Biological background in Reservoir computing (RC): Studies linking the properties of RC networks with emerging properties in animal brains organizations

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Biological background in Reservoir computing (RC)

Studies linking the properties of RC networks with emerging properties in animal brains organizations

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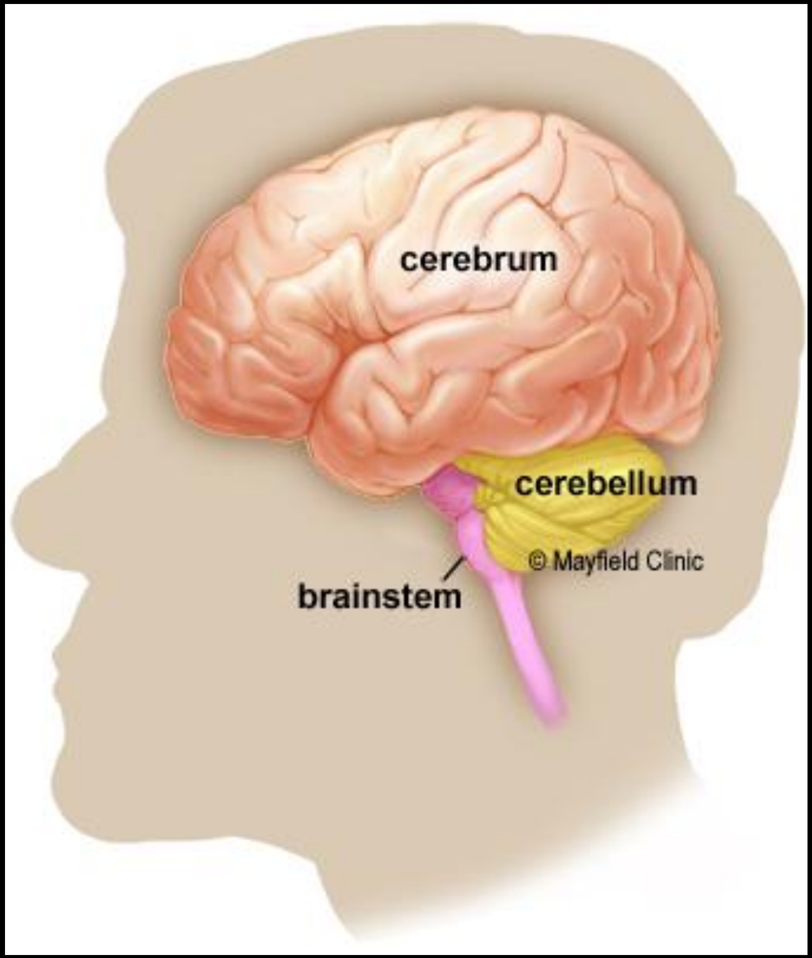
Greatest challenge of 21st century

- Understanding (function) Human Brain!
- Brain facts: (Source HBP)
  - Memory >2.5 Million Giga Bytes
  - Neurons 80,000,000,000
  - Synapses 100,000,000,000,000
  - Power 20W
  - Size 1450 cc

