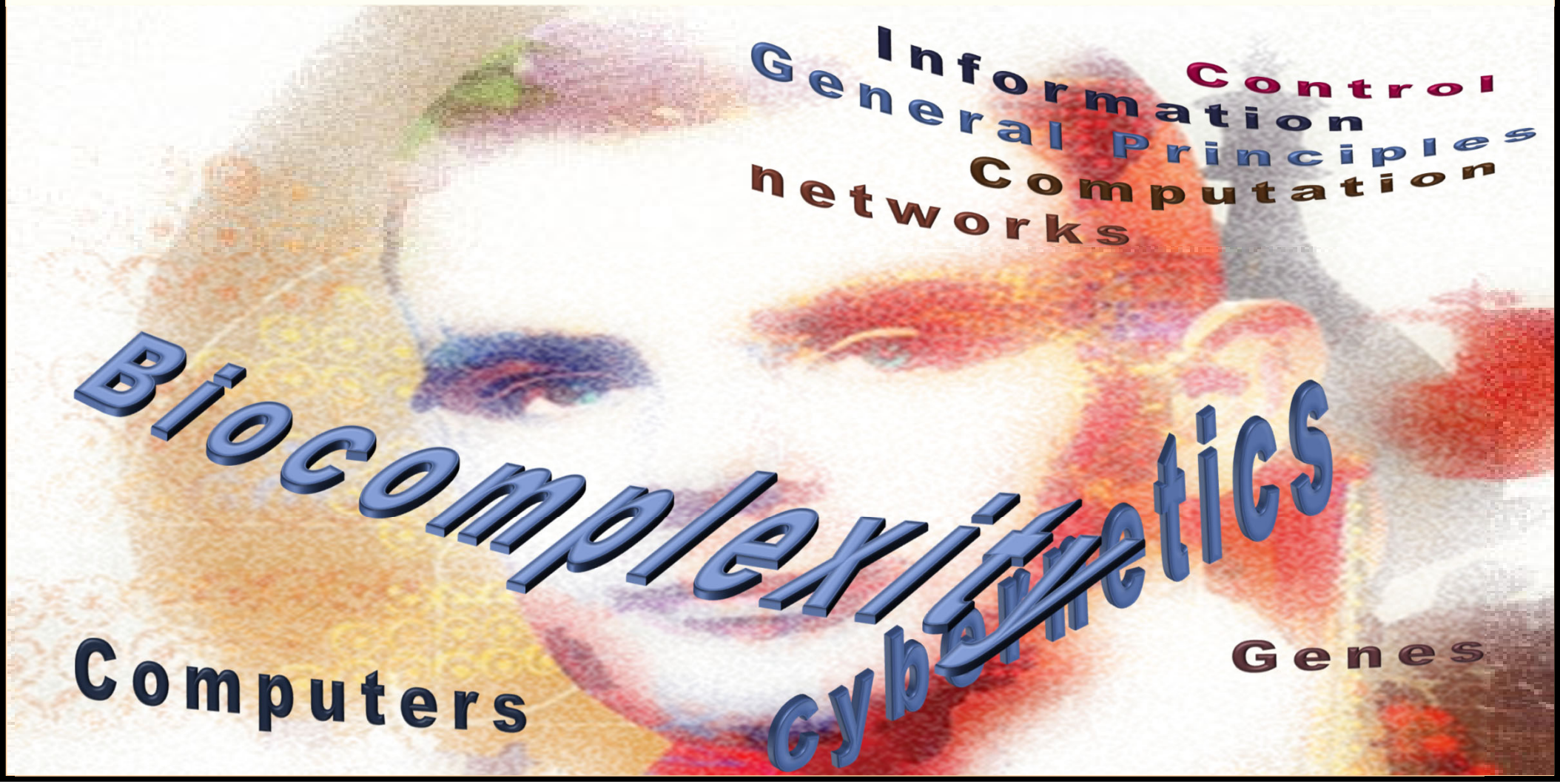
lecture 4: the information turn in the life sciences



differences and explanations

- Evolution
  - adaptation, learning, innovation, social evolution
- Mechanism
  - Reproduction, transmission, variation, selection
- Design causes
  - Natural selection
- explanation?
  - Contingent, historical, context/specific
  - Does not seem lawful

Natural Selection

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path to Darwin

- Evolution by natural selection
  - Organisms vary from one another
  - New variation appears from time to time
  - Variation is passed from parent to offspring
  - “struggle for existence” (limited resources)
- Recognized before Darwin
  - Empedocles (490–430 BC)
    - why animals adapt to environment
  - Lucretius (99 - 55 BC) – Epicurus (341-270 BC)
    - Random evolution, free will
  - Al-Jahiz (781 – 869 AD)
    - on the struggle for existence
  - Thomas Hobbes (XVII)
  - Erasmus Darwin (XVIII)
  - Thomas Malthus (XVIII)
    - Populations grow exponentially, re
  - Charles Lyell (XIX)
    - Gradual change in geological lands
  - Jean-Baptiste Lamarck (XIX)
    - Mechanism: mutation and (acquire
  - Alfred Russel Wallace
    - Reached same conclusion as Darv
  - Charles Darwin
    - Evolution, **inevitable**

(Cosma Shalizi citing Aristotle citing) Empedocles:
A difficulty presents itself: why should not nature work, not for the sake of something, nor because it is better so, but just as the sky rains, not in order to make the corn grow, but of necessity? What is drawn up must cool, and what has been cooled must become water and descend, the result of this being that the corn grows. Similarly if a man's crop is spoiled on the threshing-floor, the rain did not fall for the sake of this--in order that the crop might be spoiled--but that result just followed. Why then should it not be the same with the parts in nature, e.g. that teeth should come up of necessity -- the front teeth sharp, fitted for tearing, the molars broad and useful for grinding down the food -- since they did not arise for this end, but it was merely a coincident result; and so with all other parts in which we suppose that there is purpose? **Wherever then all the parts came about just what they would have been if they had come be for an end, such things survived, being organized spontaneously in a fitting way; whereas those which grew otherwise perished and continue to perish**, as Empedocles says his 'man-faced ox-progeny' did.

