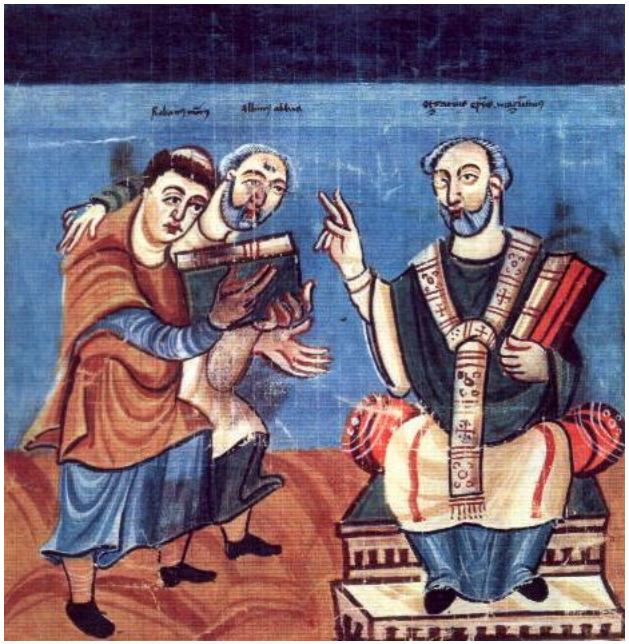
How evolution designs living matter

Ard Louis



Alcuin of York
735-804

Propositiones ad acuendos iuvenes
"Problems to sharpen the young"

- Problem 13:

"*A king ordered his servant to collect an army from 30 manors, in such a way that from each manor he would take the same number of men he had collected up to then. The servant went to the first manor alone; to the second one he went with one other; to the next he took three with him, How many were collected from the 30 manors?"*

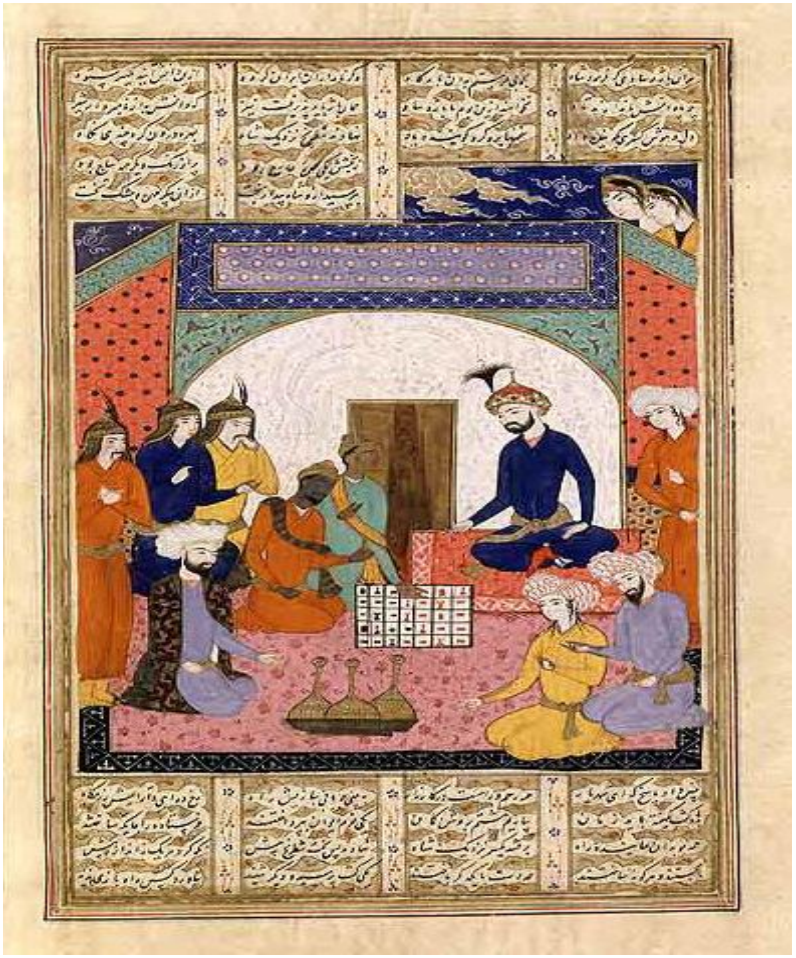
2^{30}-1= 1,073,741,823 (1 billion) soldiers,

A barley-corn: to a single barley-corn I increased,
2 barley-corns in the 1st day;
4 barley-corns in the 2nd day;
8 barley-corns in the 3rd day;
..
..
30 2 ‘thousand’ 7 ‘hundred’ 37 talents 1/2 mina 2 1/3 shekels 4 barley-corns in the 30th day.

Mari 08613 tablet
(Old Babylonian. 1900-1600 BC)

Jöran Friberg (2005), *Unexpected Links Between Egyptian and Babylonian*

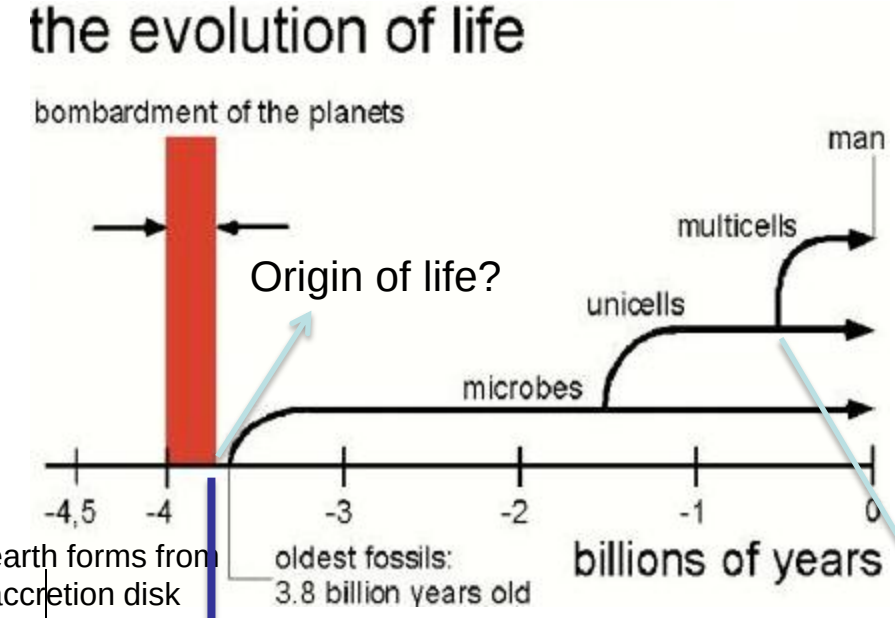
$2^{64}-1= 18,446,744,073,709,551,615$

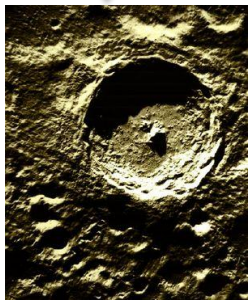


Shah-nama (Persian: شاهنامه Šāhnāmeh, "The Book of Kings")