HBP
Human Brain Project

BRAIN RESEARCH THROUGH ADVANCING INNOVATIVE NEUROTECHNOLOGIES
BRAIN INITIATIVE

Structure of Human brain



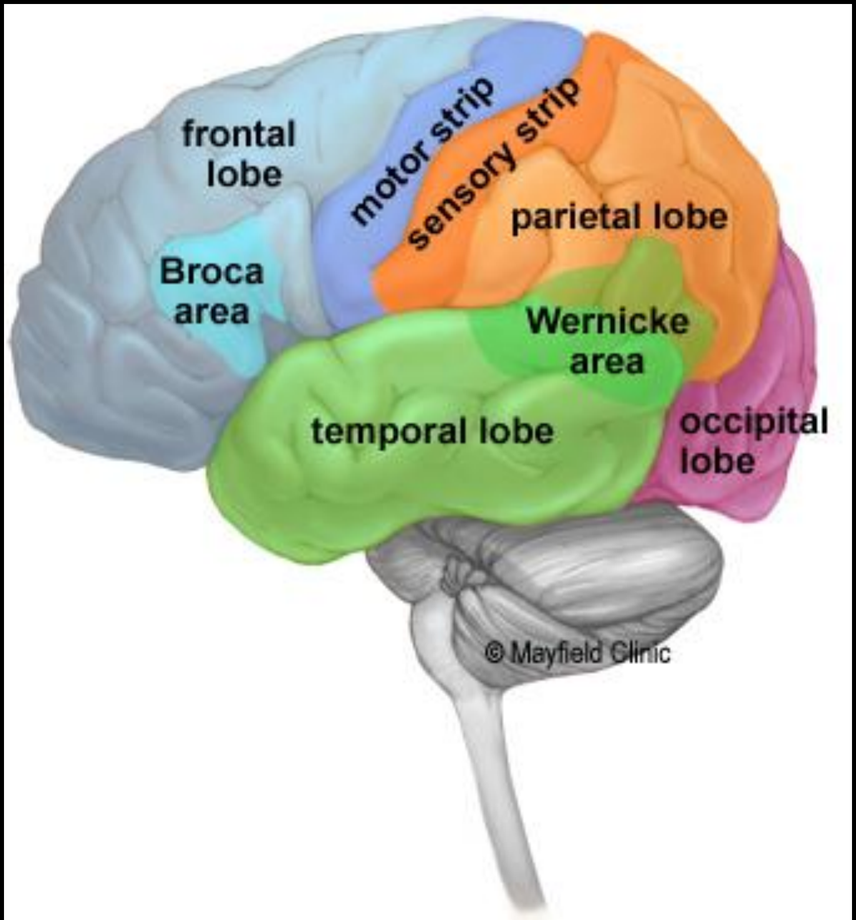
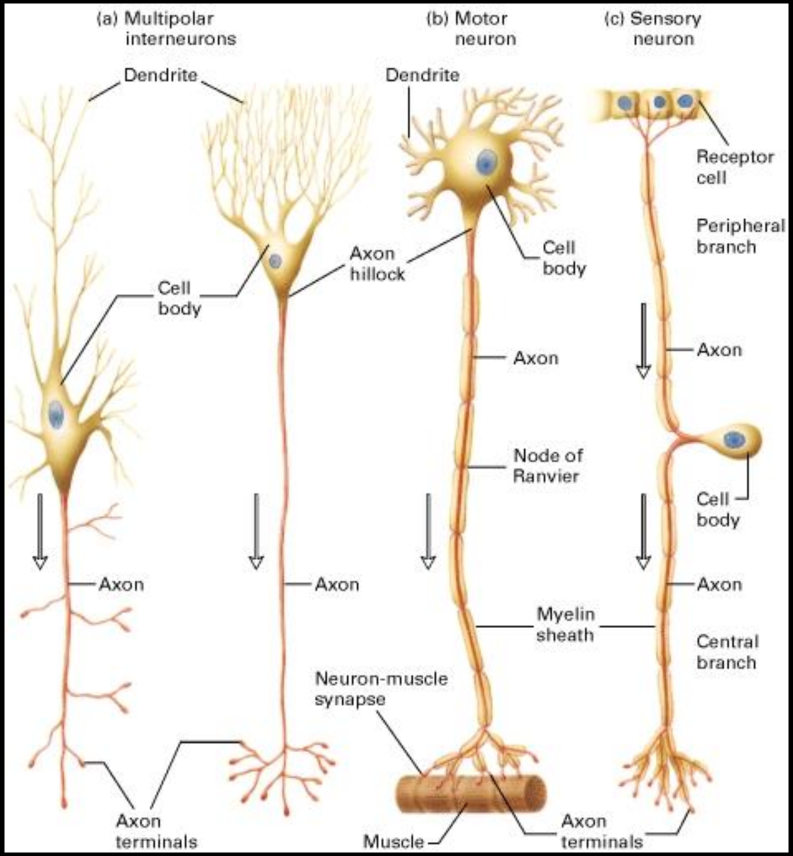


Image courtesy: Mayfield Clinic
https://mayfieldclinic.com/pe-anatbrain.htm

Structure of Human brain



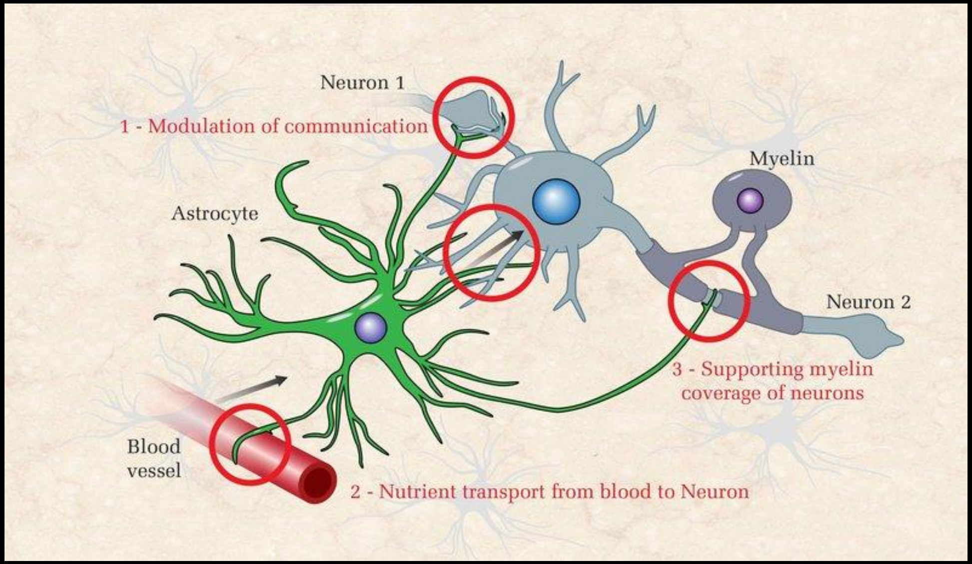
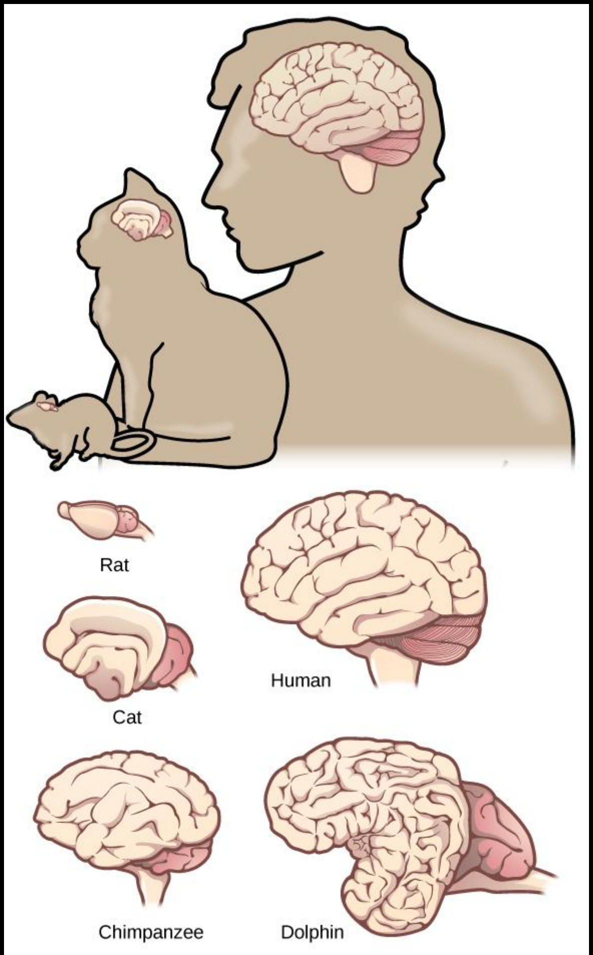


