Samples of miscalculation (t: the true value, p: prediction)



500 iterations, 95.8% accuracy, 20min

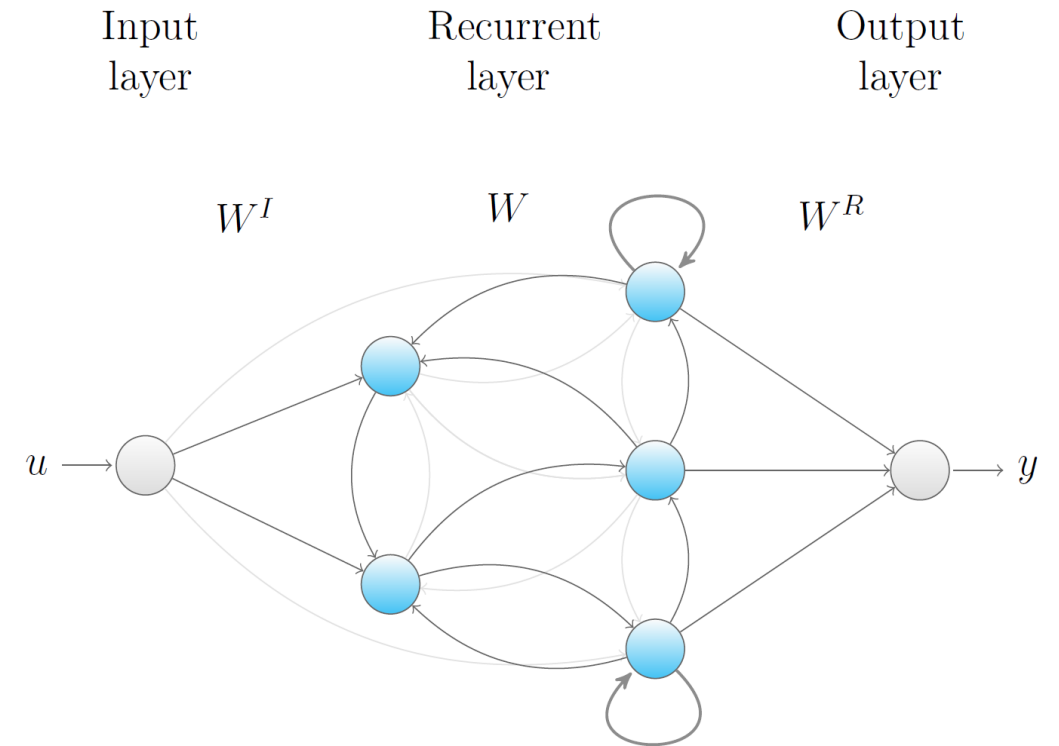


1000 iterations, 96.4% accuracy, 35min

# MODERN A.I. PROBLEMS

## Artificial Neural Networks

- Huge training set
- Slow training procedure
- High energy consumption rate

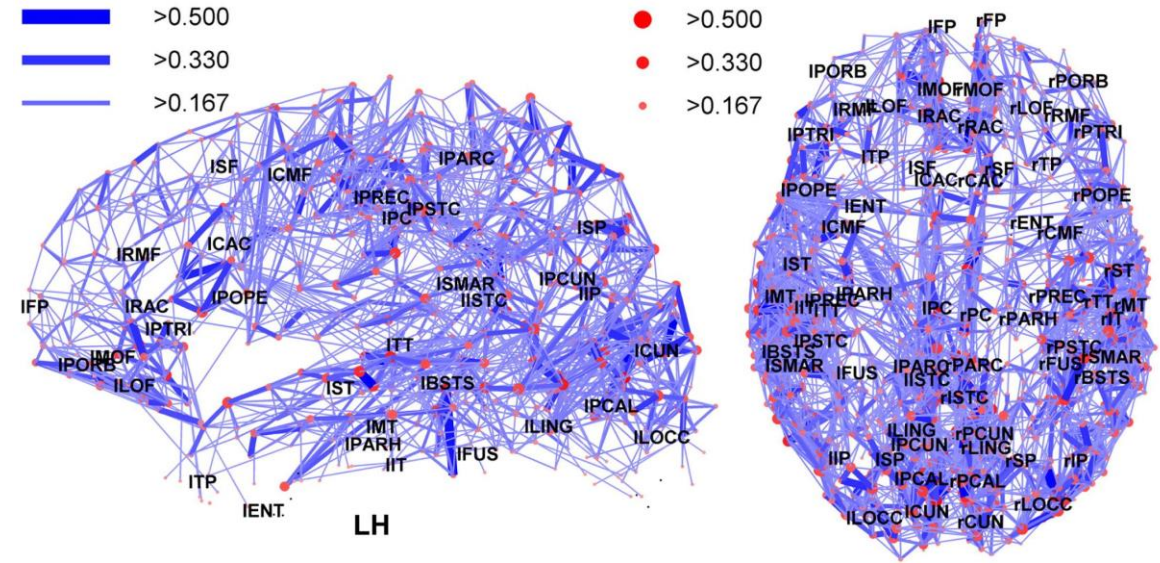
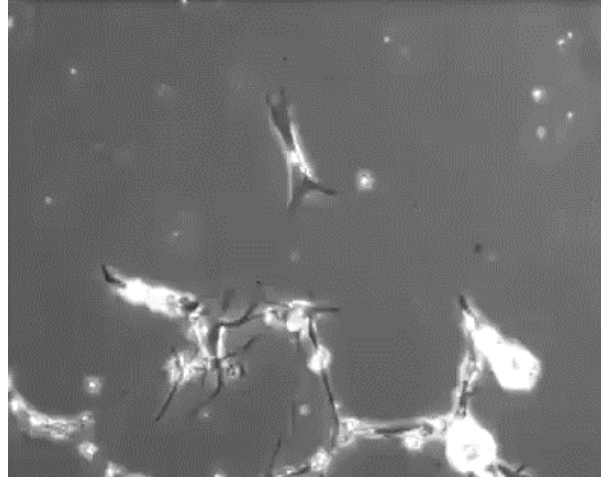