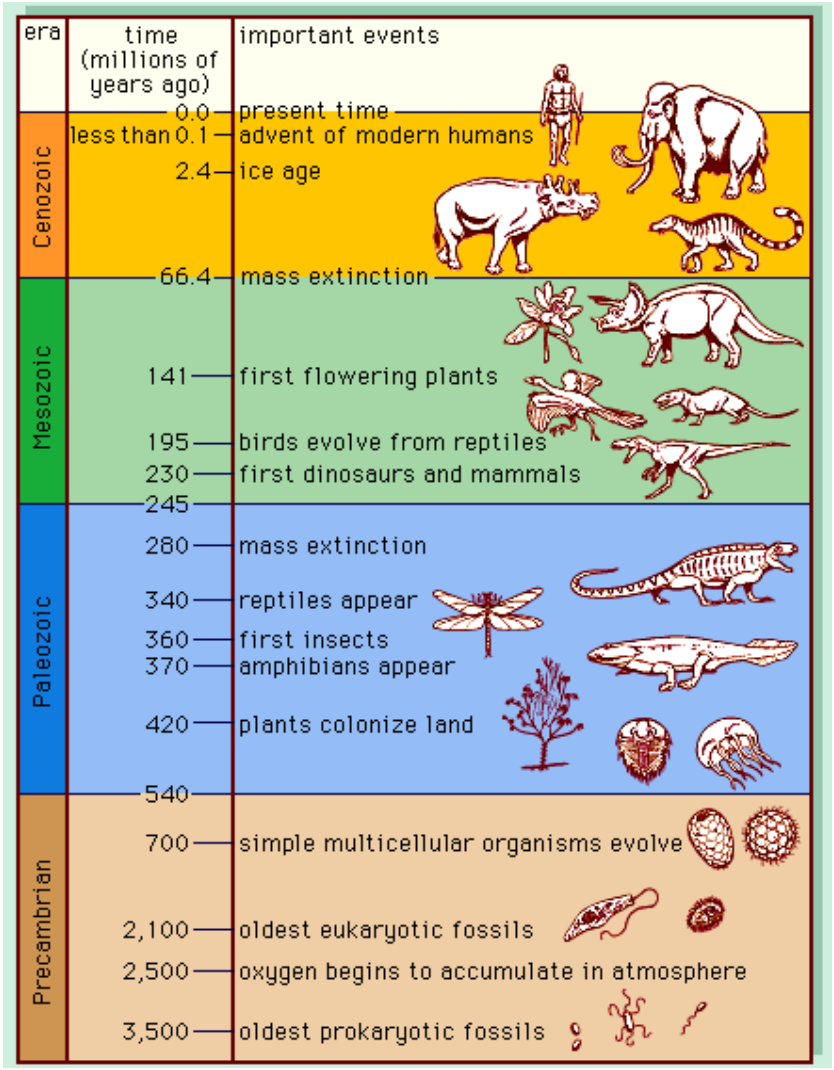
by Ferdowsi(فردوسی) 940 – 1020

History of life on earth

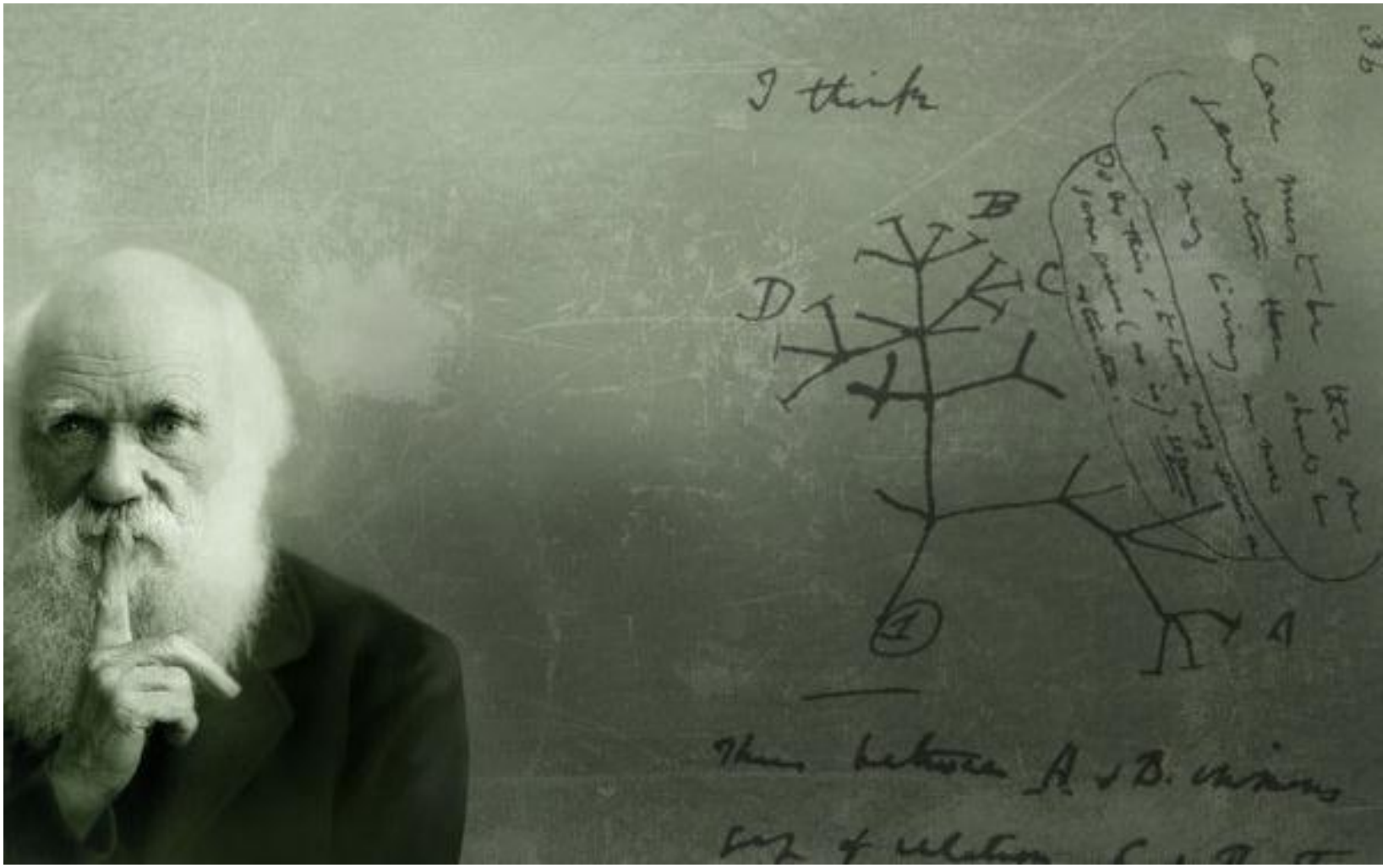




Late heavy bombardment



1859: Variation and Natural Selection



Arrival of the fittest?

where does variation come from?

“Natural selection may explain the survival of the fittest, but it cannot explain the arrival of the fittest.”

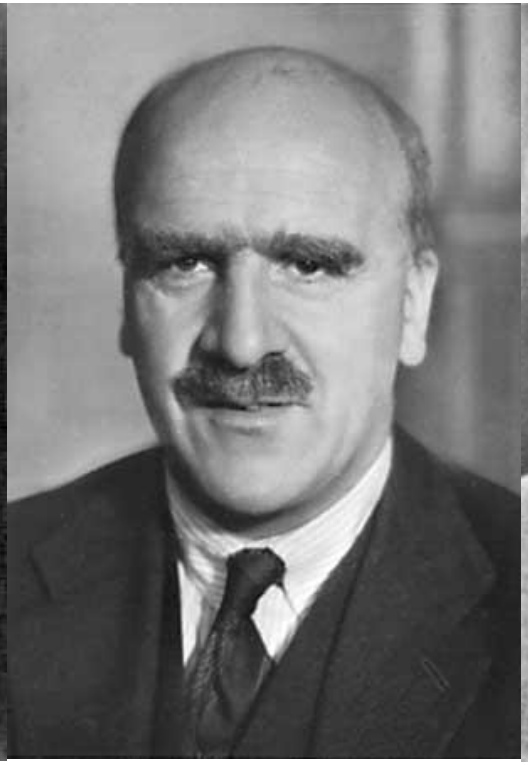
Species and Varieties. Their Origin by Mutation. Chicago: Open Court (1904)

Natural selection as a sieve?

Hugo de Vries 1848-1935

Modern Synthesis

R.A. Fisher
1890 –1962



JBS Haldane
1892 –1964

Sewall Wright
1889 – 1988

How big is evolutionary search space?

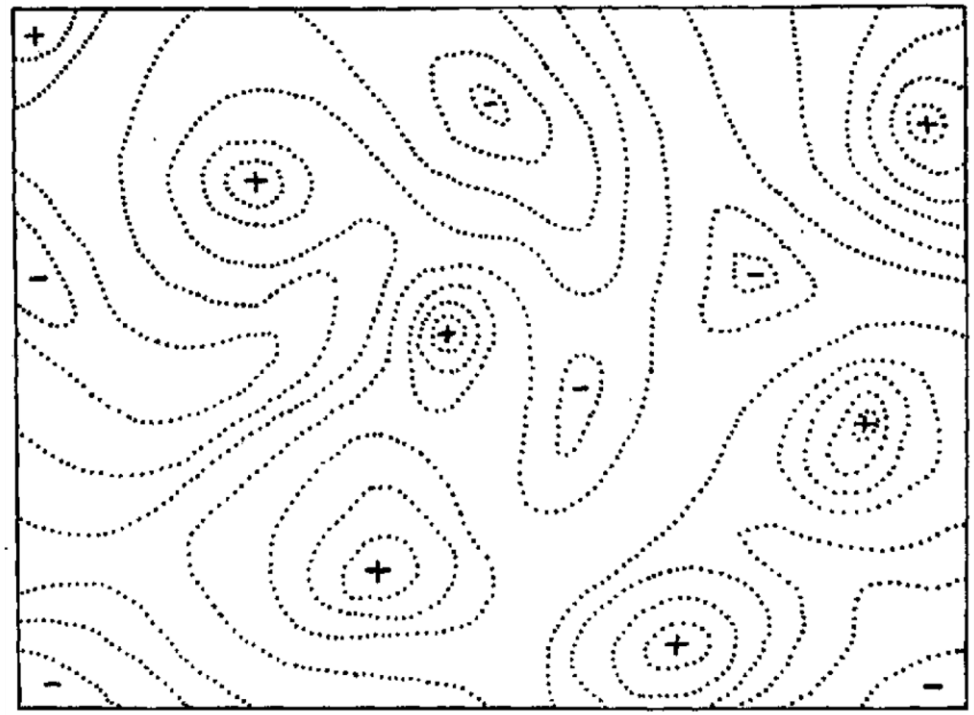


FIGURE 2.—Diagrammatic representation of the field of gene combinations in two dimensions instead of many thousands. Dotted lines represent contours with respect to adaptiveness.

Sewell Wright

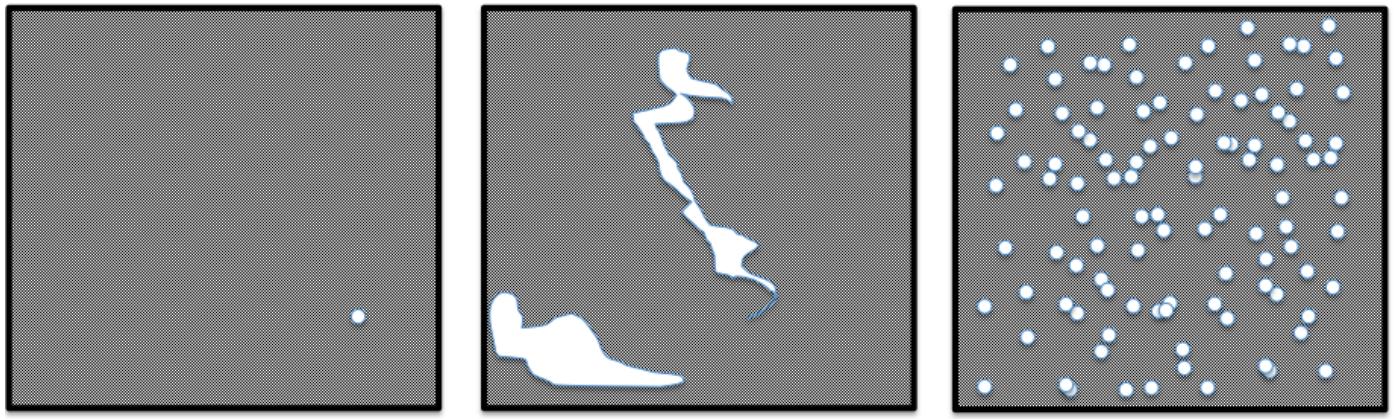
Estimates of the total number of genes in the cells of higher organisms range from 1000 up ... With 10 alleomorphs in each of 1000 loci, the number of possible combinations is 10^{1000} which is a very large number. It has been estimated that the total number of electrons and protons in the whole visible universe is much less than 10^{100}"

hyperastronomical

Wright, S. (1932). *Proceedings of the Sixth International Congress on Genetics*. pp. 355–366.

"*The population is thus confined to an infinitesimal portion of the field of possible gene combinations*"

1. Nature can only explore an unimaginably small fraction of all theoretically possible genomes.



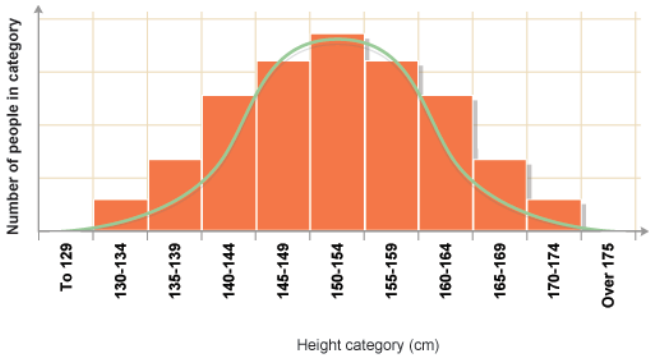
"The chance that a random combination is as adaptive as those characteristic of the species may be as low as 10^{-100} and still leave room for 10^{800} separate peaks [adaptive gene combinations], each surrounded by 10^{100} more or less similar combinations. ''

2. The current instantiation of genetic possibilities (life as we know it) is largely contingent, since it could just have well occupied a different part of genotype space.

"... under biparental reproduction a very low rate of mutation balanced by moderate selection is enough to maintain a practically infinite field of possible gene combinations within the species "

3. The variation for natural selection to act on is abundant.

4. Variation does not introduce a significant bias in evolutionary trajectories

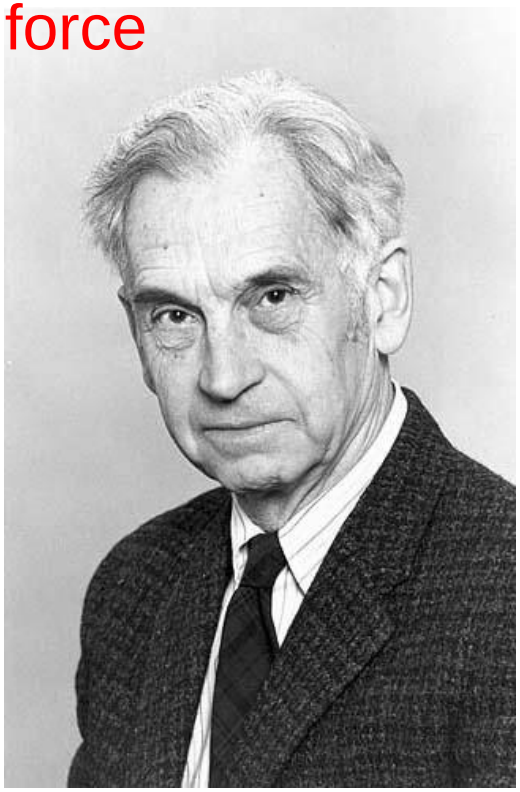


Where does evolutionary novelty come from?