Image courtesy: Biochemstyles
https://biochemstyles.wordpress.com/

Image courtesy: wings for life
https://www.wingsforlife.com/en/latest/astrocytes-the-star-cells-1637/

Why humans are special?



- Brain structure:
  - Primates vs. non-primates
  - Humans vs. other primates
- Evolutionarily advanced structure
- Acquired Intelligence, consciousness, language and other higher cognitive and executive functions
- Attributes of cerebral cortex!

Why cerebral cortex is so special?

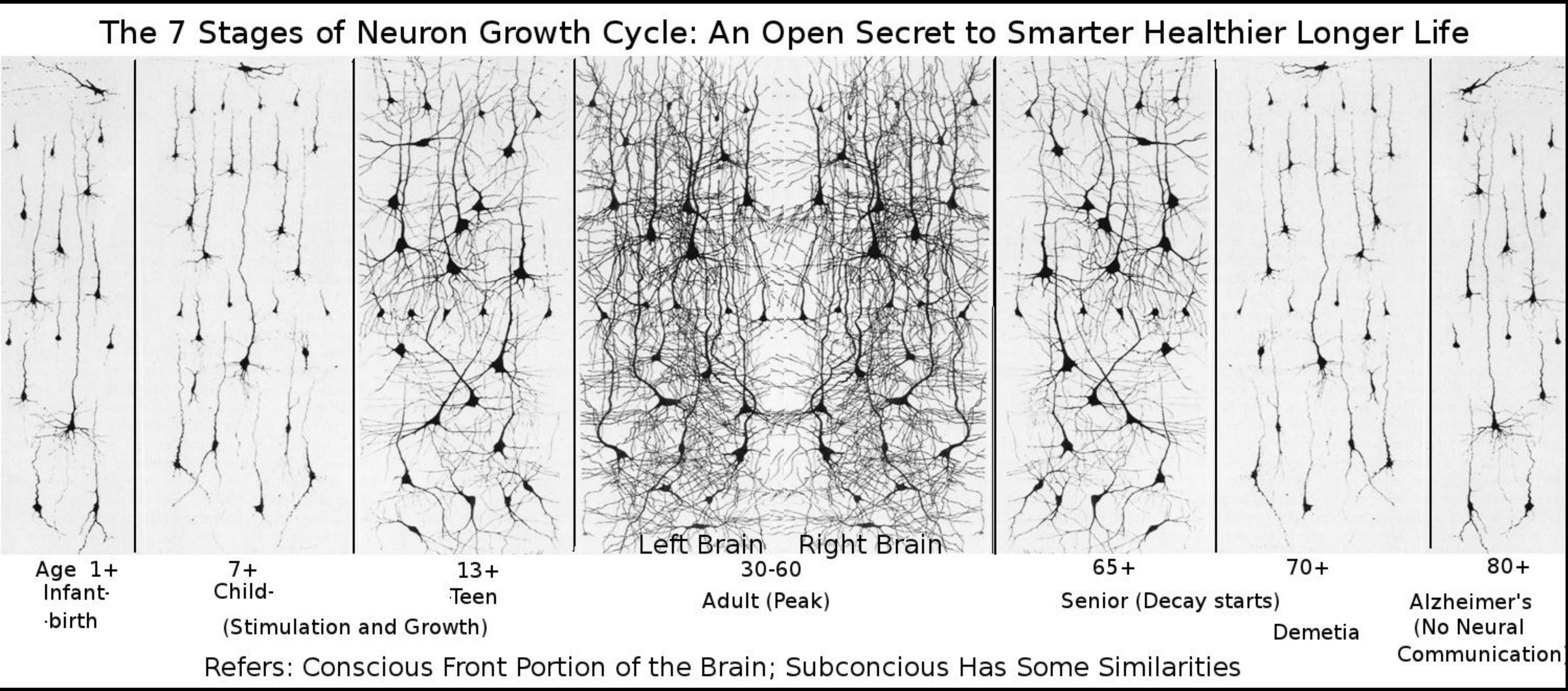


Image courtesy: https://aumni7.files.wordpress.com/2013/02/neuron-growth-cycle-2.jpeg

Visual scene processing

Natural system vs Artificial system

- Biological brain
- Electrical (analog) domain: all or none spikes and Sub threshold oscillations.
- Flow of ions (Na^+,K^+,Ca^{2+},Cl^- ,etc)
- Slow conduction and thus slower computation (Action potential in ms)
- Highly efficient (less m/y space, power)
- Small training data
- High fidelity
- Excellent performance

- Computer brain (Microprocessor)
- Electrical (digital) domain: bits: 0s or 1s
- Flow of electrons (e^-)
- Faster conduction and thus faster computation (clock speed of µp in ns)
- Not efficient (consumes m/y space and power)
- Huge training data
- Low fidelity
- Poor performance

What's happening in the brain?