$$\mathbf{x}(n) = f(W^I \mathbf{u}(n) + W \mathbf{x}(n-1)), \quad n = 1, \dots, T,$$

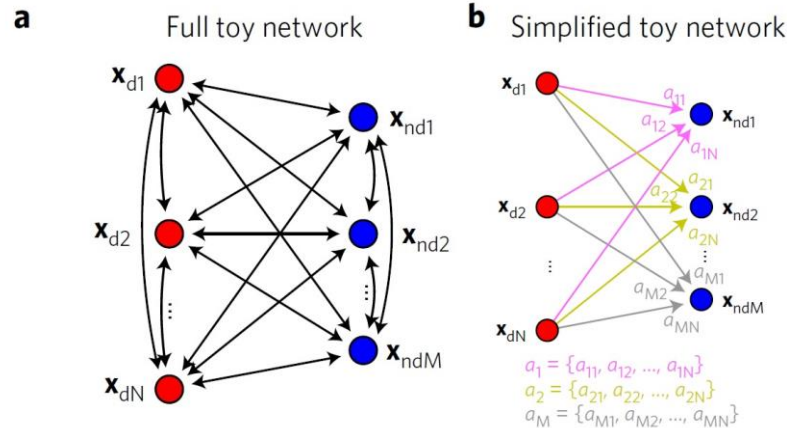
$$\mathbf{y}(n) = W^R \mathbf{x}(n)$$

# BRAIN

## Structure and network

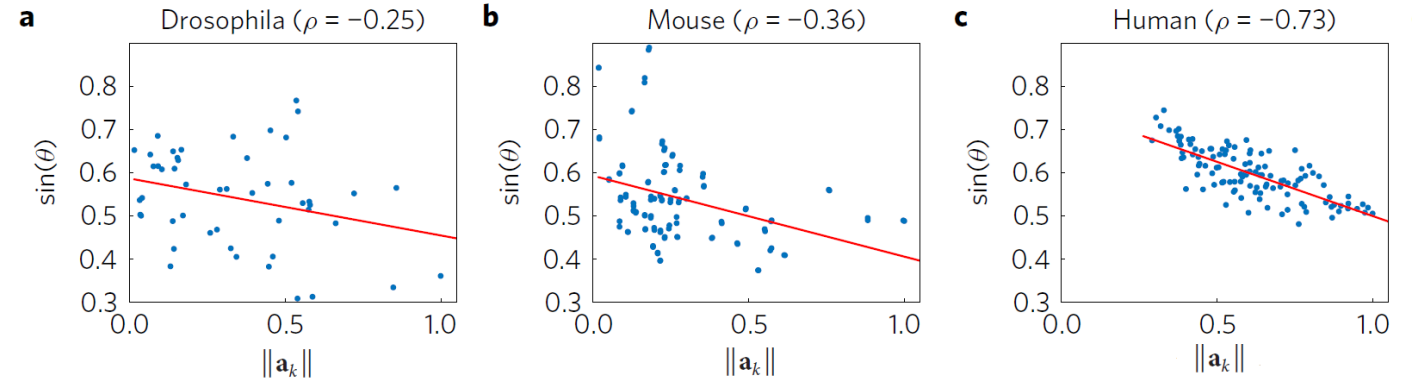


## “Human Brain is energy favorable”



$\theta_k$  is the angle formed between  $\mathbf{a}_k$  and the parallelotope formed by  $\mathbf{a}_{j \neq k}$

