HOW HUMANS BUILD MODELS OF THE WORLD

WIDS – UNIVERSITY OF PENNSYLVANIA
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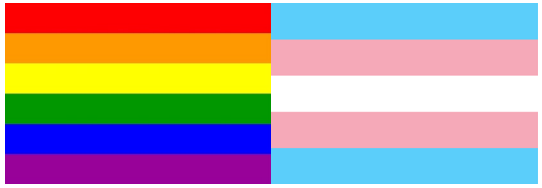
In support of all gender minorities in data science, including cisgender and transgender women, transgender men, and genderfluid & non-binary people.



What is knowledge?

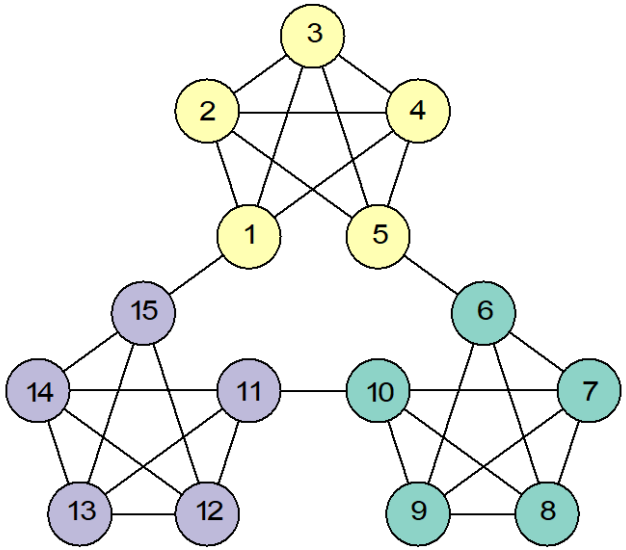
From Henri Poincare's 1905 *Science and Hypothesis*:

"The aim of science is not things themselves, as the dogmatists in their simplicity imagine, but the relations among things; outside these relations there is no reality knowable."

From Dewey's 1916 *Democracy and Education* (NY: Simon & Brown, 2011):

"...[K]nowledge is a perception of those connections of an object which determine its applicability in a given situation. [...] Thus, we get at a new event indirectly instead of immediately - by invention, ingenuity, resourcefulness. An ideally perfect knowledge would represent such a network of interconnections that any past experience would offer a point of advantage from which to get at the problem presented in a new experience" (185).

Knowledge is a network learned by example



Suppose I must translate 15 ideas to a class.

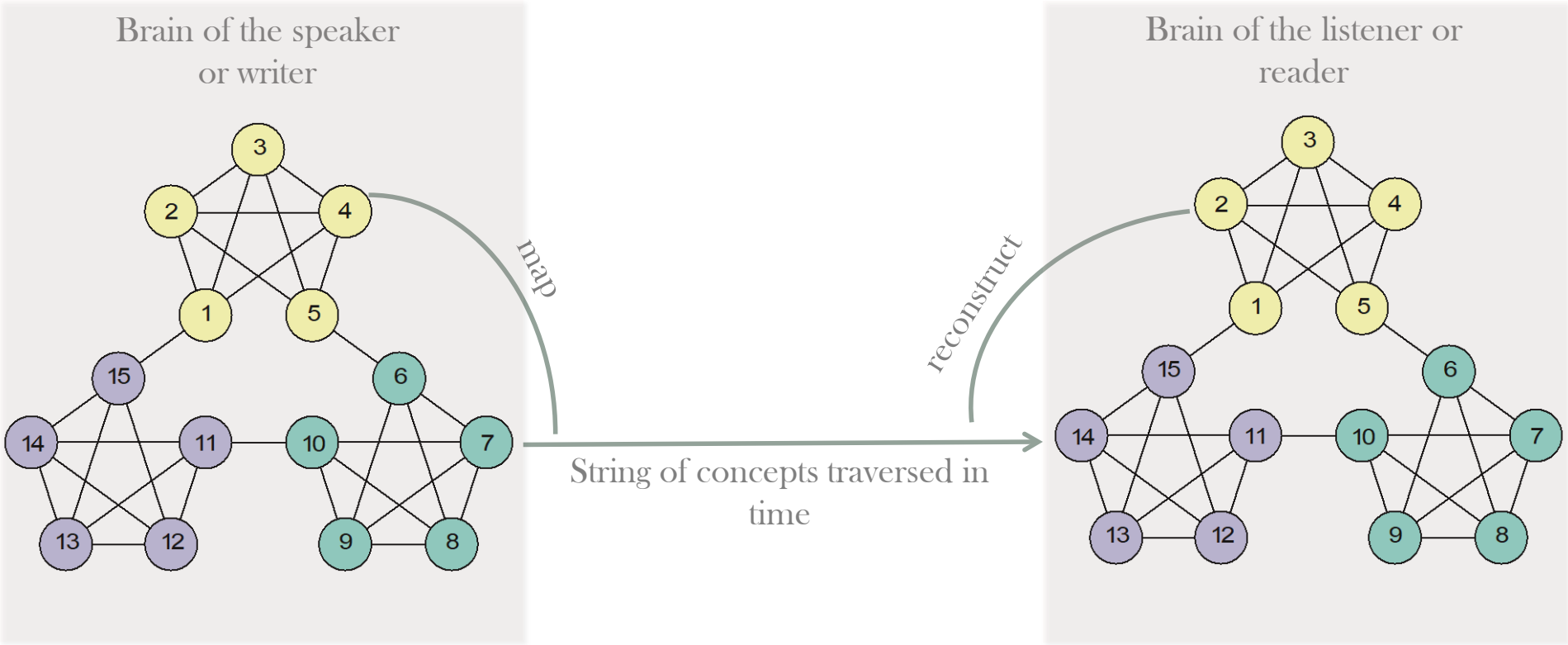
Those 15 ideas are related to one another in a heterogeneous manner, making a network.

I must translate that information linearly; time is one-dimensional and uni-directional.

How should I create this information time series in a way that maximizes learning?