MS: selection (not variation) is primary causal force

Evolution is not primarily a genetic event. Mutation merely supplies the gene pool with genetic variation; it is selection that induces evolutionary change.

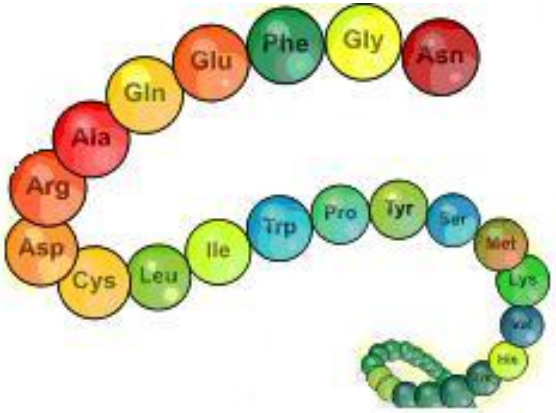
-- Ernest Mayr, *Animal Species and Evolution, HUP* 1963)



Ernest Mayr – 1904-200

Evolution and hyper-astronomical numbers

Proteins: linear chains made from an alphabet of 20 amino acid

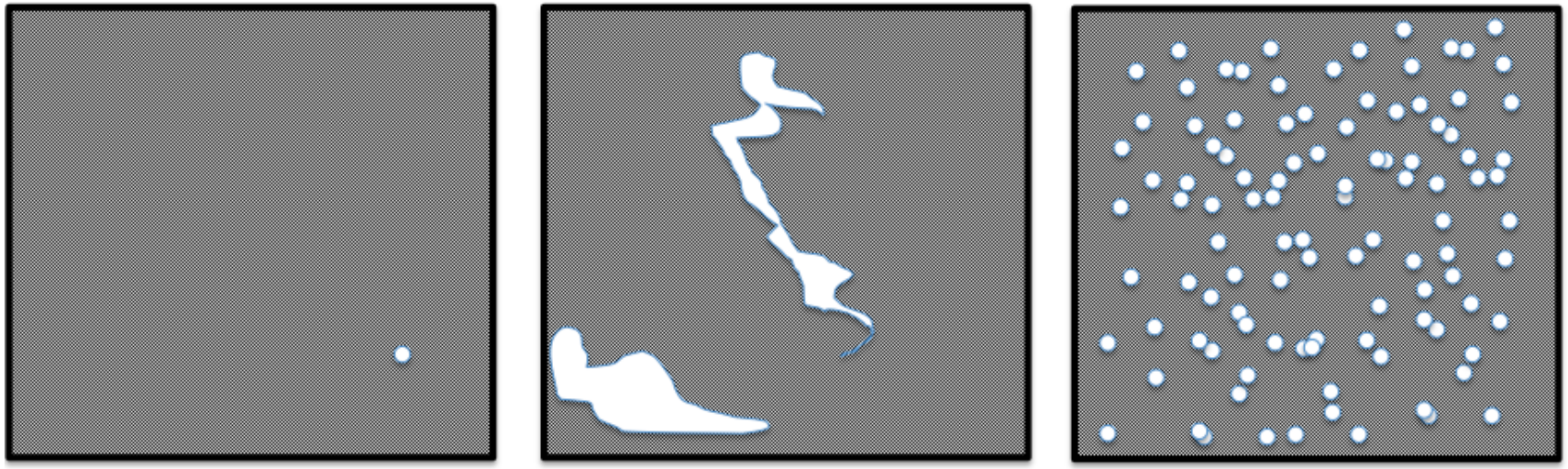


Hoyle Paradox

all combinations pf length 100 proteins would weigh more than the visible universe.

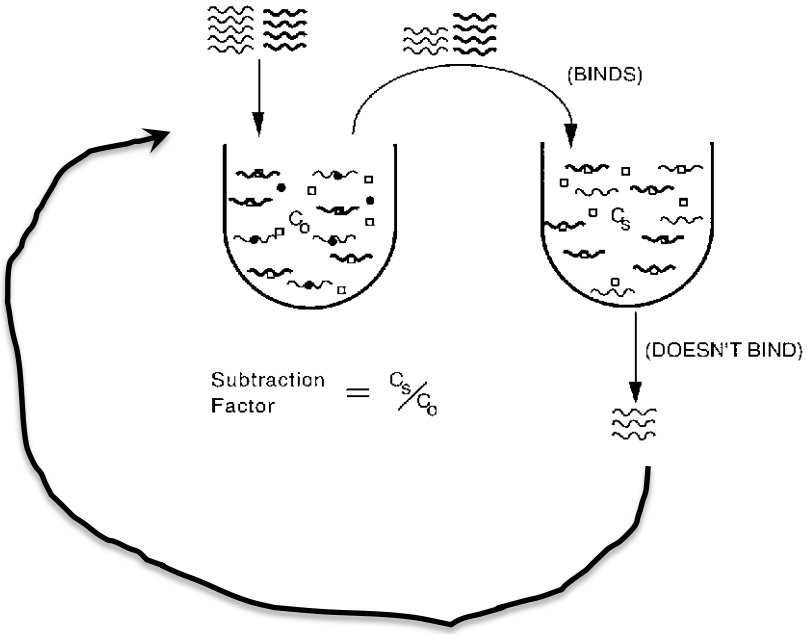
Fred Hoyle 1915-2001

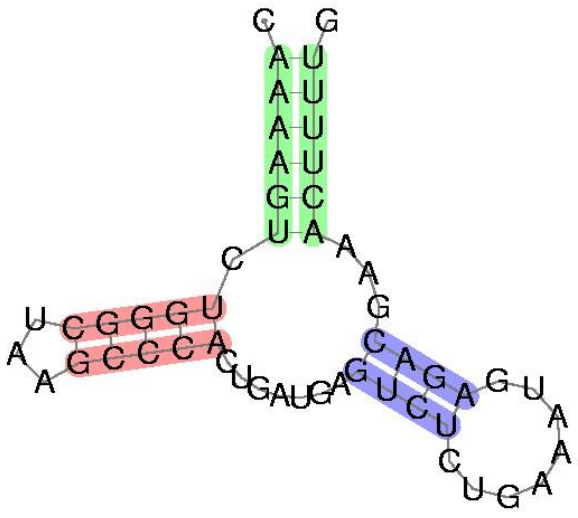
what does search space look like?



Convergent Evolution?

Hammerhead ribozyme keeps emerging from SELEX in-vitro evolution





RNA: alphabet of 4 nucleotides, so L=55 means $4^{55} \sim 10^{33}$

Salehi-Ashtiani K, Szostak JW. In vitro evolution suggests multiple origins for the hammerhead ribozyme. Nature. 2001 Nov 1;414(6859):82-4.

Convergent Evolution?

North America:

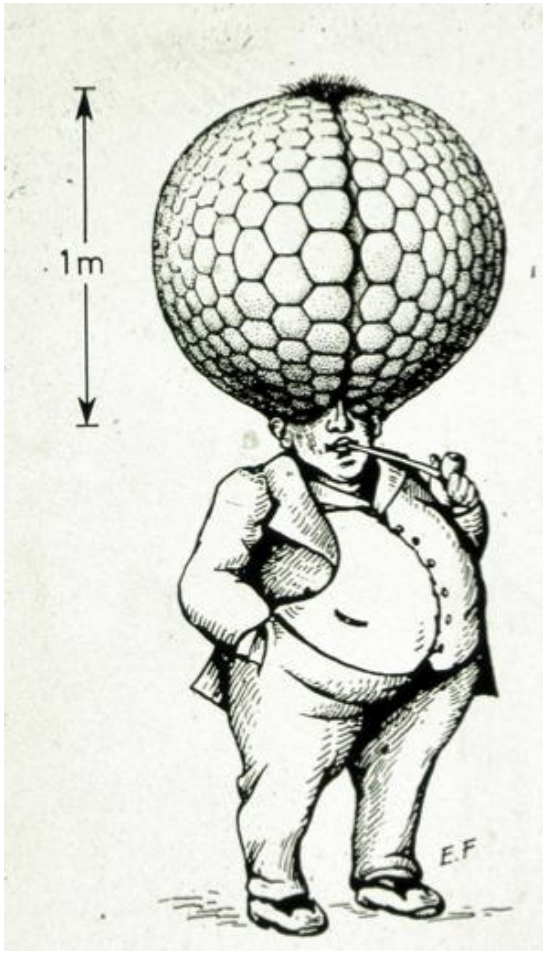
Placental Sabre-toothed cat

South America”

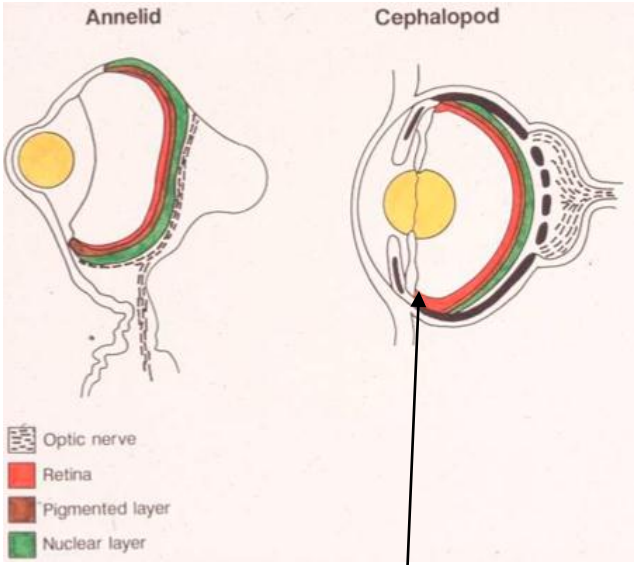
Marsupial Sabre-toothed cat

Convergent Evolution?