Average vector magnitude versus  $\sin(\theta)$  for all brain regions



# ELECTRONIC BRAIN (?)

## Towards Neuromorphic Computing

### Computer vs. Brain

#### Von-Neumann

- MHz to GHz clock frequencies
- Sequential operations  
Each cell typically connects to 2-6 other cells with a maximum around 20
- Power density around  $100 \frac{W}{cm^2}$
- Separation between memory and computation

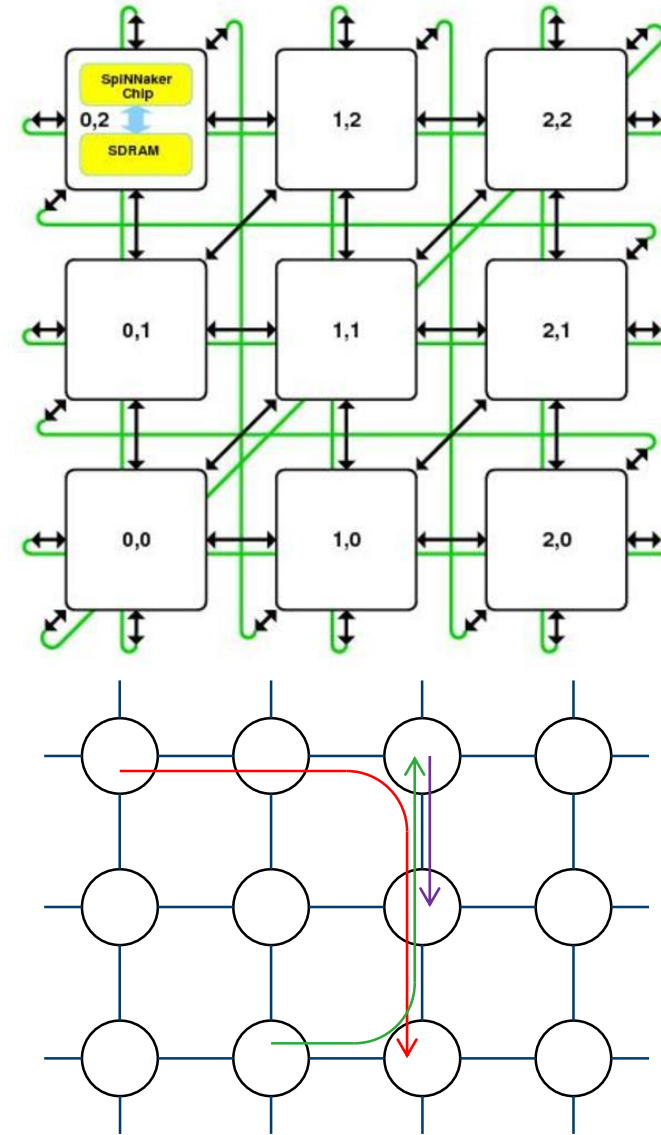
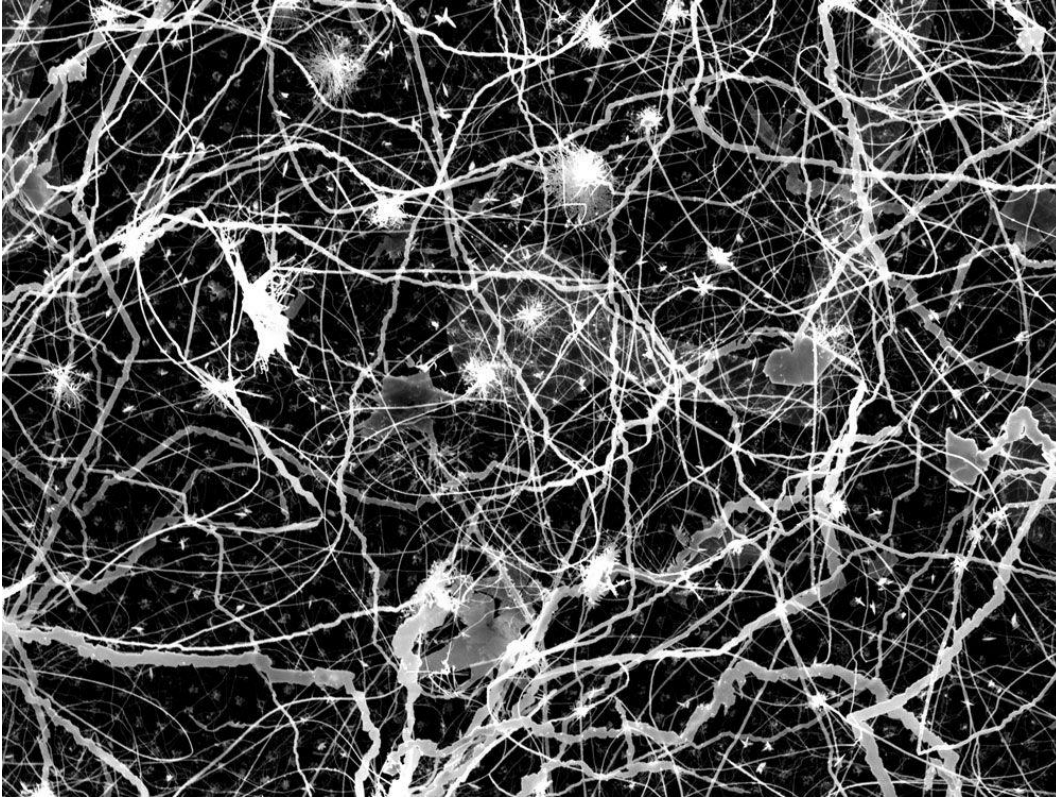
#### Human Brain