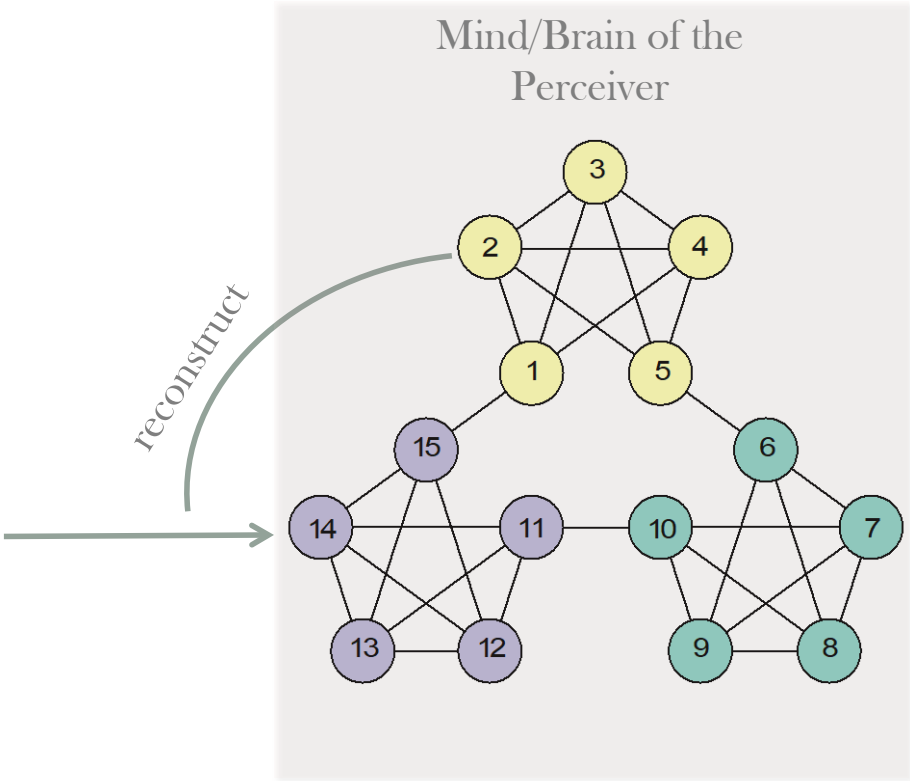
A "good walk" minimizes reconstruction error

and maximizes perception of the network's topology



The problem of inferring the patterns of pairwise dependencies from incoming streams of data allows us to:

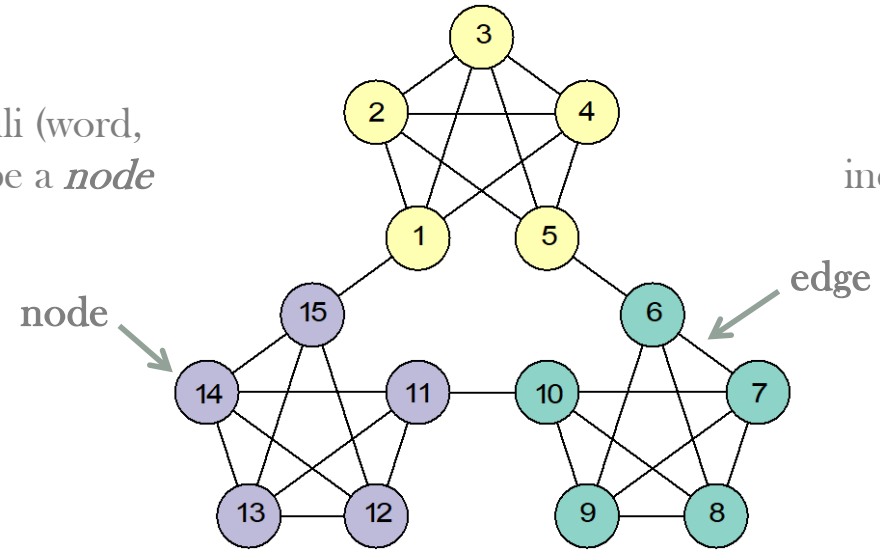
Learn **language**
Segment **visual** events
Parse **tonal** groupings
Parse **spatial** scenes
Infer **social** networks
Perceive distinct **concepts**



Can we measure perception of network topology

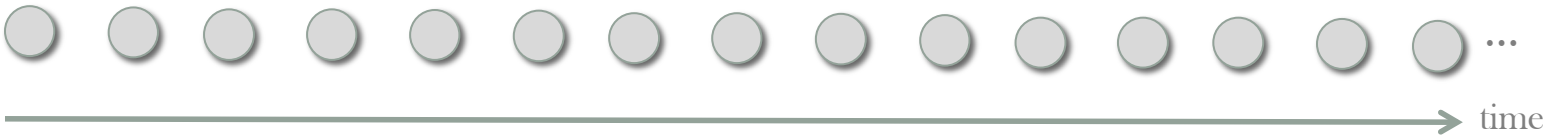
in a continuous stream of stimuli?

Let each specific stimuli (word, image, or movement) be a ***node in a graph***.