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  - Thomas Ho
  - Erasmus Da
  - Thomas Ma
    - Populatio
  - Charles Lye
    - Gradual c
  - Jean-Baptis
    - Mechanis
  - Alfred Russ
    - Reached same conclusion as Darwin (with less evidence)
  - Charles Darwin
    - Evolution, **inevitable**

Lucretius and Epicurism (translated by Stephen Greenblatt):
"... moving randomly through space, like dust motes in a sunbeam, colliding, hooking together, forming complex structures, breaking apart again, in a ceaseless process of creation and destruction. There is no escape from this process. ... There is no master plan, no divine architect, no intelligent design. […] All things, including the species to which you belong, have evolved over vast stretches of time. The **evolution is random**, though in the case of living organisms, it involves **a principle of natural selection**. That is, **species that are suited to survive and to reproduce successfully, endure, at least for a time; those that are not so well suited, die off quickly**. But nothing — from our own species, to the planet on which we live, to the sun that lights our day — lasts forever. Only the atoms are immortal ..."

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  - Alfred Russel Wallace
    - Reached same conclusion as Darwin (with less evidence)
  - Charles Darwin
    - Evolution, **inevitable**

"I happened to read for amusement Malthus on population, and being well prepared to appreciate the struggle for existence…it at once struck me that under these circumstances favourable variations would tend to be preserved, and unfavourable ones to be destroyed. The result of this would be the formation of new species." [Charles Darwin]

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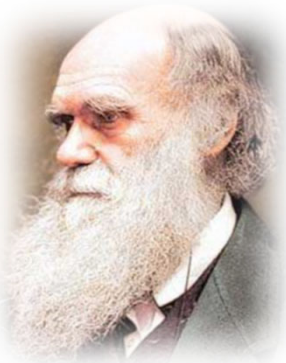
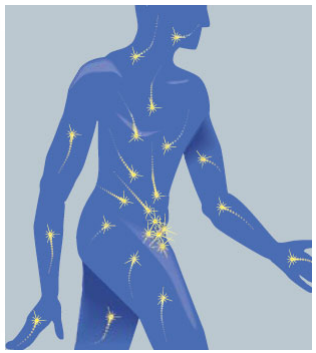
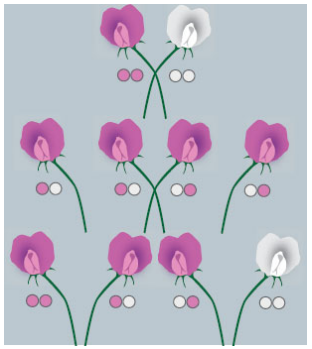
Inheritance mechanism

- XIX Century
  - Evolution of species quickly accepted
  - Natural selection as most important engine of change, was not
    - What was the mechanism?
- Jean-Baptiste Lamarck (XIX)
  - mutation and (acquired) inheritance
- Charles Darwin
  - "gemules" ejected from each tissue and traveling to sex organs
- Gregor Mendel
  - discrete factors corresponding to traits
  - Each individual would carry two copies (one from each parent), but only one would be "expressed"
- "Synthesis" only in the XX century







Sci. American, Jan 2009

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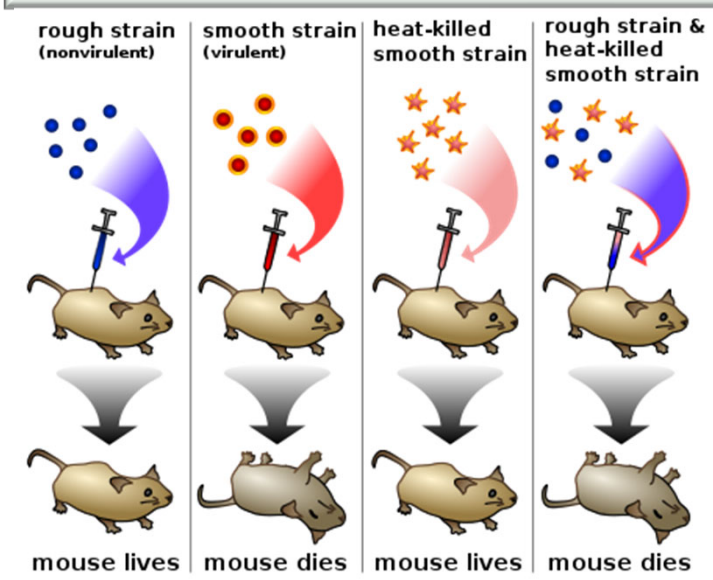
identifying the loci of genetic information

- Frederick Griffith's experiment
  - In 1928: Identified a "transforming principle"
- Avery's experiment
  - Oswald Avery, Colin MacLeod, and Maclyn McCarty
  - 1944: DNA as the loci of "transformation"
    - Chemically knocking off various cellular constituents until trying DNA
    - Considerable resistance in the community accepting this result until the early 1950's (Schrodinger, Delbruck, phage group)



initially not
well accepted
(No auto-catalysis with DNA)