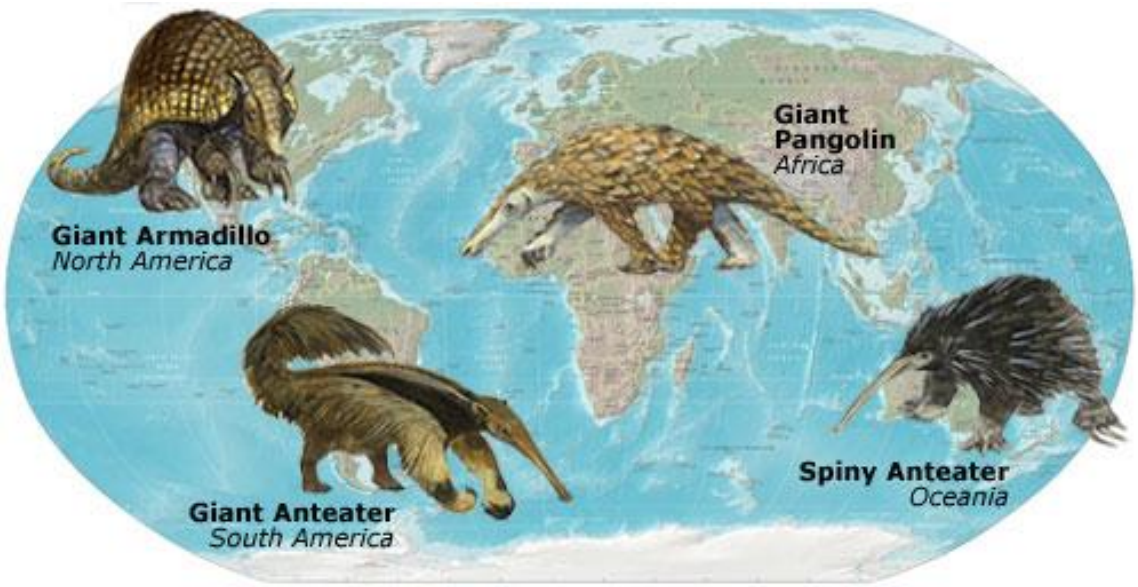
compound eye



camera eye



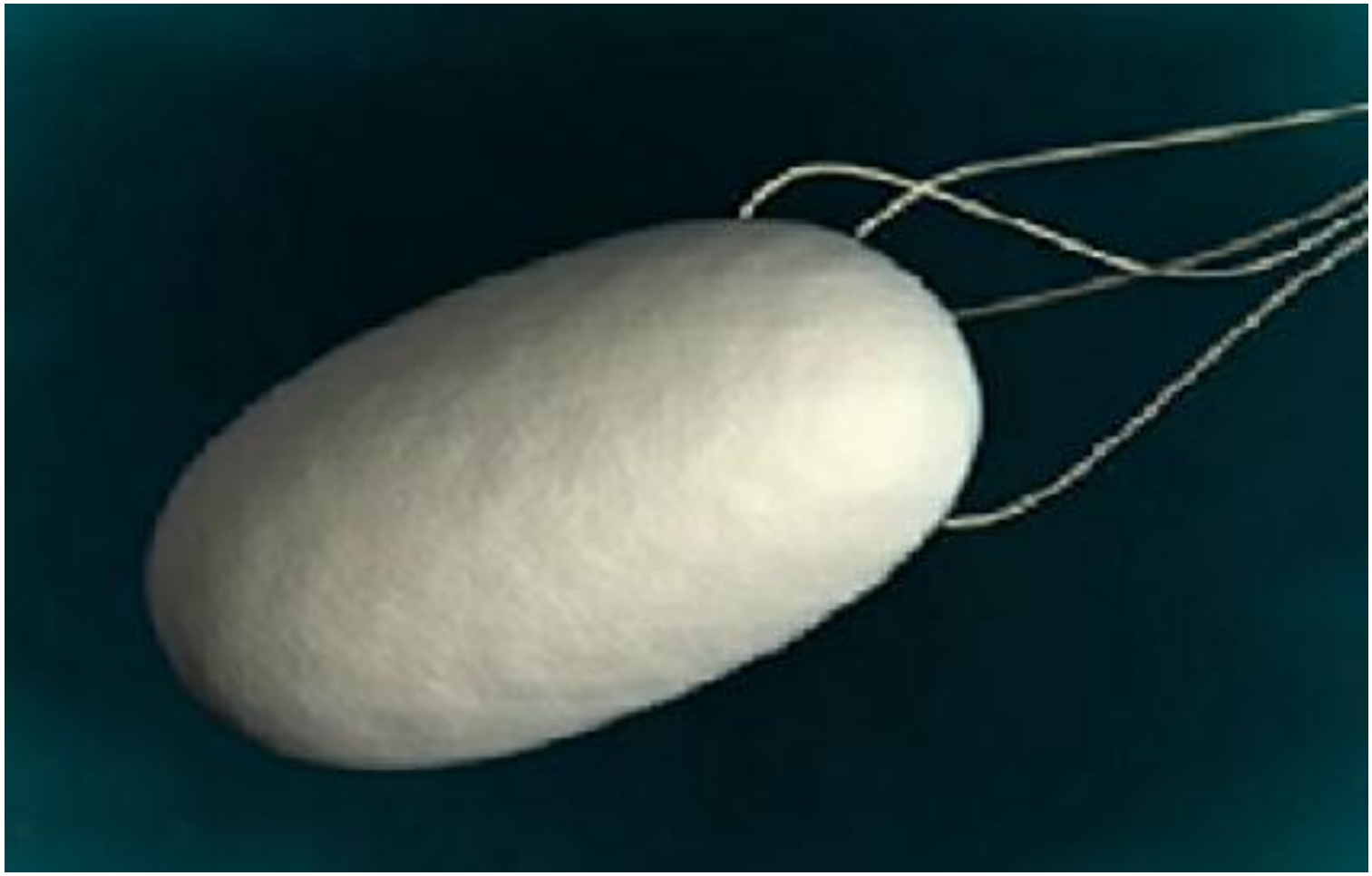
Convergent Evolution?



- Enormous number of examples ... from proteins to vision up to societies to intelligence.
- http://www.mapoflife.org
- Why all this convergence? variation or selection or something else?

The principal aim of this book has been to show that the constraints of evolution and the ubiquity of convergence make the emergence of something like ourselves a near-inevitability. Simon Conway Morris, “Life’s Solution”, (CUP 2003) pp328

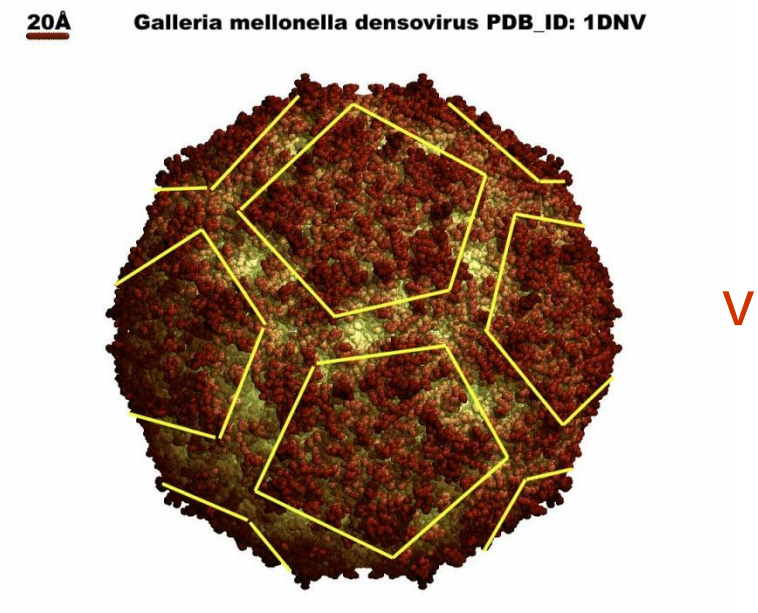
Biological self-assembly



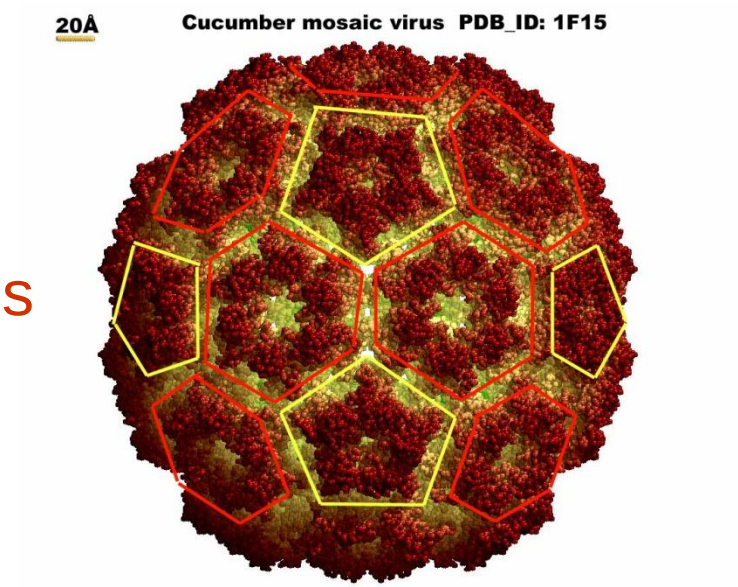
Movie from: Keiichi Namba, Osaka ERATO project

- Can we understand?
  - Self-assembly
  - Evolution
- Can we emulate (nanotechnology?)