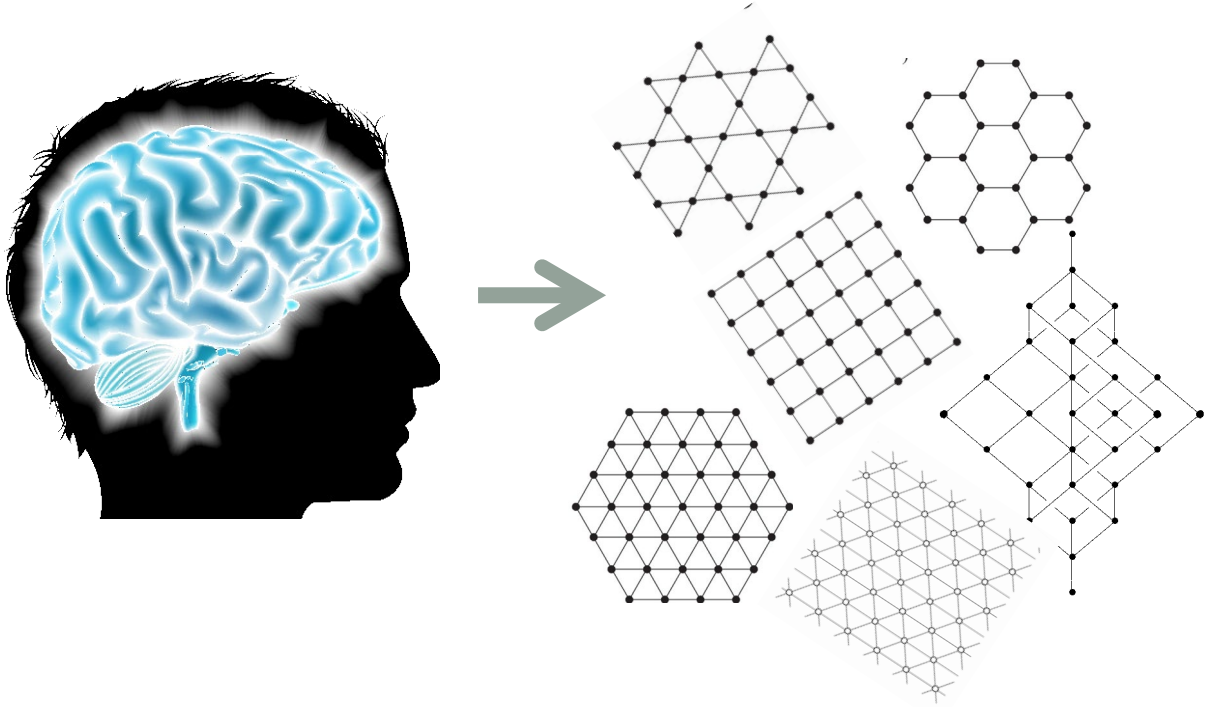
Let each ***edge in the graph*** indicate an allowable transition between nodes.

Construct a sequence of stimuli by a random walk on the graph.



At each stimuli, require the participant to perform a task, so that their time-to-react can be used as a measure of how well that edge in the graph was learned.

What do we know about this problem?



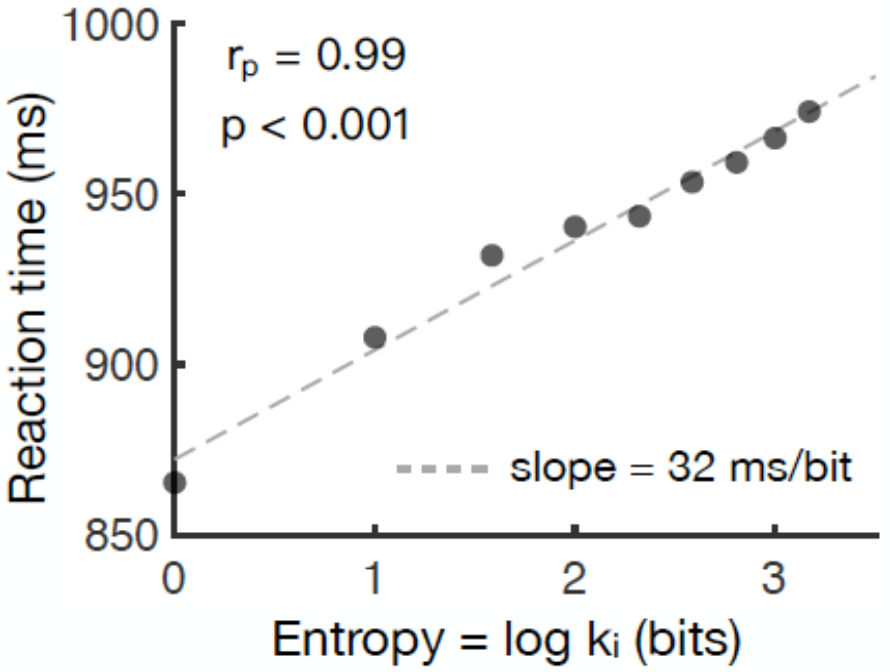
From work in the field of statistical learning and the study of artificial grammars, we know that humans are sensitive to transition probabilities.

Human reactions depend on environmental complexity

Human reactions should vary with the local complexity of the environment.

The complexity is measured by the number of possible event outcomes from a point on the network.

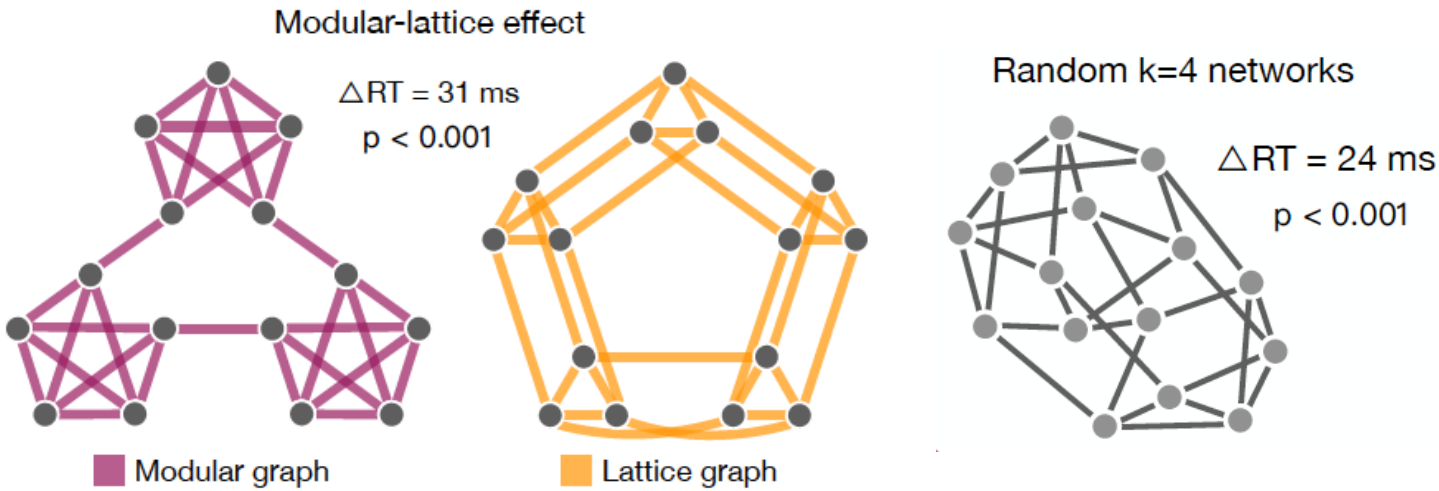
Formally, the complexity is referred tot as the entropy.