2 different strains
of pneumococcus
bacteria

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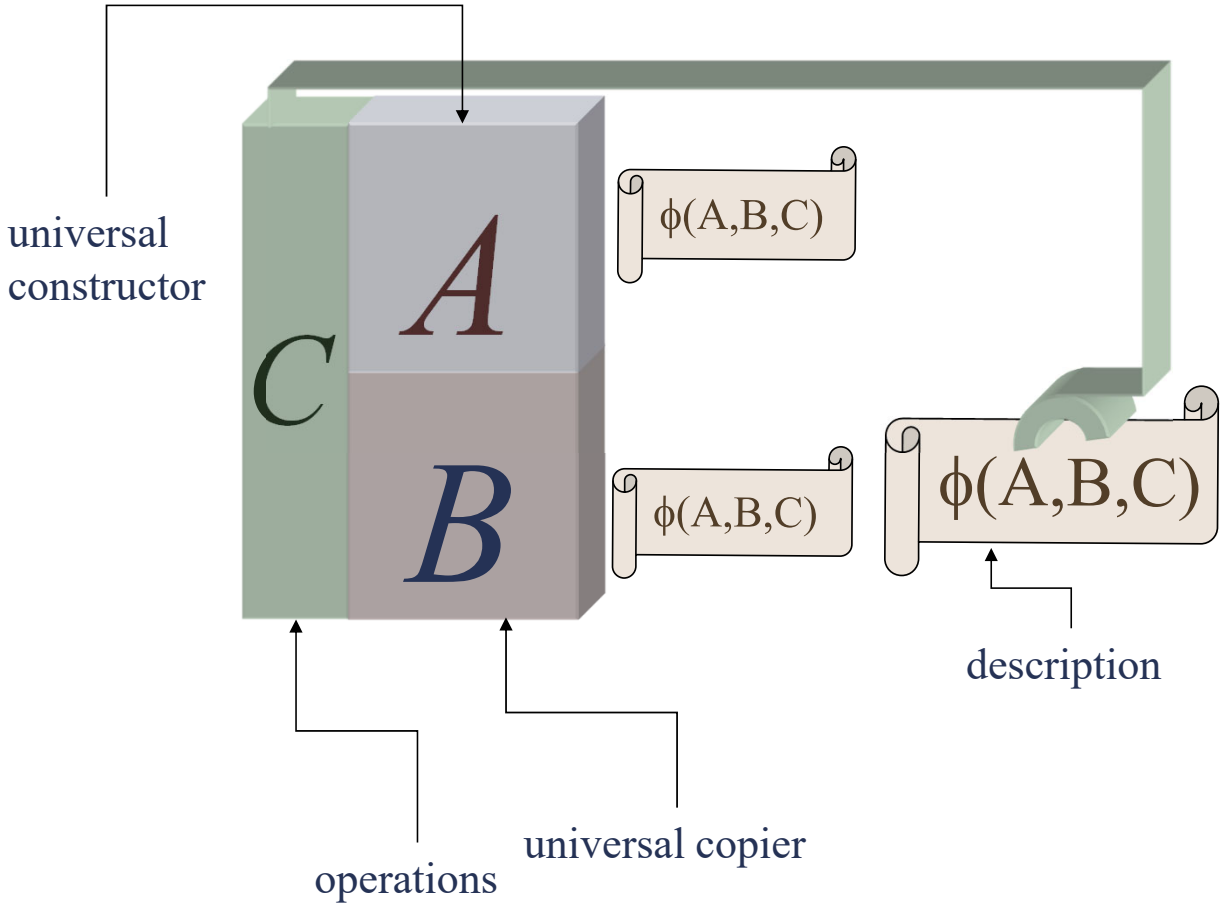
Von Neumann's generalization of Turing's tape

as a general principle (system) of **self-replication**

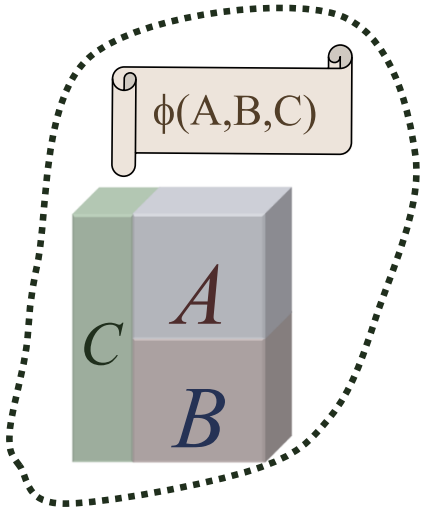


Description is copied **separately**

Construction: interpreted
(horizontal transmission)

Copy: uninterpreted
(vertical Transmission)

code



distinction between *numbers that mean things*
and *numbers that do things*.

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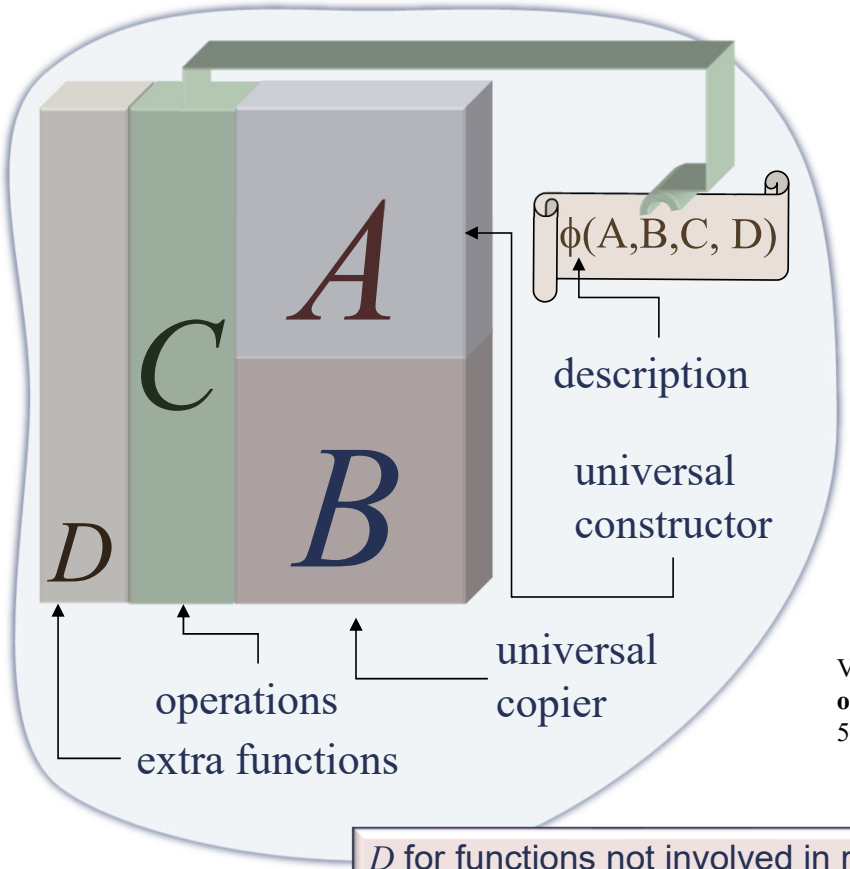
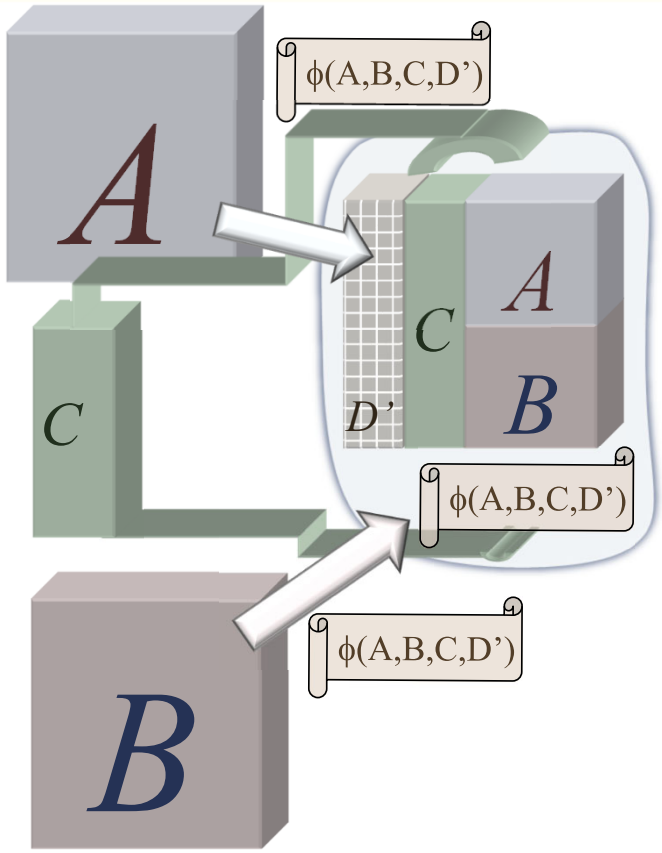
Von Neumann's generalization of Turing's tape