Virus self-assembly

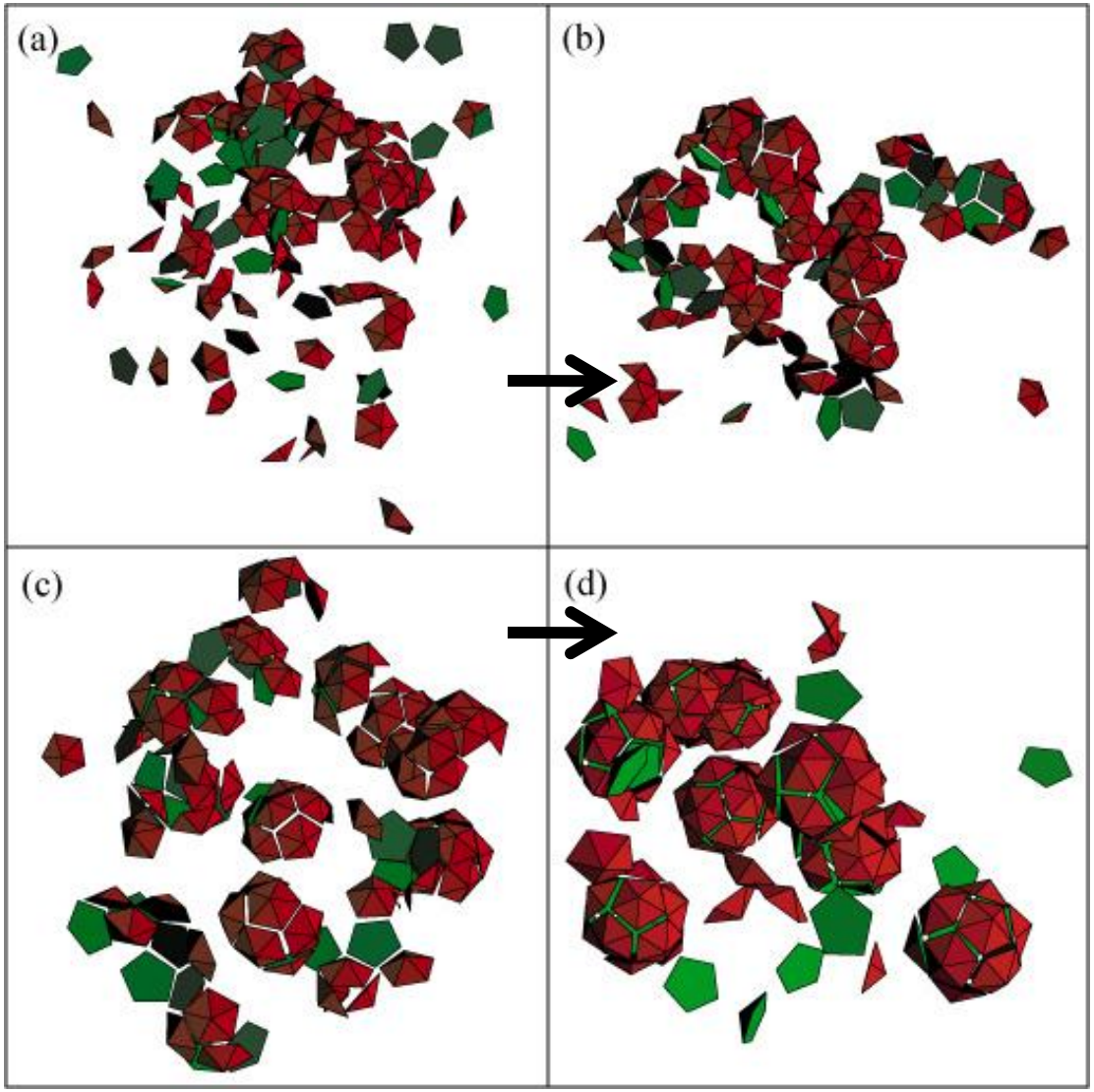


viruses



viruses assemble from identical capsomeric units

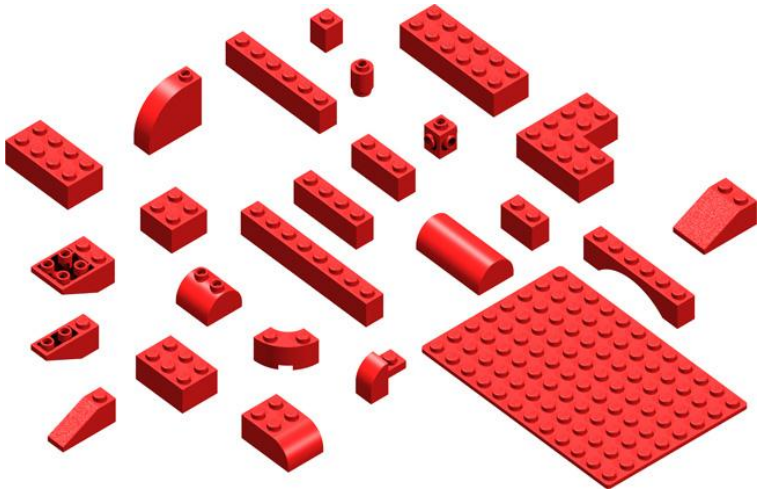
“computer virus” self-assembly



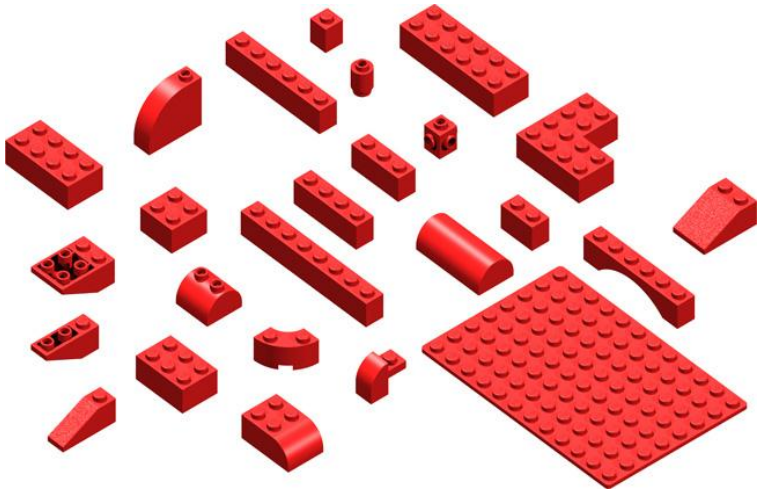
Computer viruses?

Iain G. Johnston, AAL & J.P.K. Doye, J. Phys.: Condensed Matter, **22** , 104101

Biological self-assembly



Science is fun!



Protein folding (self-assembly)

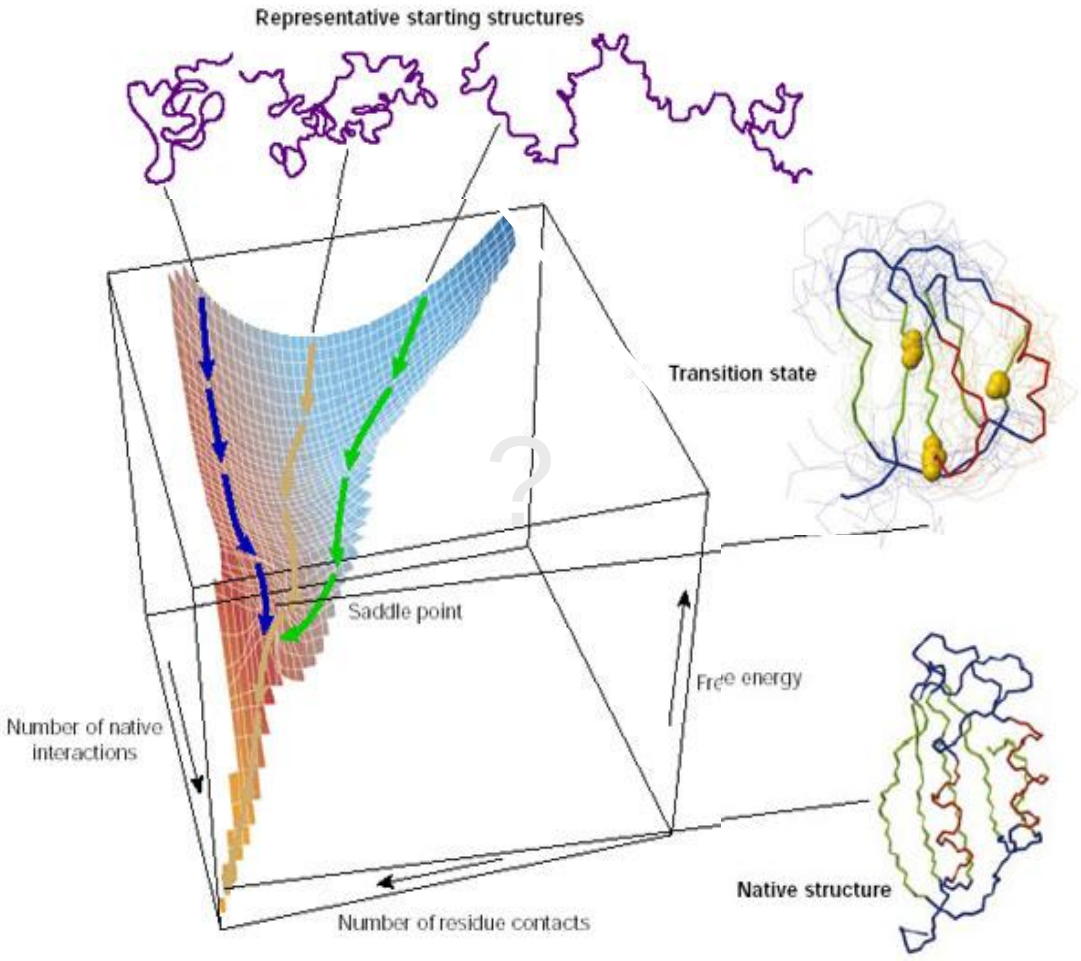
Levinthal Paradox (1968):

150 amino acids

~10 angles between them

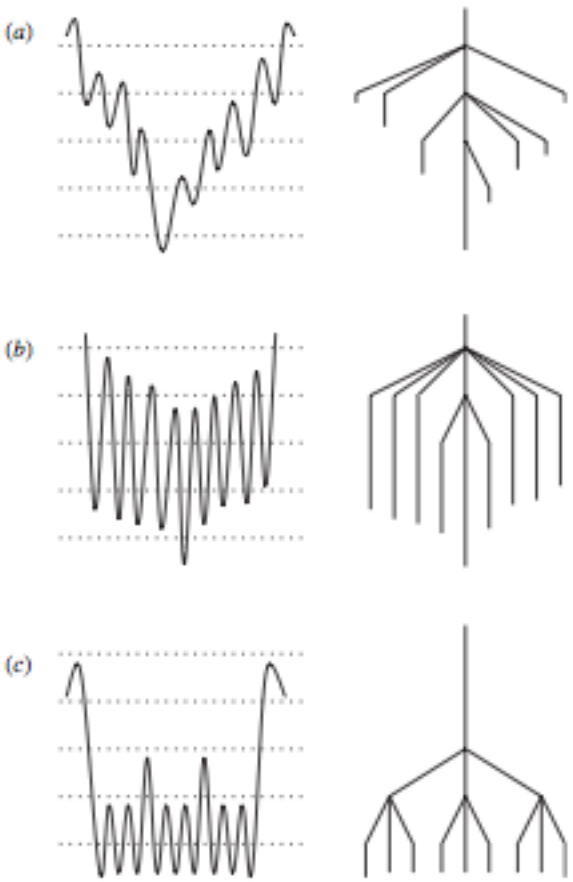
~10^{150} different states.

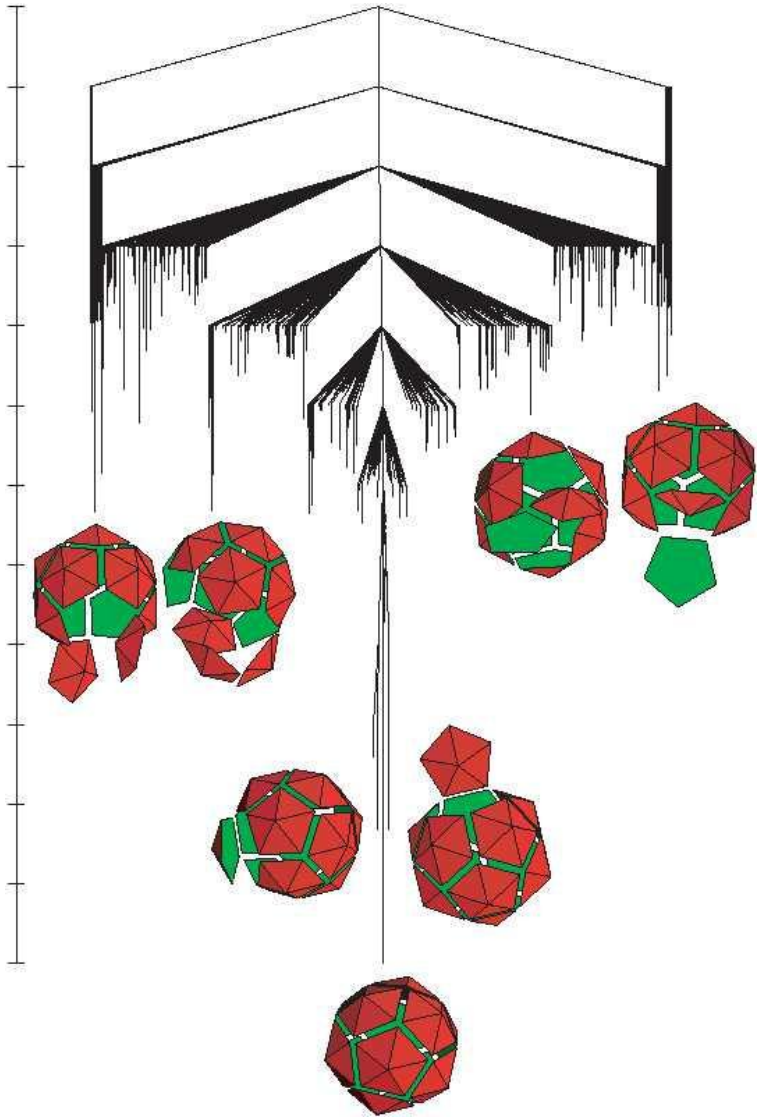
How does protein find its folded native structure?