In this experiment, humans appear to process 1 bit of information in 32 ms.

Beyond local environmental complexity: humans are sensitive to shape

Compared to lattice and random graphs with equal entropy, reactions in the modular graph are significantly faster overall, indicating a decreased in perceived information.



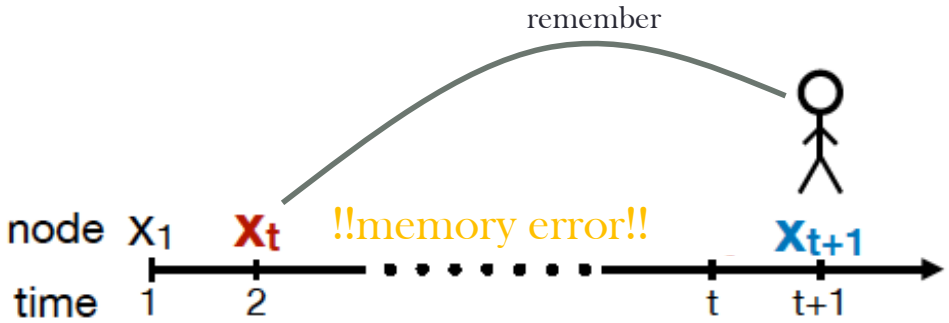
Together, these results reveal that humans process information beyond entropy in a manner that depends systematically on network topology (or shape).

"You know how most of us in idle moments, or perhaps even more in moments when we are officially supposed to be occupied, lapse into a reverie, in which a stream of thought -- it may be placid, it may be vehement -- sweeps through the brain from the flushed reservoir of the mind. Suppose you check yourself suddenly in one of these reveries. Try to put down in words what you have been thinking of, and as you thought it. You will find it to be ludicrously impossible. Half the thoughts have passed without clothing themselves in any vesture of word, one thing has suggested another, often enough by some trivial similarity of superficial form. The whole thing is evasive, elusive, irrecoverable."

Benson, *Ruskin: A Study in Personality*

What are people thinking?

Accurate Memory



Fuzzy Memory

Posit: the human brain maximizes accuracy and minimizes computational complexity, leading to a free energy model of people's internal representations of events.

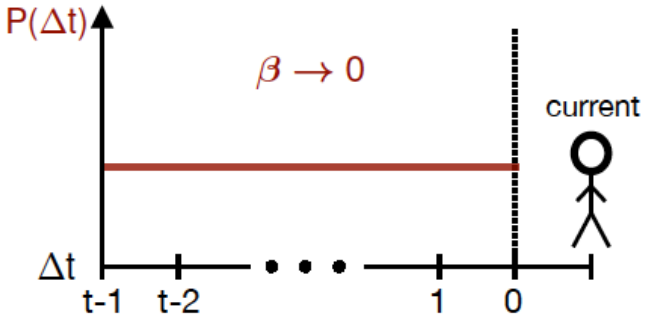
$$F(Q) = \beta E(Q) - S(Q)$$

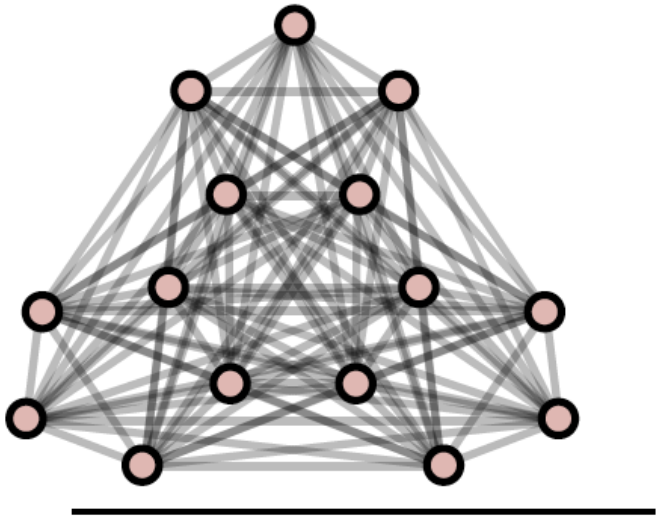
The distribution that minimizes the free energy:

$$P(\Delta t) = \frac{1}{Z} e^{-\beta \Delta t}$$

From a poor memory arises biases in learning

No memory;
Minimizes mental resources





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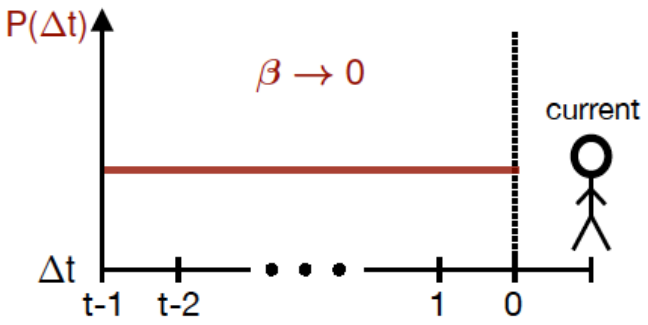
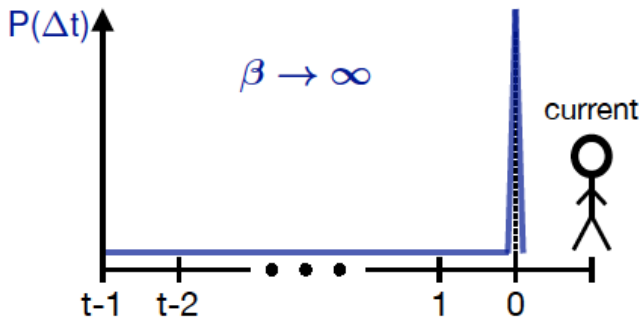
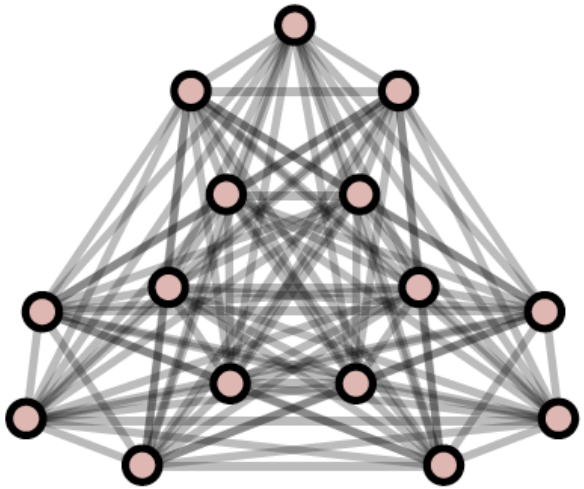
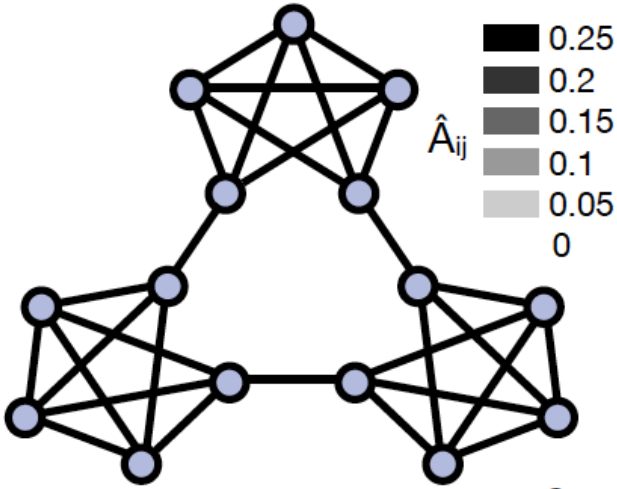


Perfect memory;
Maximizes mental resources







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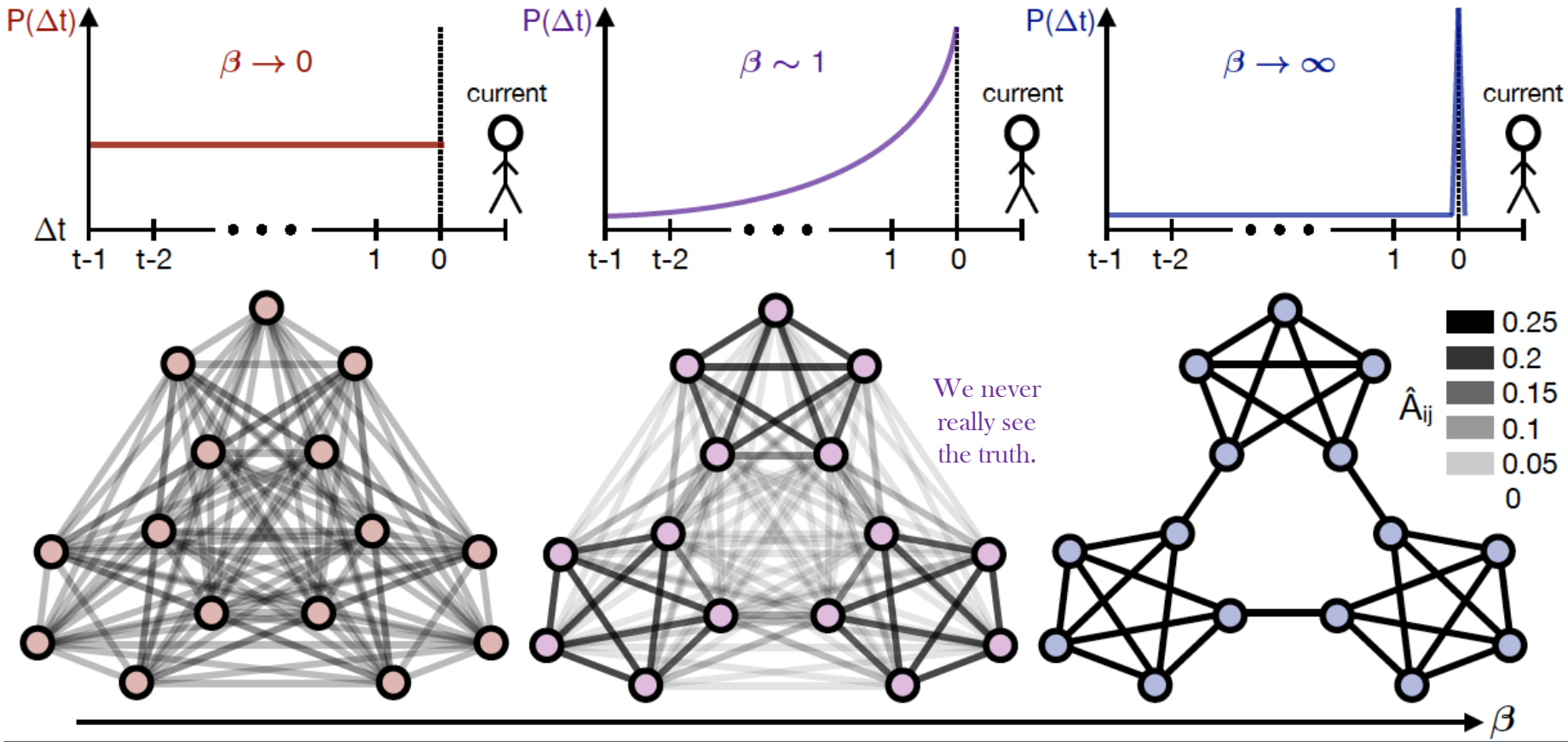
From a poor memory arises biases in learning