How nature surpasses the artificial?

- How could a 2D retinal surface processes a 3D information and can faithfully reproduce?
- Moreover, the retina is just sensitive to two parameters: Frequency and Amplitude of Electromagnetic radiation!

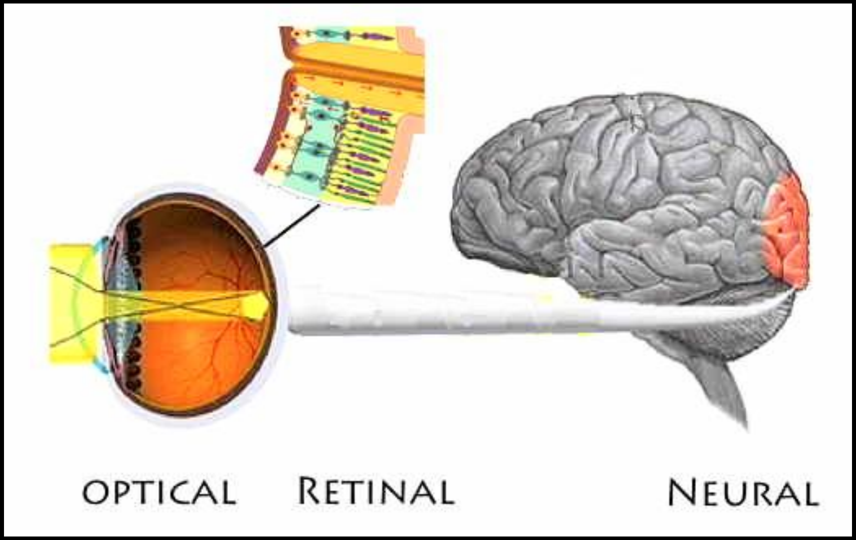
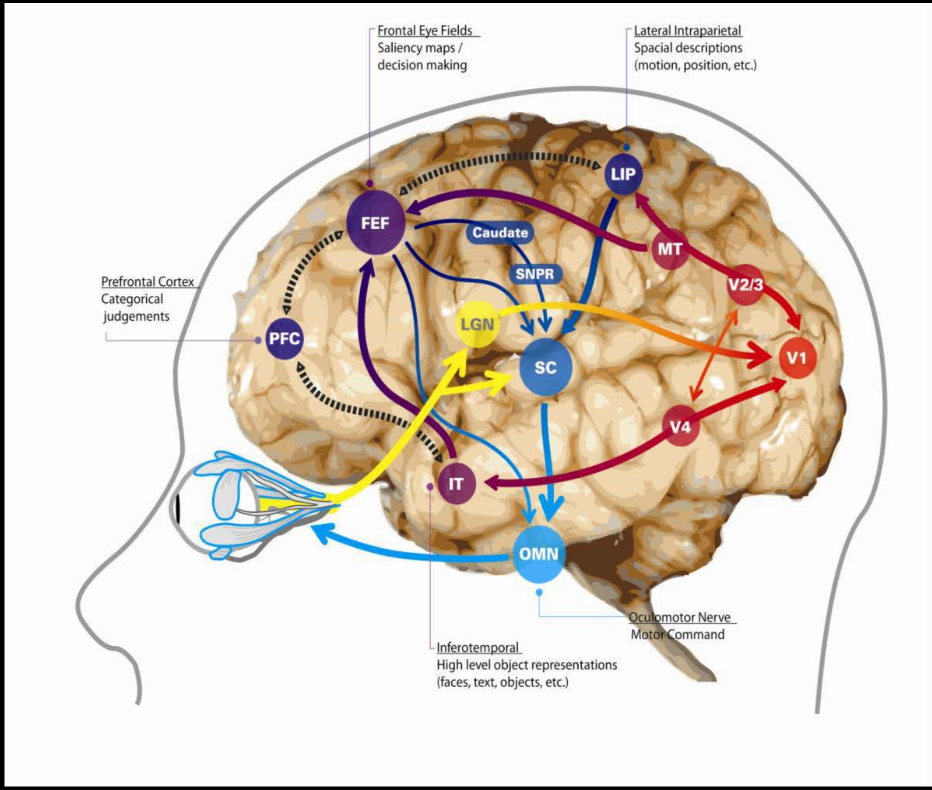


Image courtesy: MeyeSight
http://www.meyesight.net/stages-of-visual-processing/

What's happening in the brain?

How can we perceive the external world?

- Hint: Reconstruction of external world!
- Internal representation of the complex world
- Spatio-temporal integration
- Apriori information stored in the brain?
- Creation of internal models (latent) within a high dimensional space?
- Some simple read-outs of these models gives scene perception within a less time?



"It's not what we see,
it's what we are!"

-Prof. Emiliano Ricciardi,
IMT Lucca, Italy

Image courtesy: Cerf(2009)
https://thesis.library.caltech.edu/6020/5/Moran_Cerf_-_PhD_Thesis.pdf

What's happening in the brain?

How brain establishes internal model?