The search is not random!

Energy landscape for a virus capsid



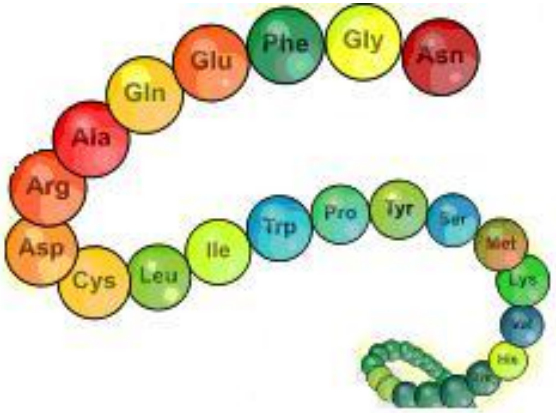


The search is not random!

David Sherrington works on landscap

Evolution and hyper-astronomical numbers

Proteins: linear chains made from an alphabet of 20 amino acid



Hoyle Paradox

100 residue protein; 20 amino acids => combinations would weigh more than all the atoms in the visible universe.

Fred Hoyle 1915-2001

how are genotypes distributed over phenotypes?

$N_G >> N_P$

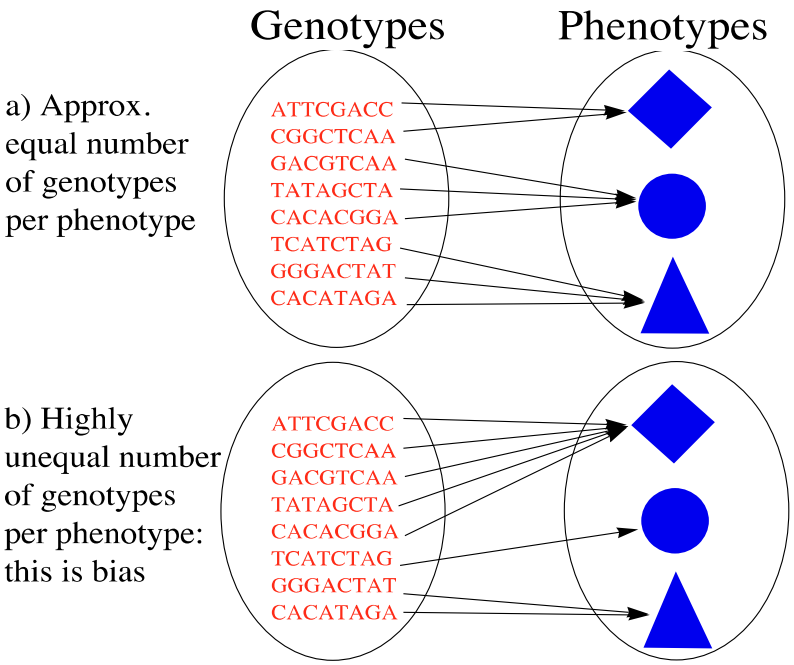
Neutral theory of evolution:
Kimura 1968
King and Jukes 1969

Lots of mutations are neutral …
e.g. proteins can have the same function with > 50% sequence dissimilarity

Motoo Kimura
1924-1994

how are genotypes distributed over phenotypes?

$$N_G >> N_P$$

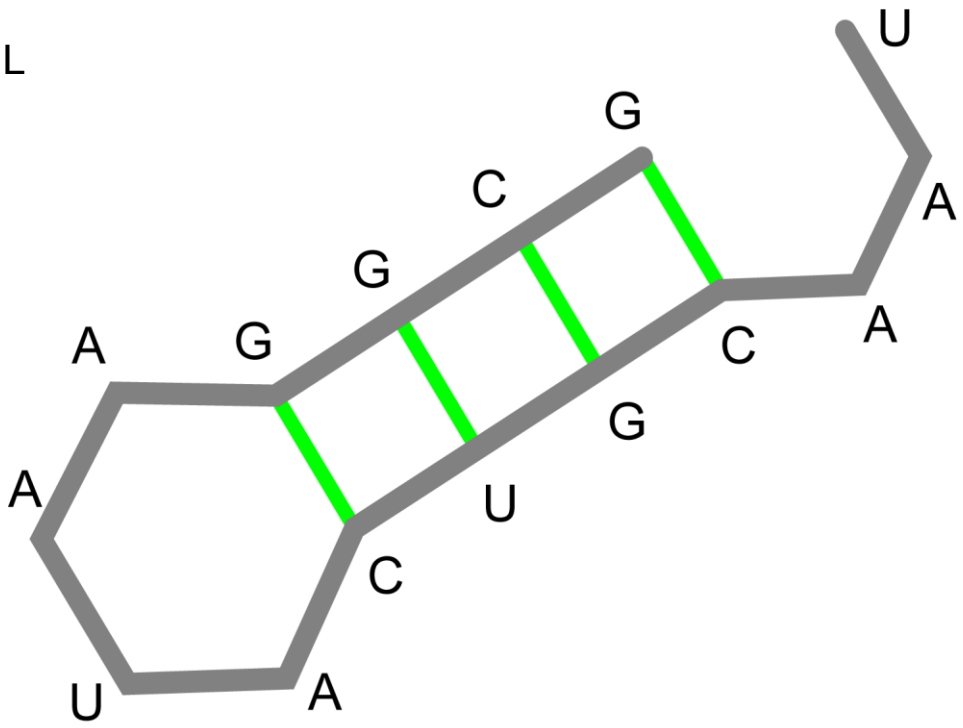


Model GP map: RNA secondary structures

$N_G = 4^L$

$N_P = 0.02 \times 1.93^L$

$N_G >> N_P$



Genotype

Phenotype

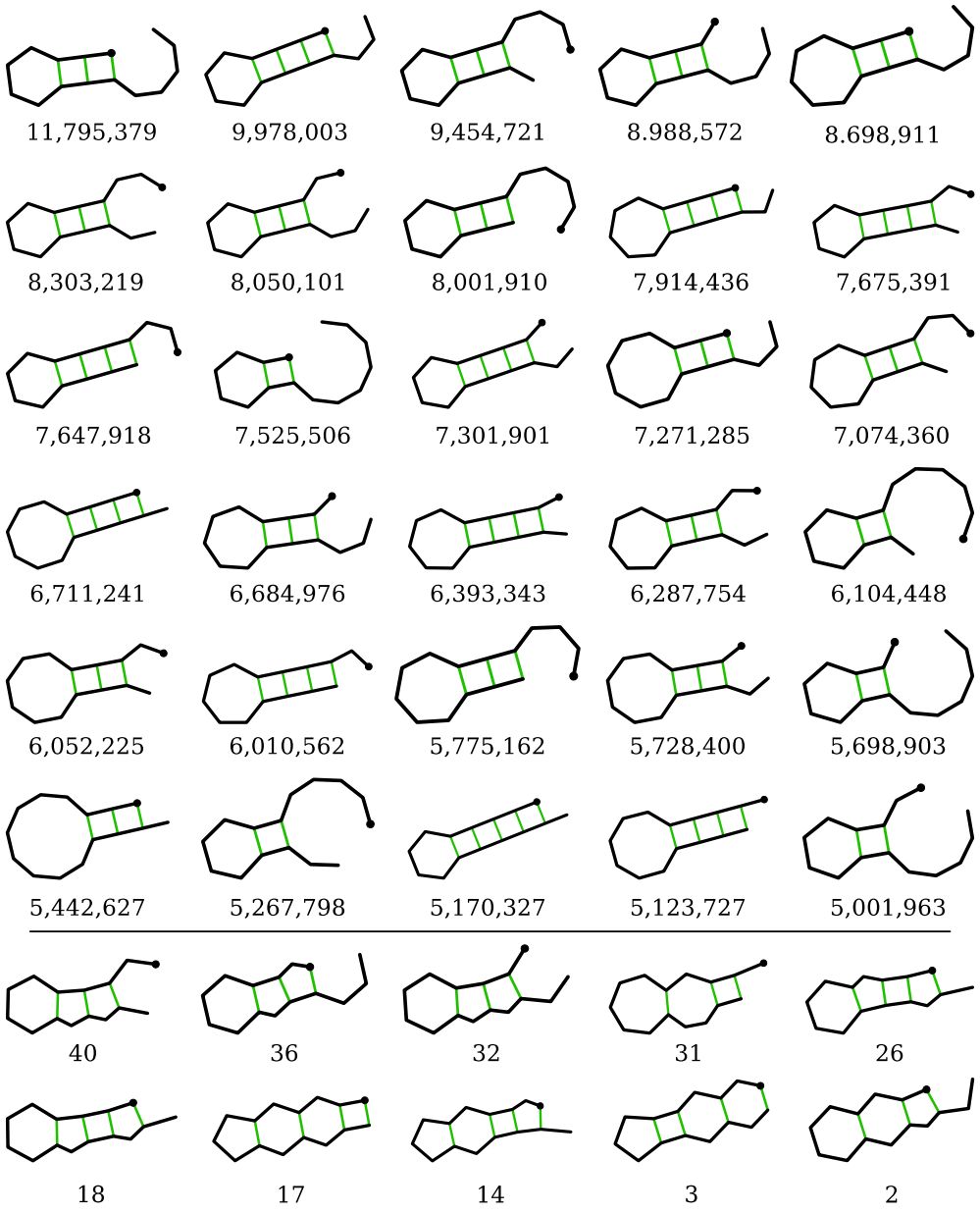
GCGGAAUACUGCAAU

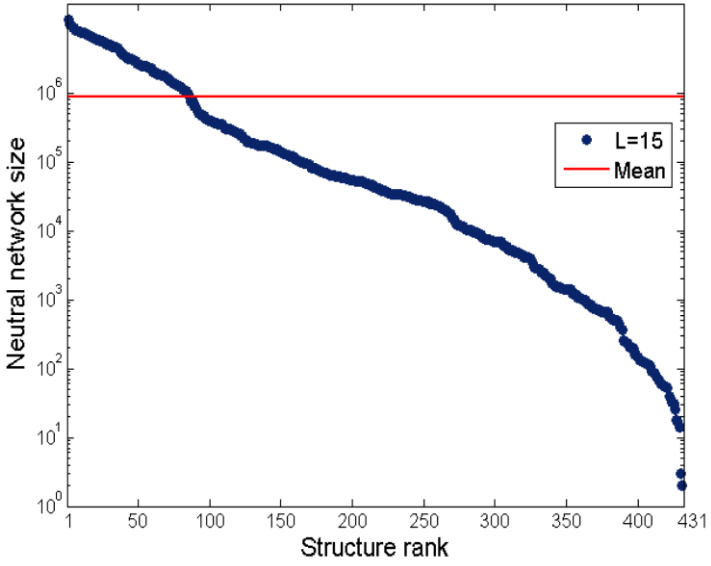
(((((....)))))...