as a general principle (system) of evolution or **open-ended complexity**



Von Neumann, J. [1949]. "**Theory and organization of complicated automata**." 5 lectures at University of Illinois



D for functions not involved in reproduction
Mutations in *D* can be propagated *vertically*
Leads to **open-ended evolution**

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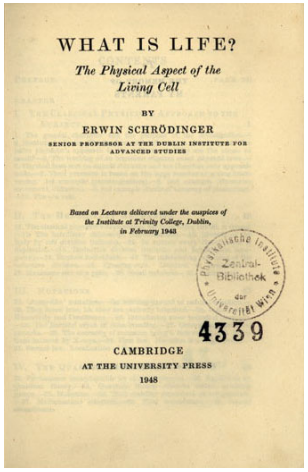
Erwin Schrödinger(1943-1944)



- puzzled by the persistence of living structures
  - Call to understand how life stores and perpetuates order
  - "[…] **chromosomes**[…] contain in some kind of **code-script** the entire pattern of the individual's future development."
    - "complete (double) copy of the code-script."
- **aperiodic crystals as structures that can replicate themselves**
  - "We believe a gene—or perhaps the whole chromosome **fiber**—to be an aperiodic solid."
    - "structure without predictable repetition"
  - DNA is entirely regular
    - Instead of "aperiodicity" we have **encoded information**: separated description/construction

"Turing invented the stored-program computer, and von Neumann showed that the description is separate from the universal constructor. This is not trivial. Physicist Erwin Schrödinger confused the program and the constructor in his 1944 book *What is Life?,* in which he saw chromosomes as "*architect's plan and builder's craft in one*". This is wrong. The code script contains only a description of the executive function, not the function itself." (Sydney Brenner)

Brenner, Sydney. [2012]. "Life's code script." *Nature* **482** (7386): 461-461.

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Schrodinger vs. Von Neumann

self-replication vs. decoupled, encoded information

Von Neumann, J. [1949]. "**Theory and organization of complicated automata**." 5 lectures at University of Illinois

Brenner, Sydney. [2012]. "Life's code script." *Nature* **482** (7386): 461-461.

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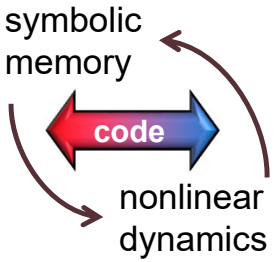
two roles of information
data/program (Turing)
passive/active (Von Neumann)
description/construction-function (Pattee)
genotype/phenotype (Biology)

semiotic closure (semiotic coupling)

fundamental principle of *organized complexity*
Leads to **open-ended evolution**
General principle that includes *Natural Selection*
Von Neumann described this scheme **before** structure of DNA molecule was identified in 1953 by Watson & Crick



Howard Pattee

Pattee, HH [2001] *Biosystems* **60** (1):5-21

Rocha, L.M. & W. Hordijk [2005] *Artificial Life* **11**:189 - 214.
Rocha, L.M. [2001] *Biosystems* **60**: 95-121.
Rocha, L.M. [1996] *Systems Research* **13**: 371-384.