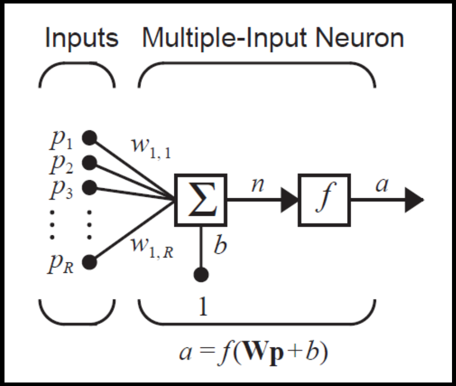
Singer & Lazar(2016)

To establish a good internal model, brain has to

- Detect the best features of external world
- Find relations or rules or transformations b/w the features
- Store these relations in an efficient way

NOTE: Simple artificial neuron exploits a similar strategy using

- Weight function
- Net input function
- Transfer function



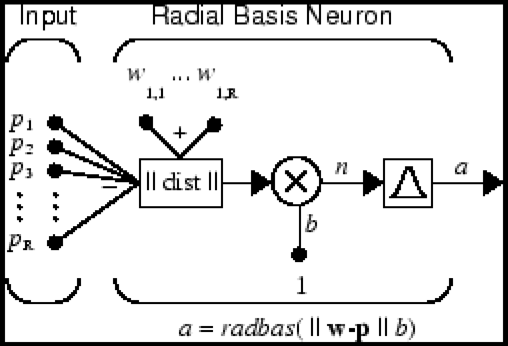


Image courtesy: MathWorks

How brain encodes information?

Spatial encoding or temporal encoding or both?

Singer & Lazar(2016)

- Spatial encoding
- Specific neurons fires to particular features of external world ("Labeled line code")
- Well suited for simultaneously present (spatial) features
- Higher features extracted through layered architecture
- Seen in visual cortex organization
- Lack of m/y and fails to handle events separated temporally
- Feed-forward NN
- Perceptron, MLP, CNN employs it Translation invariance prop.
- Back propagation learning alg.
- Supervised fashion

- Temporal (firing rate/ frequency) encoding
- Extracting features based on causal relationships (Hebbian/STDP)
- Seen in mirror neurons (Pri, Supple motor cortices): Motor learning
- Synchronized oscillations (frequency specific) leads to Temporal coherence CTC (Comm. through Coherence)
- Using recurrent architecture it combines the present and past information
- Efficient to handle sequential events due to memory
- Recurrent NN
- Hopfield nets, RBM, ART machines employs it
- Unsupervised fashion

Processing in the human brain

Complex Dynamics

Singer & Lazar (2016)

- Real world is complex and so the brain dynamics!
- Synchronization of these oscillations with stable phase relations, occur only under specific stimulation conditions
- Frequency is modulated by (top-down projections) attention, reward expectation, and working memory contents
- Evidence of random (stochastic/spontaneous fluctuations) oscillations from high dimensional space
- That is the brain is no more a simply stimulus driven, but also an active pattern generating device!
- The non-stationarity of the brain dynamics might be the key for accommodating the complex world
- NOTE: Such feature of synchronized vs. random oscillations might be due to the neuro-computational properties of **resonator vs. integrator** kind of neuronal populations?

Networks in the human brain
Variable Dynamics

- Cerebral cortex operates under 2 conditions
  - Extreme conditions (low computational power)
    - A) Synchronized activity (low dimensional) (singer 2013)
    - B) Stochastic activity (high dimensional)
  - Intermediate condition (High computational power)
    - – Normal condition
- Such pattern also exist in brain connectivity (Kawai et al., 2019)

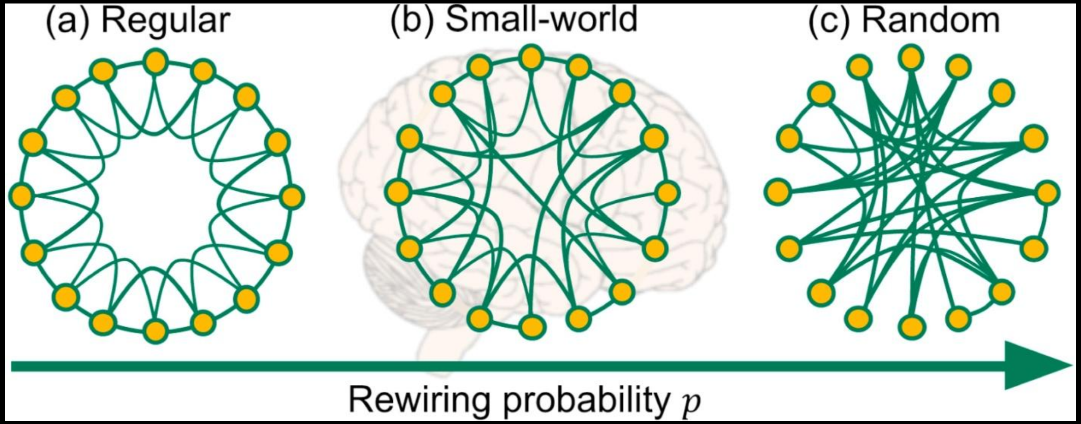


Image courtesy: Kawai et al (2019)
https://www.sciencedirect.com/science/article/pii/S0893608019300115?via%3Dihub#fig2

Processing in the human brain

Need of unified framework

- For an efficient computation, the cerebral cortex exploits both
  1) Non-linear, high dimensional space, characterized by rapidly changing oscillations, self-organized, recurrent connections based (temporal integration dominates) and unsupervised learning fashion (sequential processing)
  2) Linear, low dimensional space, characterized by sustained oscillations, regular, feed-forward based (spatial integration dominates) and supervised learning fashion (parallel processing)
- These are necessary for two important functions
  1) The storage of vast amount of information (prior knowledge) about the complex environment: ***M/y space***
  2) Ultra-fast retrieval by comparing input signal and stored knowledge (by effective classification): ***Speed***