Sequence

Structure

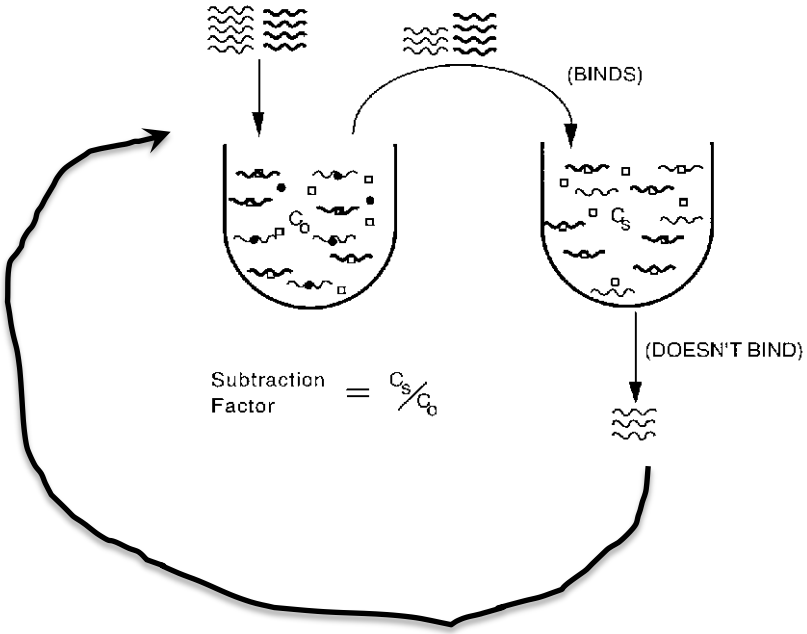
L=15: 4^{15} ~ 1 X 10^9 sequences -- 431 phenotypes – but 26/431 take up 50% of G-s

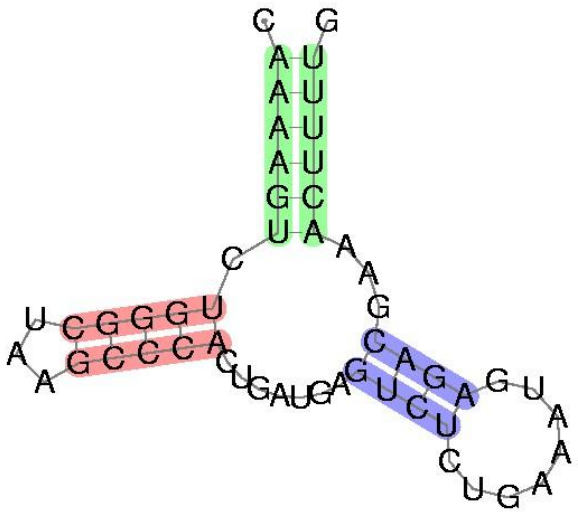




Convergent Evolution?

Hammerhead ribozyme keeps emerging from SELEX in-vitro evolution

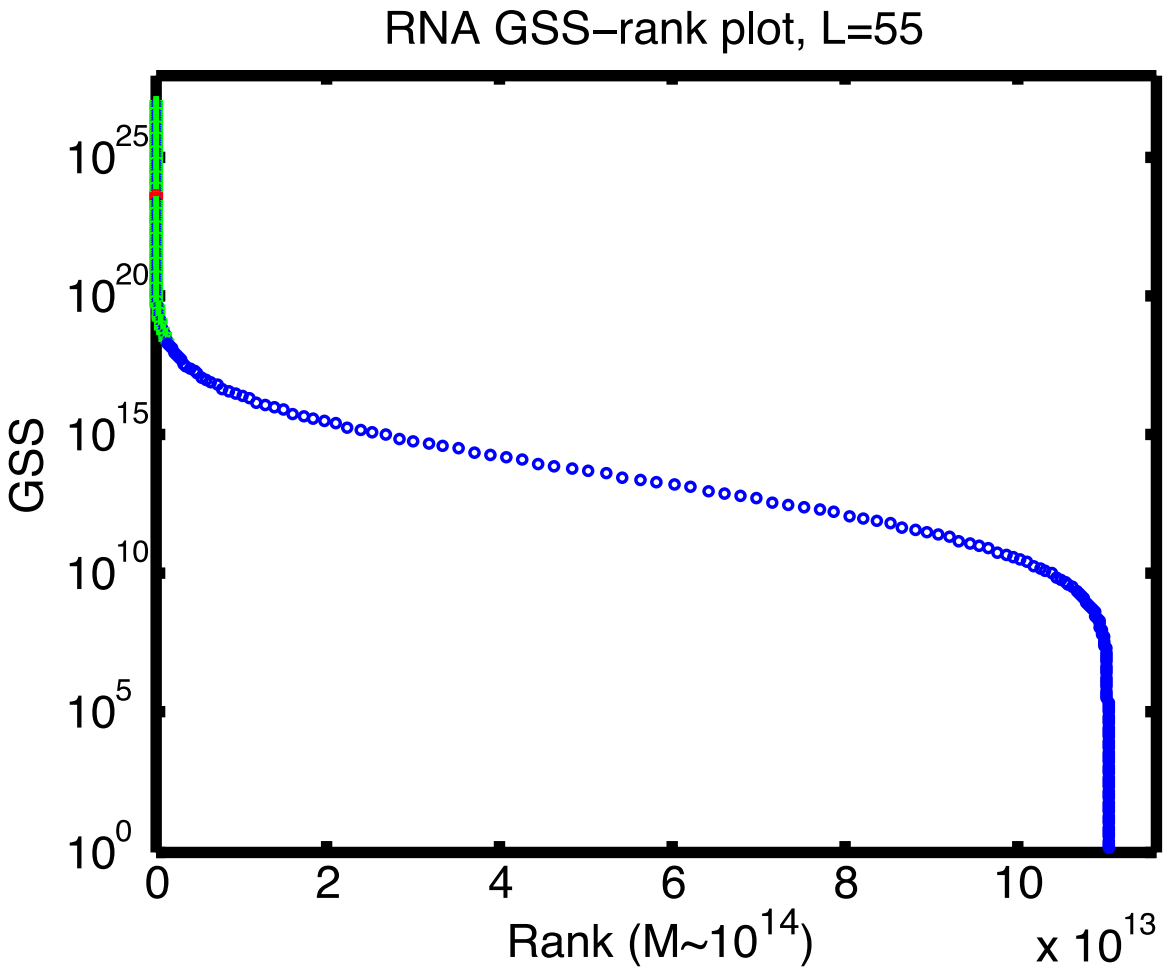




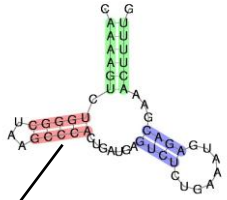
RNA: alphabet of 4 nucleotides, so L=55 means $4^{55} \sim 10^{33}$

Salehi-Ashtiani K, Szostak JW. In vitro evolution suggests multiple origins for the hammerhead ribozyme. Nature. 2001 Nov 1;414(6859):82-4.

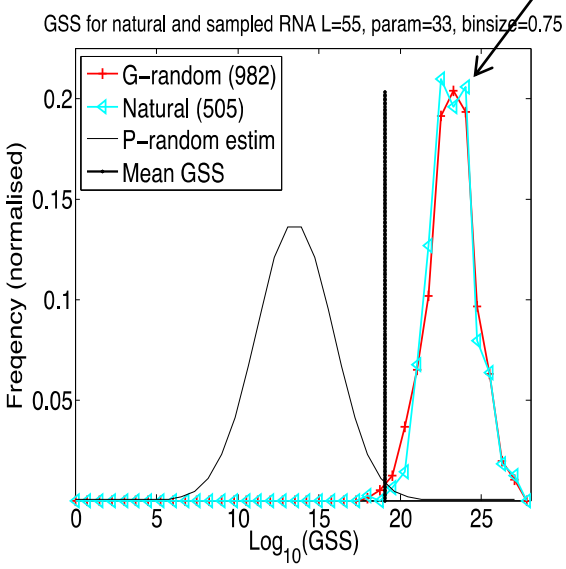
larger RNA?

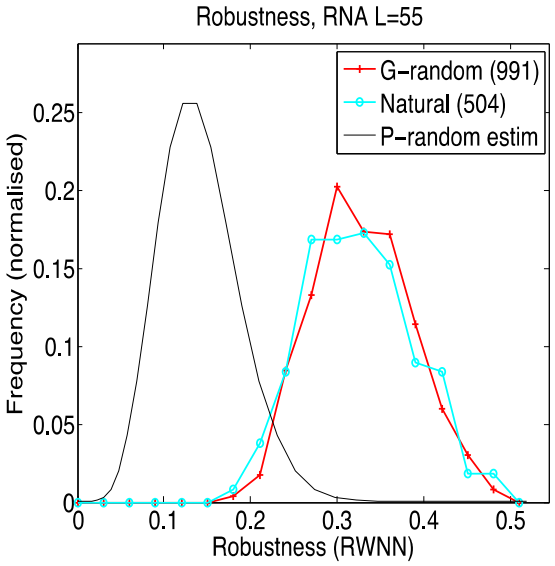

RNA GSS–rank plot, L=55
GSS
10^{25}
10^{20}
10^{15}
10^{10}
10^{5}
10^{0}
0
2
4
6
8
10
Rank (M~10^{14})
x 10^{13}