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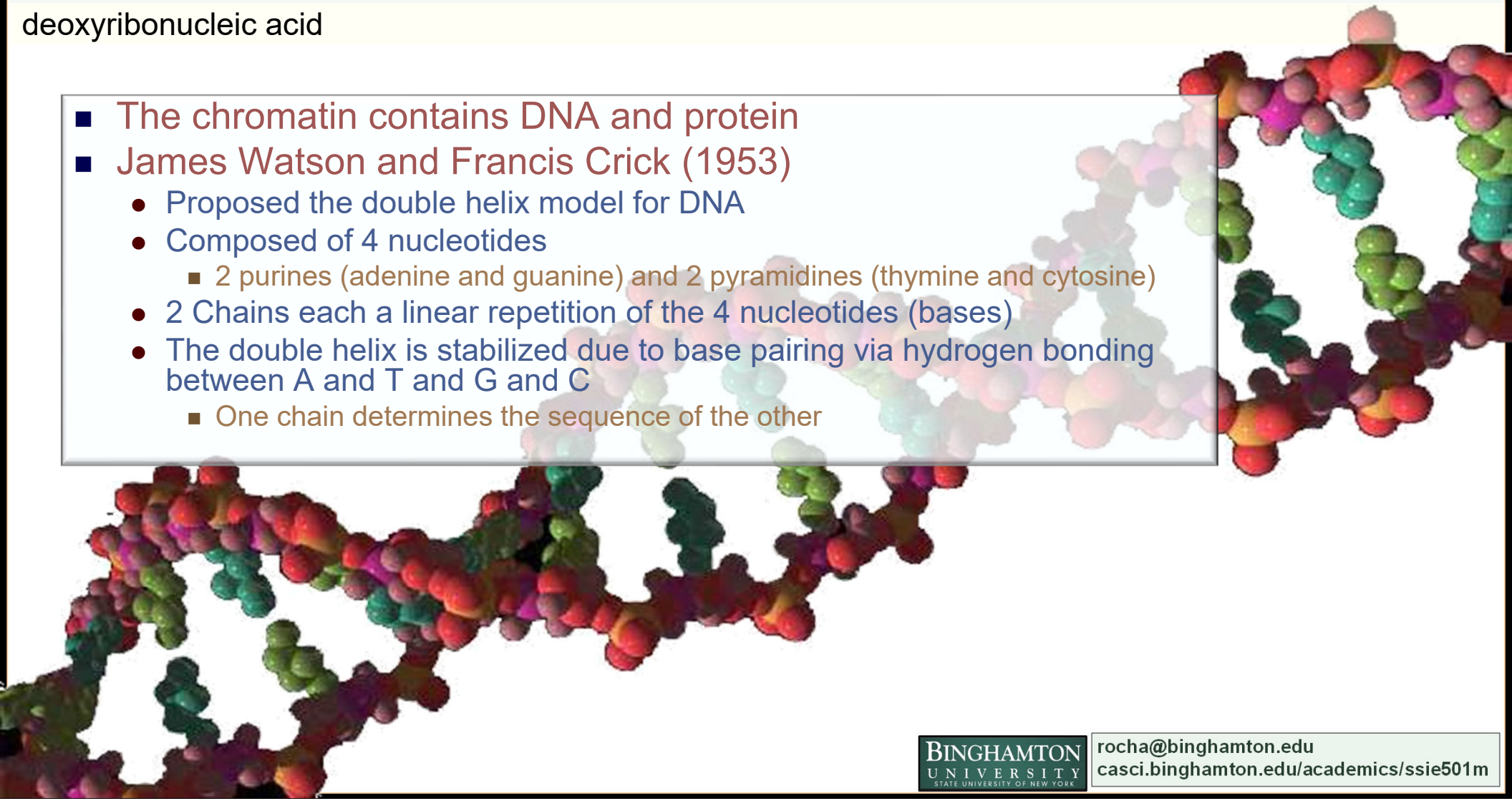
deoxyribonucleic acid

- The chromatin contains DNA and protein
- James Watson and Francis Crick (1953)
  - Proposed the double helix model for DNA
  - Composed of 4 nucleotides
    - 2 purines (adenine and guanine) and 2 pyramidines (thymine and cytosine)
  - 2 Chains each a linear repetition of the 4 nucleotides (bases)
  - The double helix is stabilized due to base pairing via hydrogen bonding between A and T and G and C
    - One chain determines the sequence of the other



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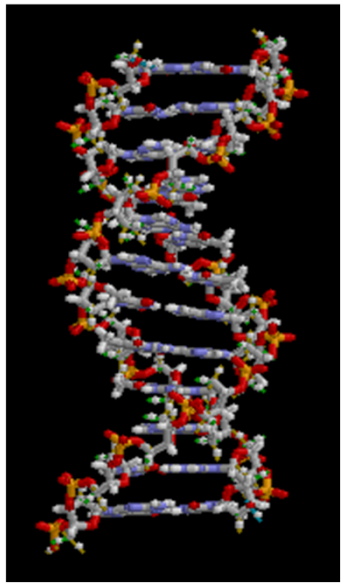
a molecular language system: nucleotide “bases” (the genotype “tape”)



Purine (R) → Adenine (A), Guanine (G)

Nucleotides

Pyrimidine (Y) → Cytosine (C), Thymine (T), Uracil (U)

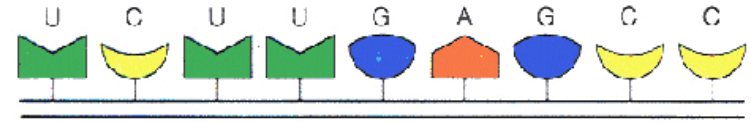
4 Letter Alphabet
DNA: A, G, C, T
RNA: A, G, C, U

Form sequences that can store information

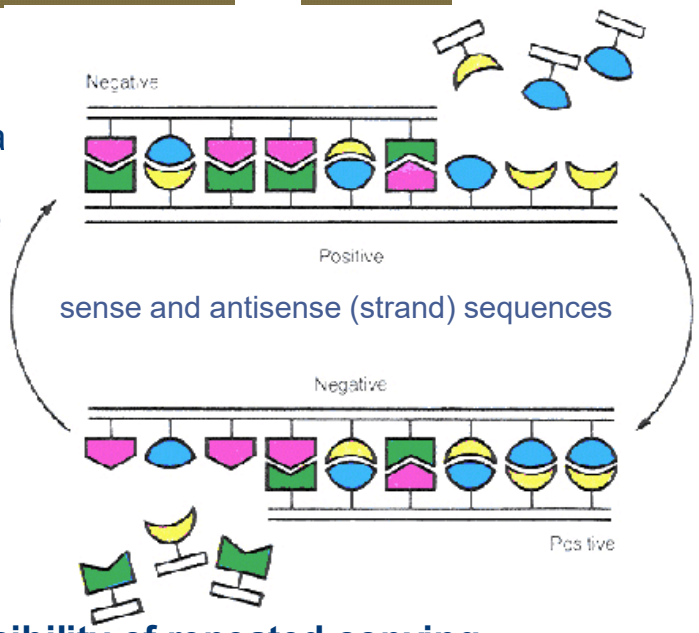
Linear molecules with a phosphate-sugar backbone (deoxyribose and ribose)

Complementary base pairing
(Hydrogen-bonding between purines and pyrimidines)

A-T (U) G-C



Figures from Eigen [1992] . *Steps Towards Life*.