No memory;
Minimizes mental resources

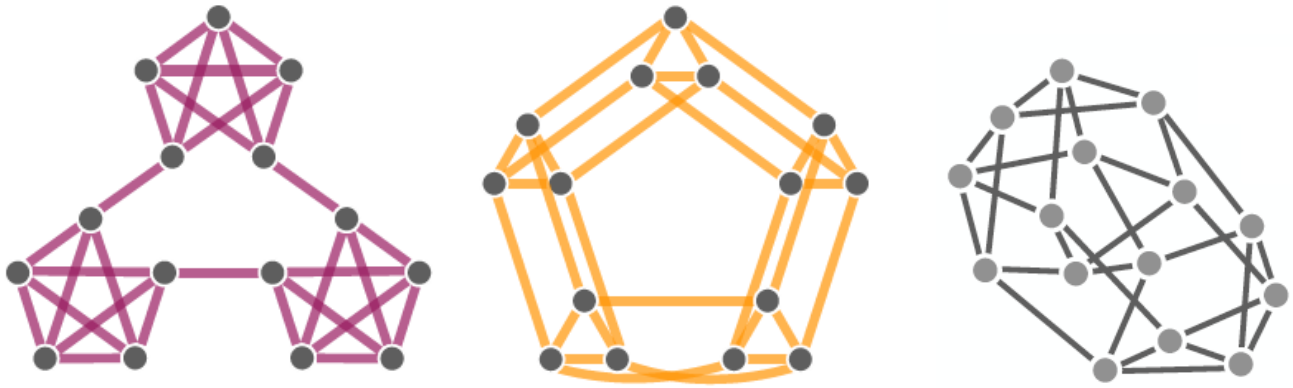
Poor memory

Perfect memory;
Maximizes mental resources



When we have built a theory, we usually wish to

1. Estimate the parameters from data.
2. Validate the mechanism of the phenomenological theory.
3. Use the theory to make a prediction about a new experiment.



But how is it, and by what art, doth the soul read that such an image or stroke in matter . . . signifies such an object? Did we learn such an Alphabet in our Embryo-state? And how comes it to pass, that we are not aware of any such congenite apprehensions? . . . That by diversity of motions we should spell out figures, distances, magnitudes, colours, things not resembled by them, we attribute to some secret deductions.

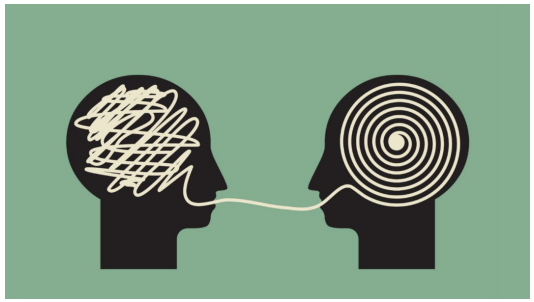
Joseph Glanvill, *The Vanity of Dogmatizing* (1661)

Information Processing in Real Networks

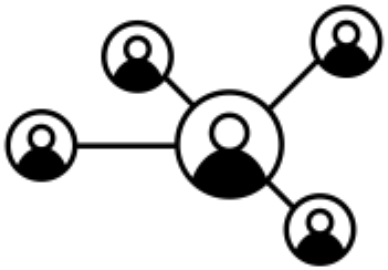
Real informational networks

What are a few common examples of human communication systems?

Language (word transitions)
Shakespeare
Homer
Plato
Jane Austen
William Blake
Miguel de Cervantes
Walt Whitman



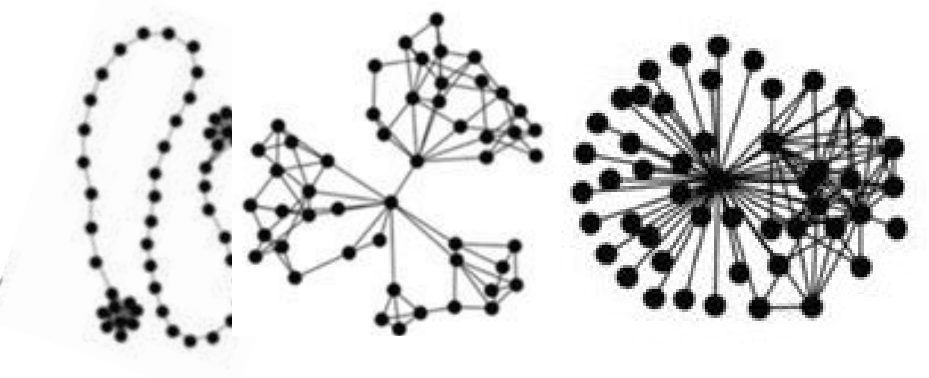
Social relationships
Facebook
arXiv Astr-Ph
Adolescent health
Highschool
Jazz
Karate club

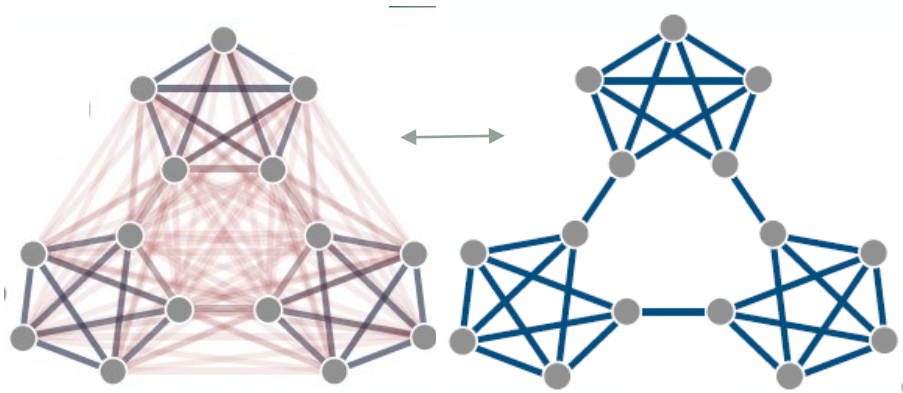


Music (note transitions)
Thriller – Michael Jackson
Hard Day's Night – Beatles
Bohemian Rhapsody – Queen
Africa – Toto
Sonata No 11 – Mozart
Sonata No 23 – Beethoven
Nocturne Op 9-2 – Chopin
Clavier Fugue 13 – Bach
Ballade No 1 – Brahms