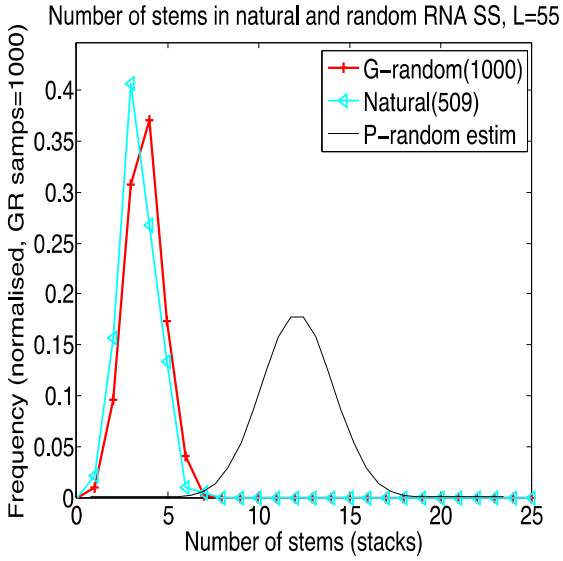
RNA topology dominated by variation



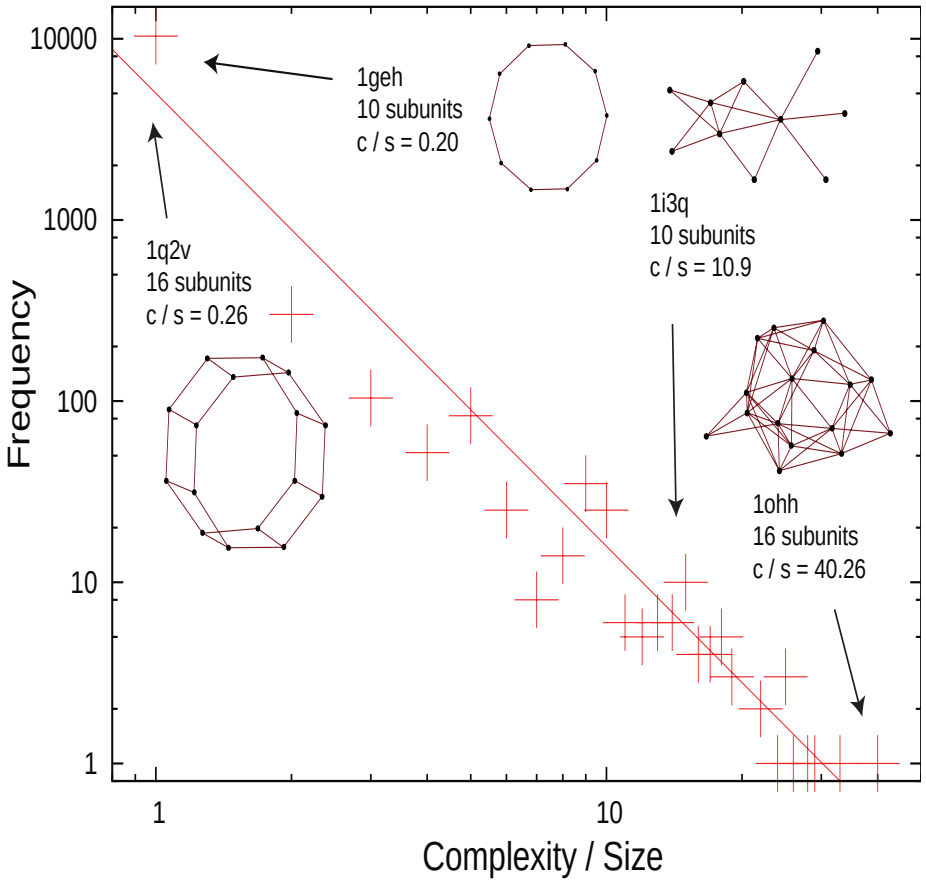
hammerhead ribozyme

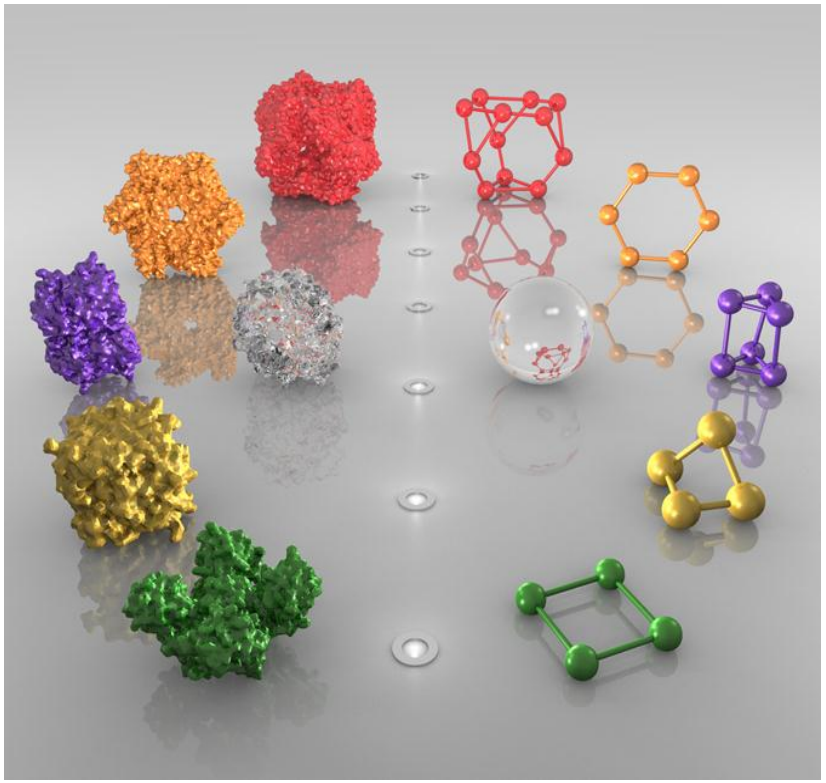






protein quaternary structure





Self-assembly, modularity and physical complexity, S. E. Ahnert, et al., Phys. Rev. E **82,** 026117 (2010),

Proteins self-assemble into quaternary structure

Movie from: Keiichi Namba, Osaka ERATO project

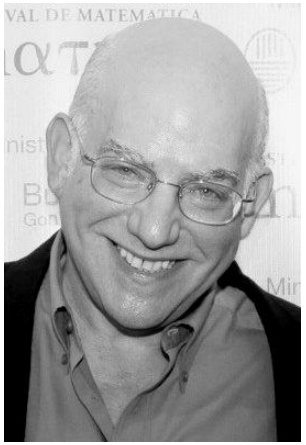
- Can we understand?
  - Assembly
  - Evolution ?
- Can we emulate?

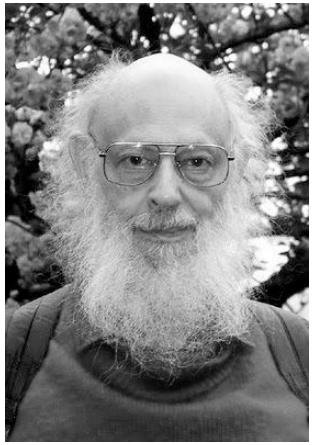
Neutral Space Topology

1) $N_G >> N_P$ (number of genotypes >> number of phenotypes)
2) Genotype set (GS) size per phenotype is highly skewed

Why the skew??

Algorithmic information theory



Kolmogorov complexity K(s) is roughly speaking the length of the shortest computer program in some fixed language L that produces s as an output, minimized over all languages L.

A.N. Kolgomorov 1903-1987

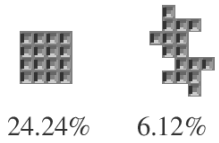
G.J. Chaitin 1947--

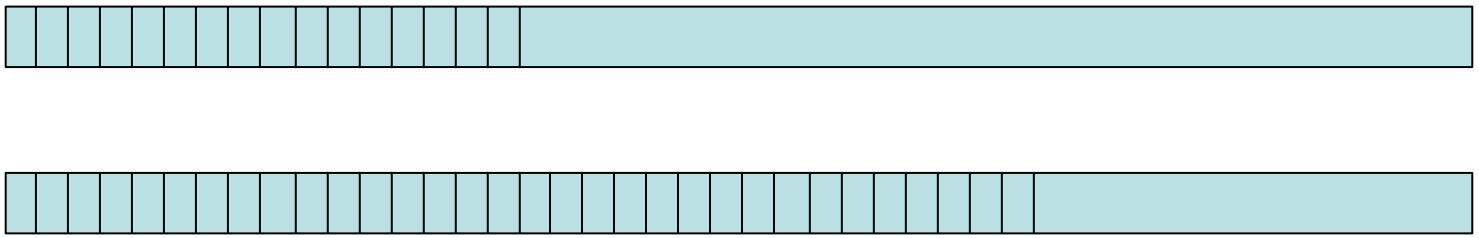
R. Solomonoff 1926-2009

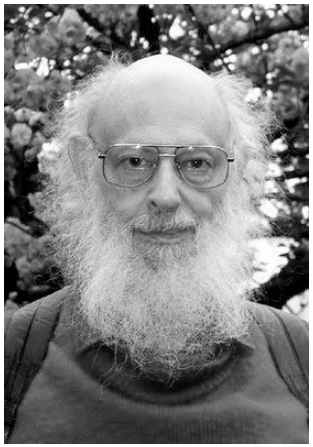
14159265358979323846264338327950288419716939937510582097494459230781640628620899862803482534211706 7

v.s.

01010101010101010101010101010101010101010101010101010101010101010101010101010101010101010101010101010101010101







R. Solomonoff
1926-2009

Universal probability and the algorithmic nature of the world

$$P(x) = \Sigma_l \, 2^{-l} \approx 2^{-k}$$

P(x) = probability that a random sequence, fed into a universal Turning machine, produces the output x

The sum is over all halting programs of length l that produce x

intuitively: simpler outputs are found more often.

Coding Theorem by Solomonoff and Levin.
deep connections to Occam's razor and Bayes priors.

W. Kircher, M. Li, and P. Vitanyi, The Miraculous Universal Distribution, The Mathematical Intelligencer, 19:4, 7–15, 1997.

The Oxford crew …

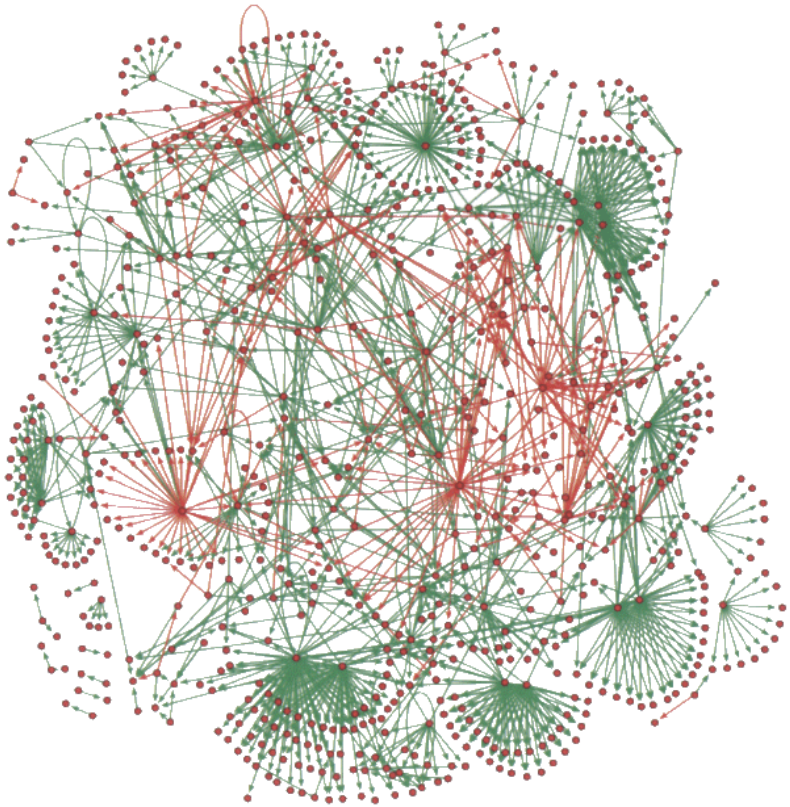
Biological networks: interacting many-body systems

Why are there so few genes?

complexity comes from the interactions (systems biology)

model as networks of differential equations? .

Random Matrix Theory
What are the collective modes?
How do they evolve



transcriptional network for yeast:
Saccharomyces cerevisiae