Requirements for structural information

Possibility of repeated copying

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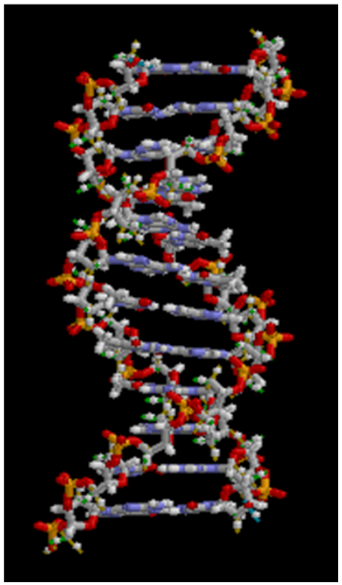

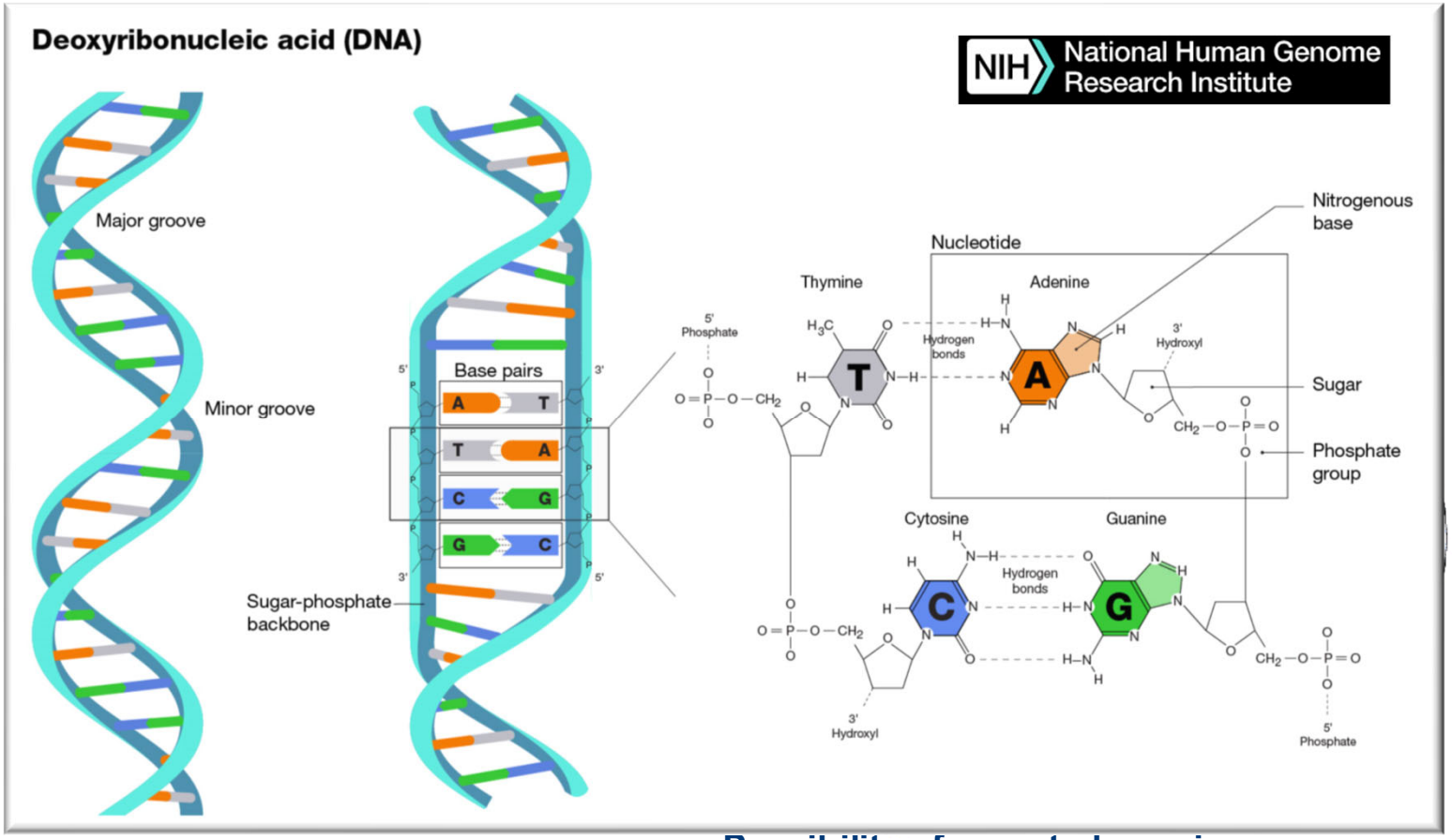

Possibility of repeated copying

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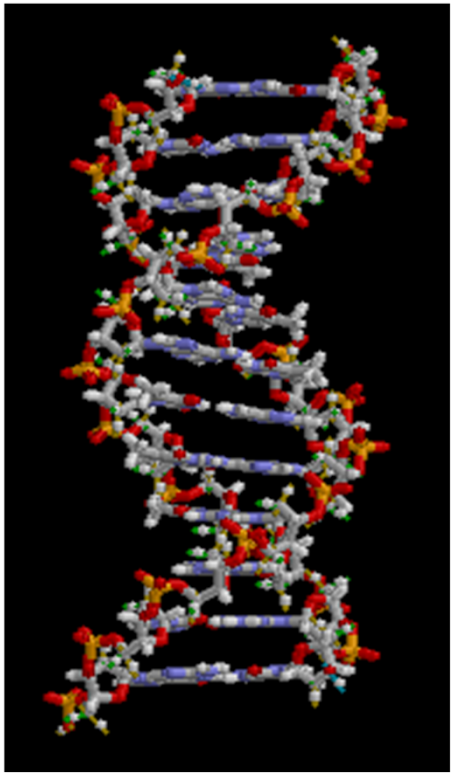
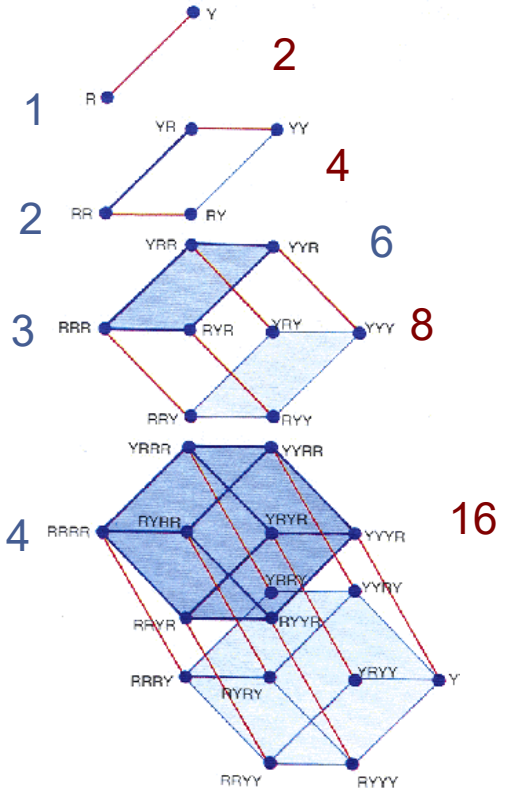
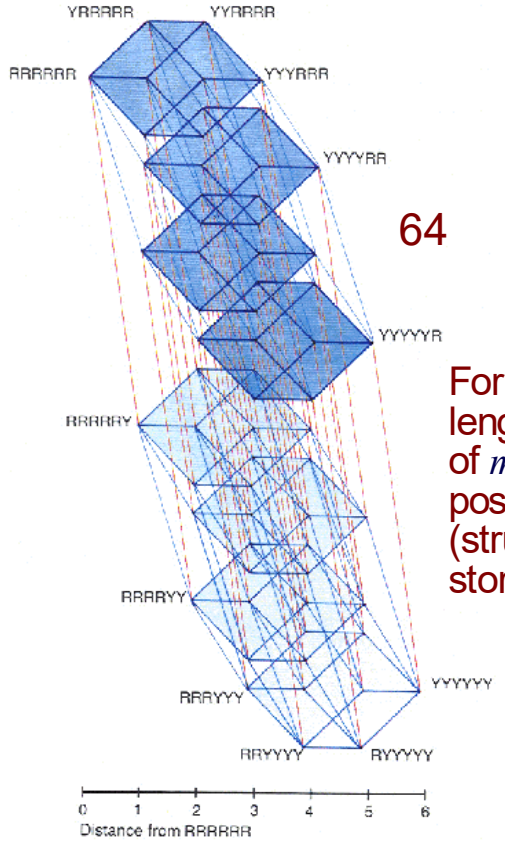
the genotype “tape” encodes an enormous amount of information







For a sequence of length n, composed of m-ary symbols, m^n possible values (structures) can be stored

Figures from Eigen [1992] . *Steps Towards Life*.

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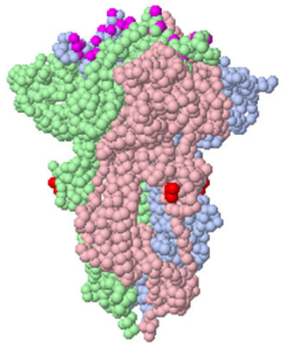
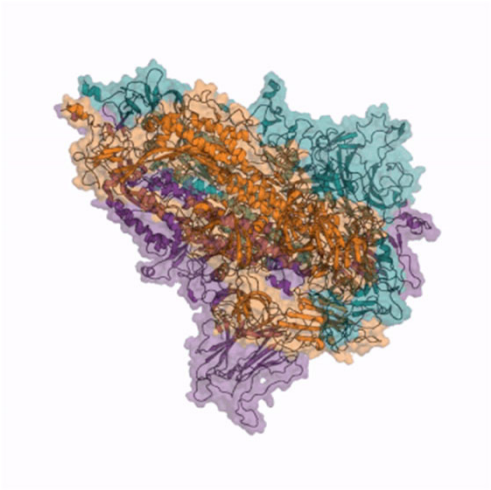
functional products that build up (self-organize) the phenotype