Perceived information of a communication system

Entropy + Divergence —





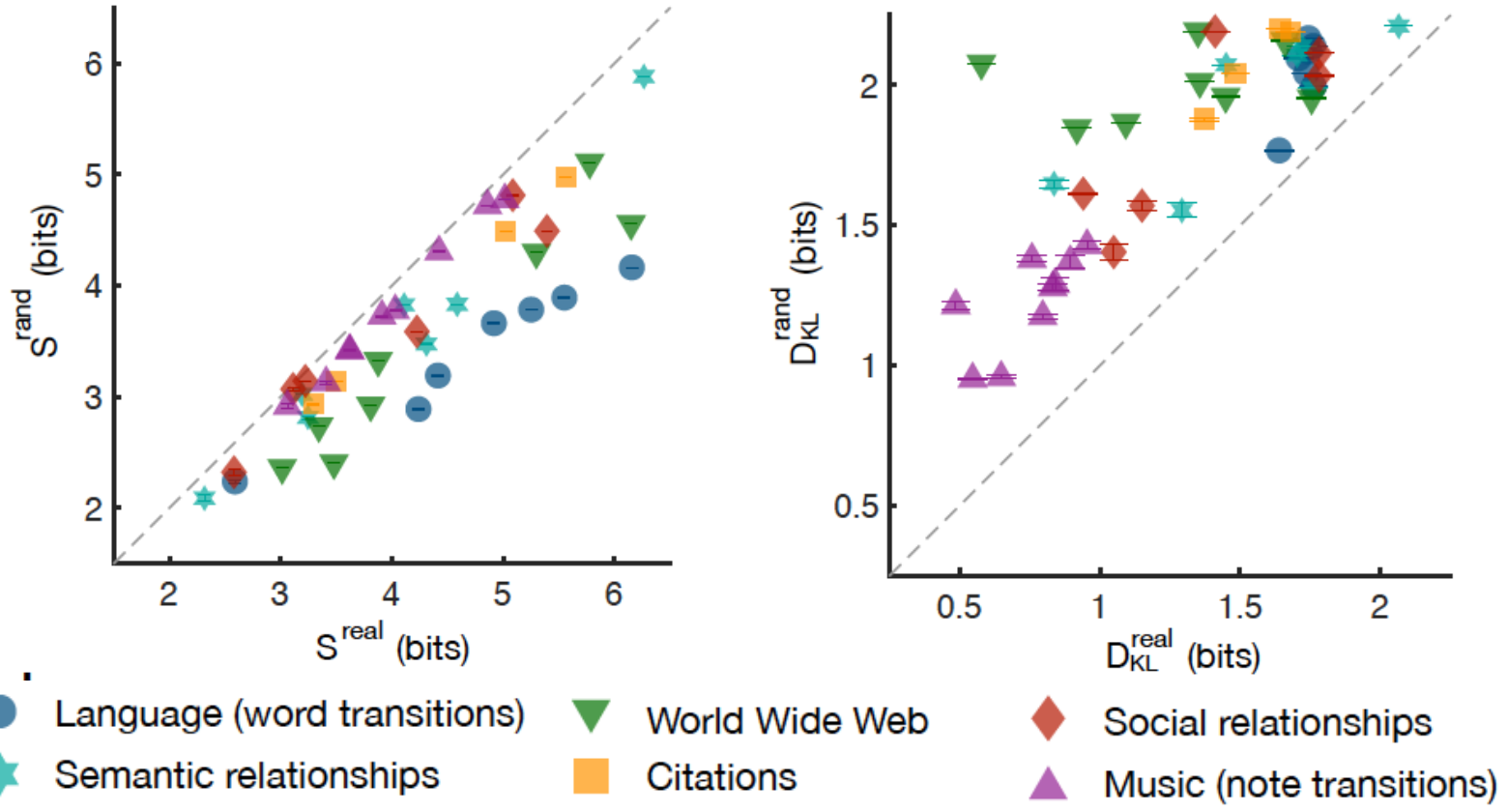
How complex is the network?

How far is our expectation from reality?

$$\underbrace{\langle -\log \hat{P}_{ij} \rangle_P}_{S(P,\hat{P})} = \underbrace{\langle -\log P_{ij} \rangle_P}_{S(P)} + \underbrace{\langle -\log \frac{\hat{P}_{ij}}{P_{ij}} \rangle_P}_{D_{\mathrm{KL}}(P||\hat{P})}$$

Real networks display high entropy and low divergence

Since the networks chosen have evolved or were designed to communicate with humans, one might expect them to produce large amounts of information (high entropy) without inducing additional processing costs (low divergence).



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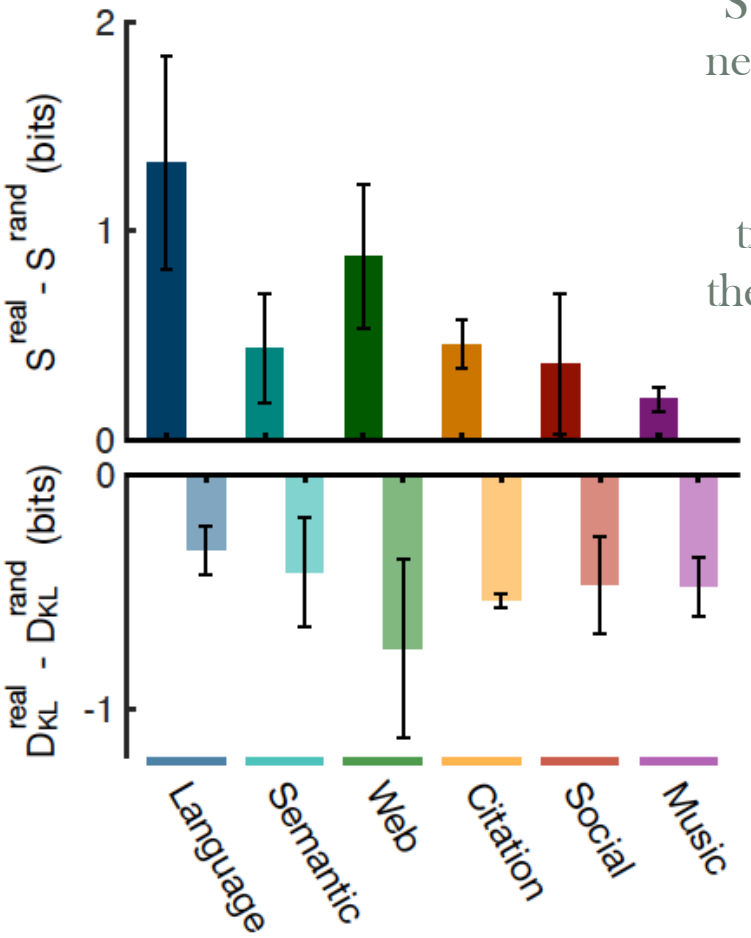
Classes of real networks differ in perceived information