Hypothesis underlying human brain
Reservoir Computing Framework

- AI/ML communities (Maass et al, Jaeger et al, etc.) independently developed a non-linear dynamic version of RNN : Liquid state networks (LSN), Echo state networks (ECN), and Reservoir computing (RC)
- Computational units: 2 components
  - Reservoir unit: Training not req. RNN, high dimensional, non-linear and has memory
  - Read-out unit: Training required Feed forward NN, low dimensional, linear and with training, has speed
- RC model of Dominey et al. 1995:
  - PFC: Reservoir unit
  - Striatum: Read-out unit

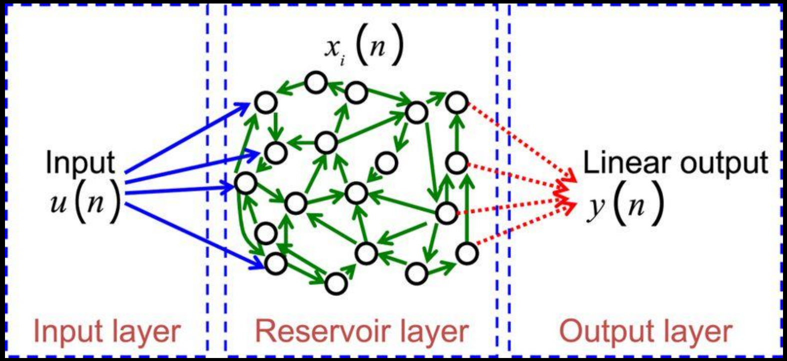


Image courtesy: Duport et al (2016)
https://www.nature.com/articles/srep22381

Hypothesis underlying human brain

How RC works in the brain?

Singer (2013)

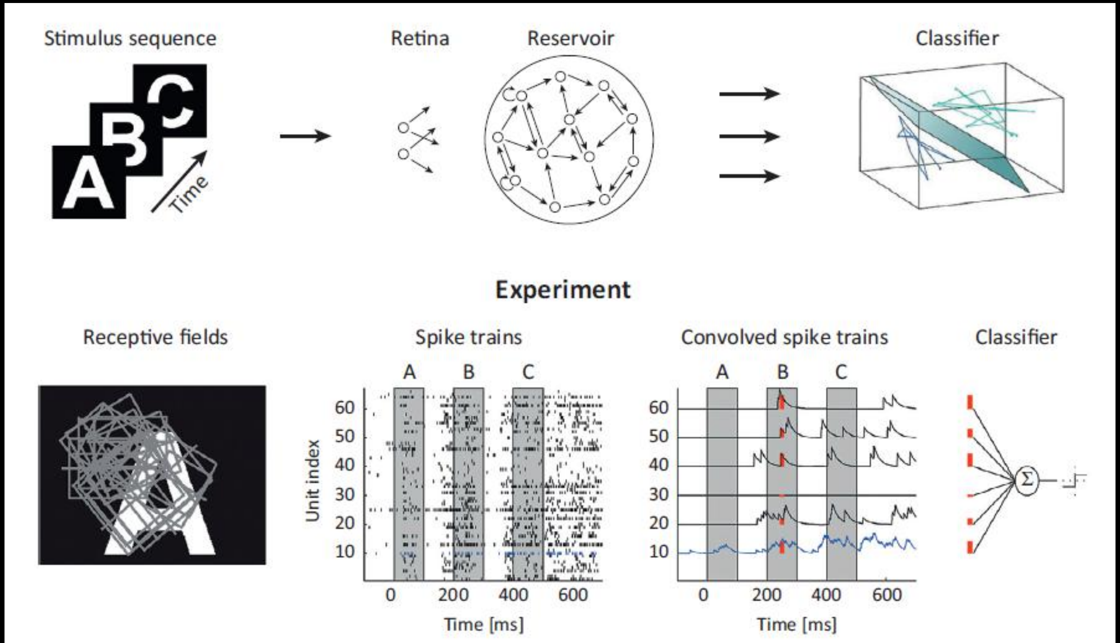
- The reservoir network could be compared to the high dimensional space of the brain where the internal models of the external world is stored. This random self organised network is initially made by genetic factors but later modulated by the experiences we developed overtime from childhood.
- The low-dimensional input signals (say retinal signals) that carries the low level features of external world excites the reservoir and are transformed into high-dimensional internal states due to their interaction with the network's dynamics. Thus the internal model is created and could be responsible for the generation of stochastic random oscillations.
- Input signals cause selective stabilisation of substates that are often distinguished by enhanced coherence and reduced dimensionality, suggesting that an initially unconstrained dynamic state of coexisting solutions (the internal model) is forced towards the most likely substate, given the structure of the internal model and the specific input constellation.
- These stimulus-constrained, low dimensional substates constitute the solution to the respective computational problem and is extracted by a simple linear read out. Dimensionality reduction might favour the fast read outs!