Polypeptide chains of aminoacids

Primary Structure

Folding

3-dimensional structure

Secondary and tertiary bonds

- In proteins, it is the 3-dimensional structure that dictates function
  - The specificity of enzymes to recognize and react on substrates
- The functioning of the cell is mostly performed by proteins
  - Though there are also ribozymes

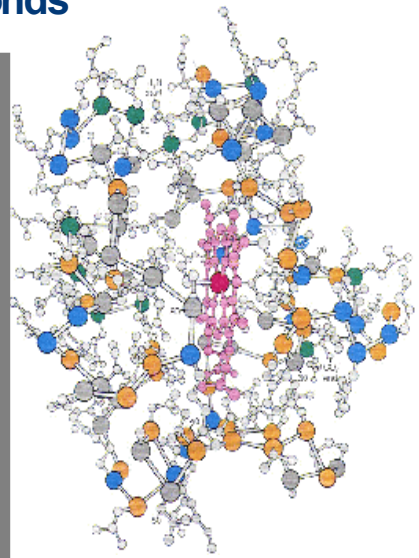


Table 1.4. Amino acid codes

Ala	A	Alanine
Arg	R	Arginine
Asn	N	Asparagine
Asp	D	Aspartic acid
Cys	C	Cysteine
Gln	Q	Glutamine
Glu	E	Glutamic acid
Gly	G	Glycine
His	H	Histidine
Ile	I	Isoleucine
Leu	L	Leucine
Lys	K	Lysine
Met	M	Methionine
Phe	F	Phenylalanine
Pro	P	Proline
Ser	S	Serine
Thr	T	Threonine
Trp	W	Tryptophan
Tyr	Y	Tyrosine
Val	V	Valine
Asx	B	Asn or Asp
Glx	Z	Gln or Glu
Sec	U	Selenocysteine
Unk	X	Unknown

Figures from Eigen [1992] . *Steps Towards Life*.