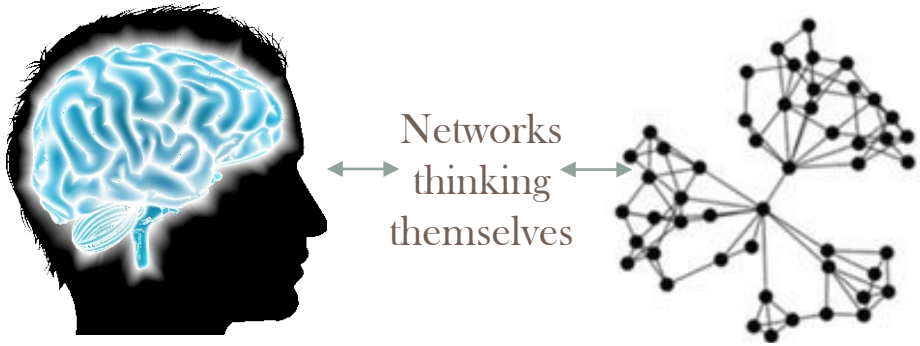


Suggests that many real networks are constrained by the pressures of information transmission, and that these pressures select for specific structural features.

Different network types exhibit these properties to varying degrees.

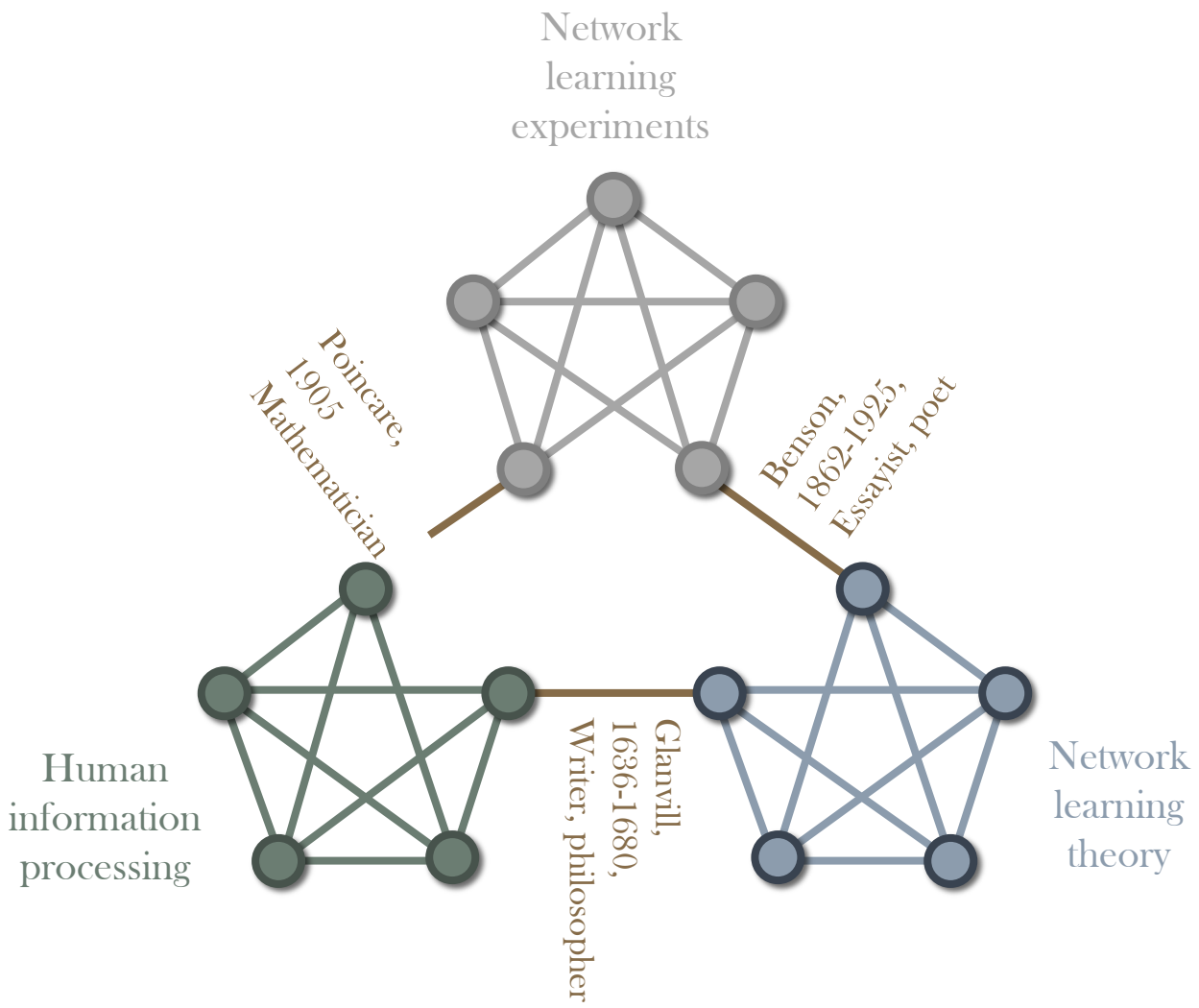
Summary

- Humans can learn the architecture of networks underlying a continuous stream of information.
- Humans display expectations that diverge from the true network, but allow them to perceive larger scale structure.
- These biases in learning (and larger-scale perceptions) can be explained by a poor memory (or fuzzy temporal integration).
- Real networks fit our biases (low divergence from expectations) while packing in large amounts of information (high entropy).



"Mind thinks itself because it shares the nature of the object of thought; for it becomes an object of thought in coming into contact with and thinking its objects, so that mind and object of thought are the same." Aristotle, Metaphysics, Book XII, 7, 1072 b 20

How humans build models of the world



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Dr. Christopher Lynn (physicist) Now postdoc at CUNY/Princeton on JSMF Fellowship

How humans build models of the world