RC properties in animal brains organizations

Recent experimental evidences

1) Fading memory (Nikolic et al. 2007,2009)

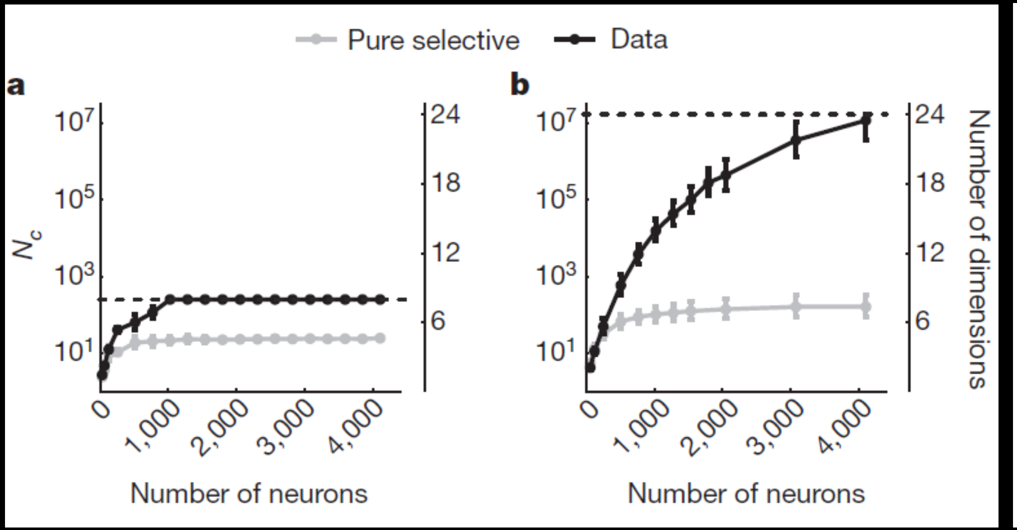
- Experiment: Sequence of alphabets (A,B,C,D,E) showed to 3 cats
- Data : multi-electrodes (4x4) recordings from cat's primary visual cortex
- Analysis: SVM (non-linear kernel) and simple Linear classification
- Inference: 1) cortical neurons does classification using parallel read-out and 2) VA has fading m/y property lasts for several hundreds of ms

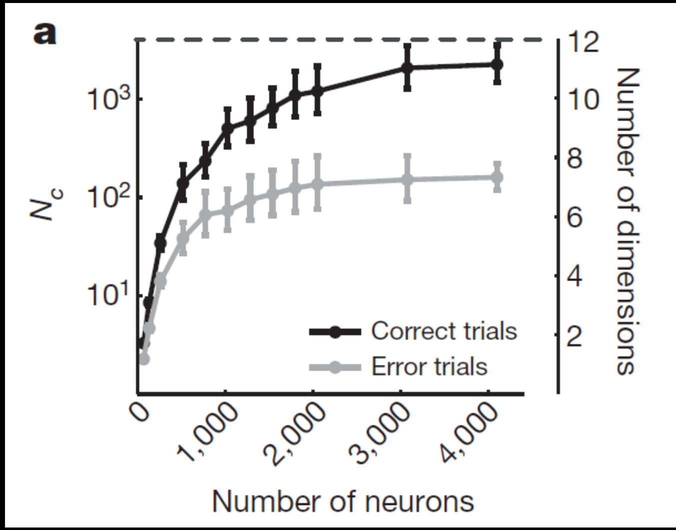


RC properties in animal brains organizations
Recent experimental evidences

2) Non-linear, mixed selectivity, High dimensionality (Rigotti et al. 2013)

- Experiment: 2 Rhesus monkeys were trained at image recognition task
- Data: multi-electrode recordings of lateral PFC neurons (area 46)
- Analysis: Novel classification and dimensionality methods
- Inference: Non-linear mixed selectivity and High dimensional nature enhances binary classification and predicts animal behaviour

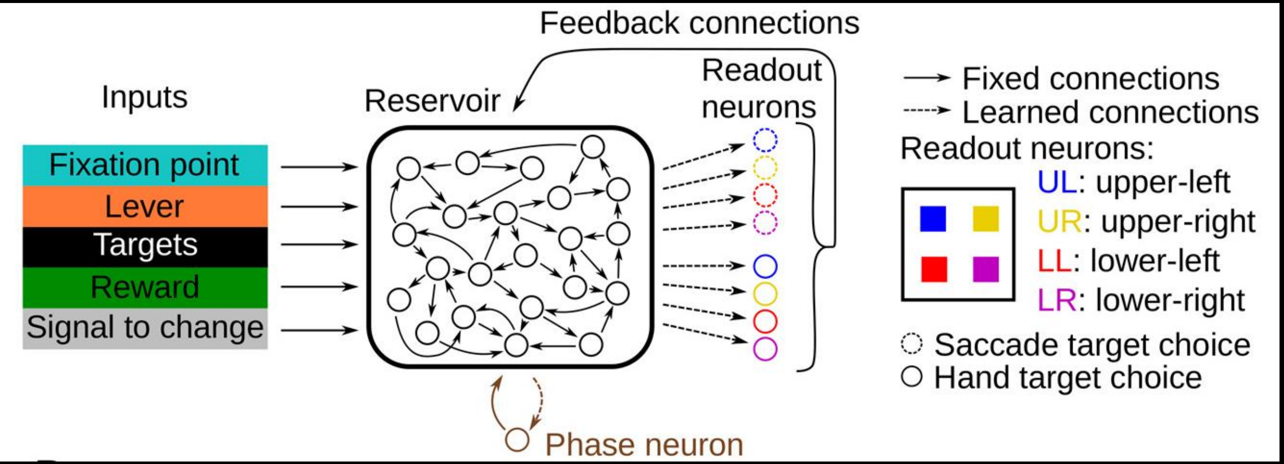




RC properties in animal brains organizations
Recent experimental evidences

3) Random RNN (Enel et al. 2016)