- Neuron firing rate < 300Hz
- Massively parallel operations  
A neuron on average connects to 10.000 other neurons, fan-out between 1.000 up to 100.000
- Power density around  $20 \frac{mW}{cm^3}$
- Memory and computational units are intertwined



# ELECTRONIC BRAIN (?)

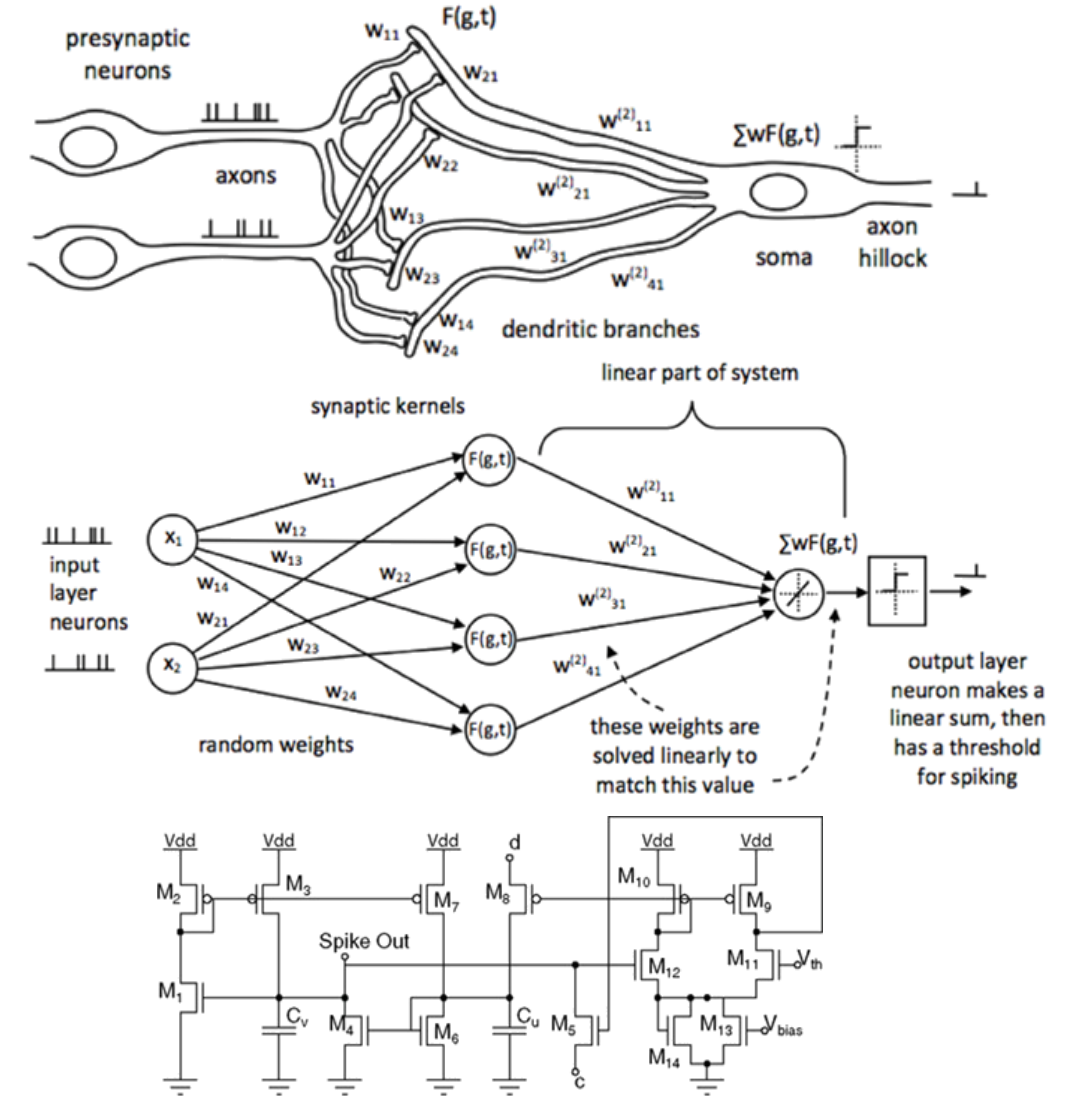
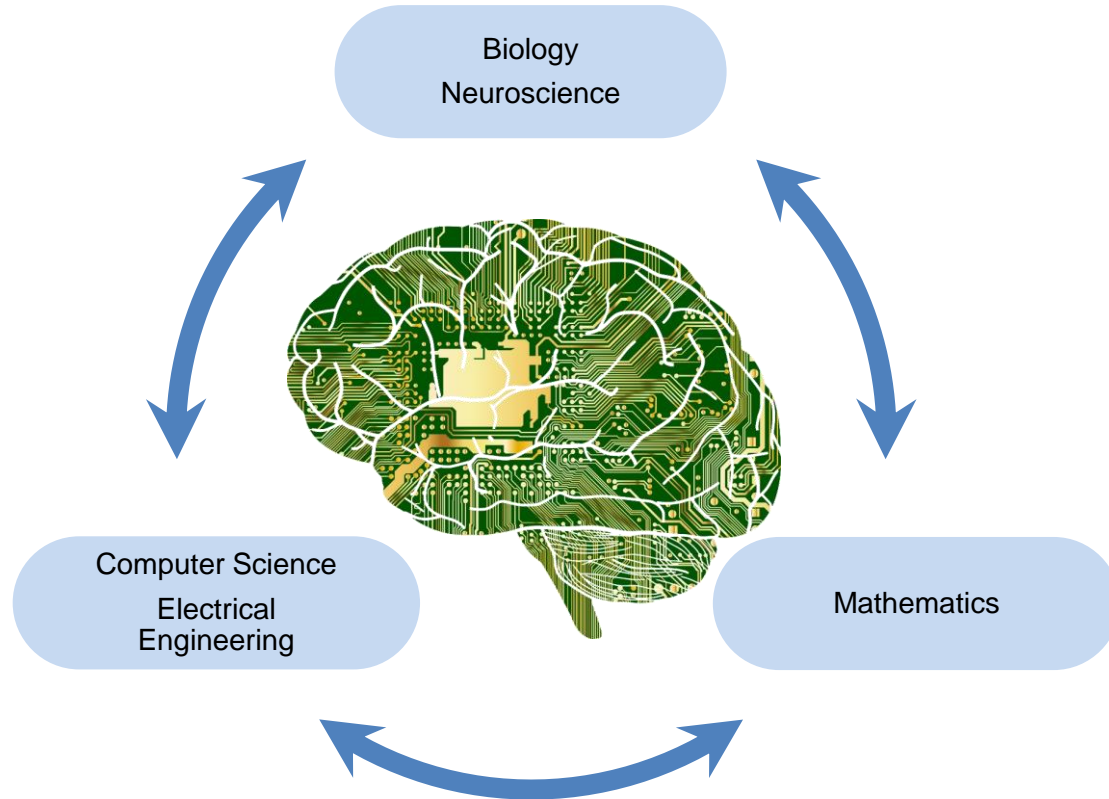
## Towards Neuromorphic Computing





# NEUROMORPHIC COMPUTING

## Bio-Inspired Computing



# QUESTION?