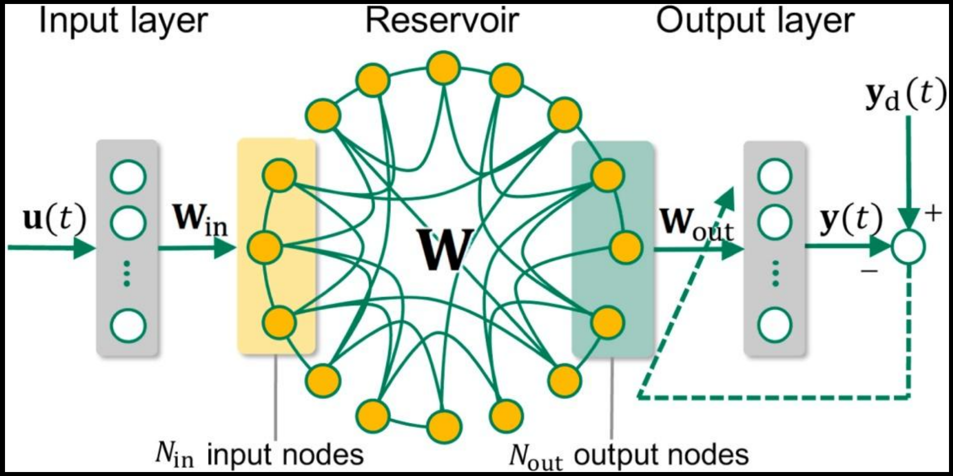
- Experiment: Quilodran et al. (2008) 2 Rhesus monkeys were trained at target finding by trial and error, and was rewarded for the correct finding!
- Data: Recorded 546 neurons in the dACC
  Hypothesis: Mixed selectivity inherently obtained from random RNN
- Analysis: RNN model using RC and tested with experimental data.
  Hyperparameters: Nr = 1000, i/p and reservoir sparsity 10%, ρ(Wr) = 0.9 , tanh non linearity
- Inference: Dynamic mixed selectivity obtained from RC framework!

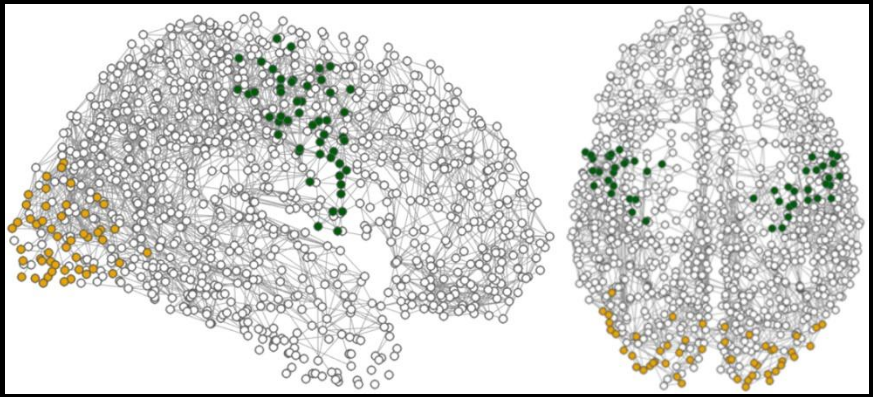


RC properties in animal brains organizations
Recent experimental evidences

4) Small world (SW) topology (Kawai et al. 2019)

- Theoretical study to investigate small-world (SW) network topology of cortical neural connectivity.
- SW: I/O segregation, Short path length and High clustering
- Method: Incorporated SW structure within RC frame work and investigated echo state property of SW-ESN. The reservoir is based on the real data of cortical anatomical connectivity of a human brain.
- Inference: Efficient signal propagation and enhancement of the echo state property are two roles of the SW topology in neural computation.





Conclusions

Does human brain really uses RC?

- Recent experimental data supports the hypothesis
- Reservoir computing is a unified framework: it handles the set of all possible ambiguities
    - Memory vs. Speed
    - Spatial vs. Temporal encoding
    - Parallel vs. Serial processing
    - Feed forward vs. Recurrent NN
    - Supervised vs. Unsupervised learning
    - Synchronized vs. Spontaneous oscillations
    - Stimulus driven mode vs. Resting state mode
    - Low dimensional vs. High dimensional space
    - Linear dynamics vs. Non linear dynamics
    - Pure selectivity vs. Mixed selectivity
    - Symmetric vs. Asymmetric connections
- Powerful and realistic higher cognitive model
- Might help to solve the deep philosophical questions such as the SELF, consciousness and the mind-body problem

References

1. Singer, Wolf. "Cortical dynamics revisited." *Trends in cognitive sciences* 17, no. 12 (2013): 616-626.
2. Singer, Wolf, and Andreea Lazar. "Does the cerebral cortex exploit high-dimensional, non-linear dynamics for information processing?." *Frontiers in computational neuroscience* 10 (2016): 99.
3. Nikolić, Danko, Stefan Häusler, Wolf Singer, and Wolfgang Maass. "Distributed fading memory for stimulus properties in the primary visual cortex." *PLoS biology* 7, no. 12 (2009): e1000260.
4. Rigotti, Mattia, Omri Barak, Melissa R. Warden, Xiao-Jing Wang, Nathaniel D. Daw, Earl K. Miller, and Stefano Fusi. "The importance of mixed selectivity in complex cognitive tasks." *Nature* 497, no. 7451 (2013): 585.
5. Enel, Pierre, Emmanuel Procyk, René Quilodran, and Peter Ford Dominey. "Reservoir computing properties of neural dynamics in prefrontal cortex." *PLoS computational biology*12, no. 6 (2016): e1004967.
6. Kawai, Yuji, Jihoon Park, and Minoru Asada. "A small-world topology enhances the echo state property and signal propagation in reservoir computing." *Neural Networks* (2019).

- *Does brain has internal model of internal world (information about our body)?*
- *Does brain has internal model of itself?*

Thank you!