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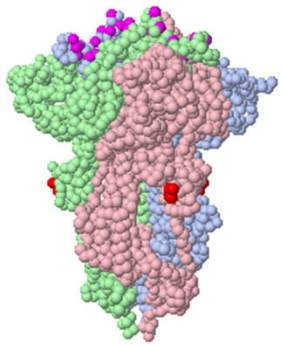
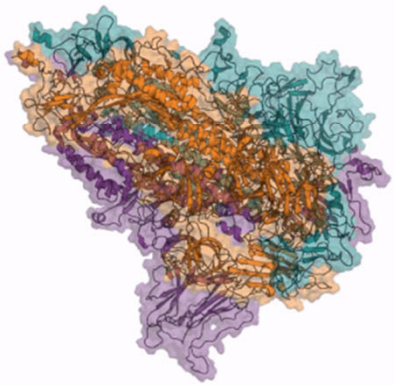
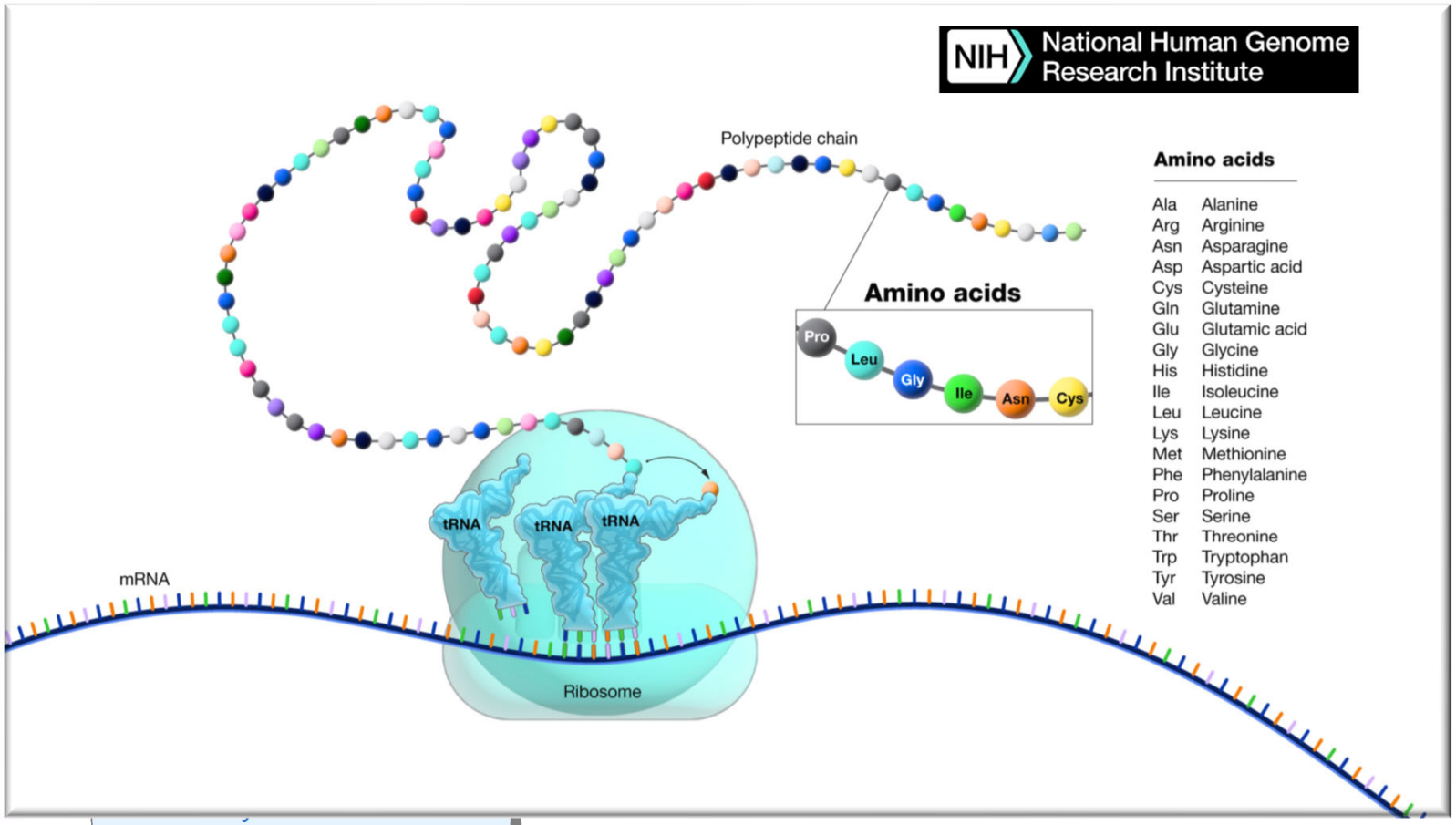
functional products that build up (self-organize) the phenotype



Jmol





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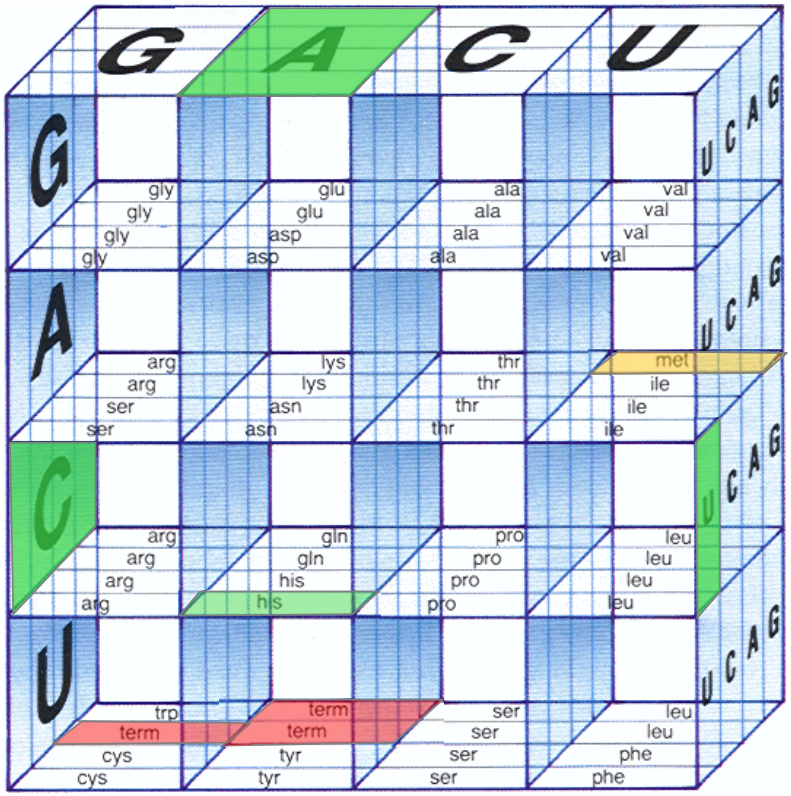
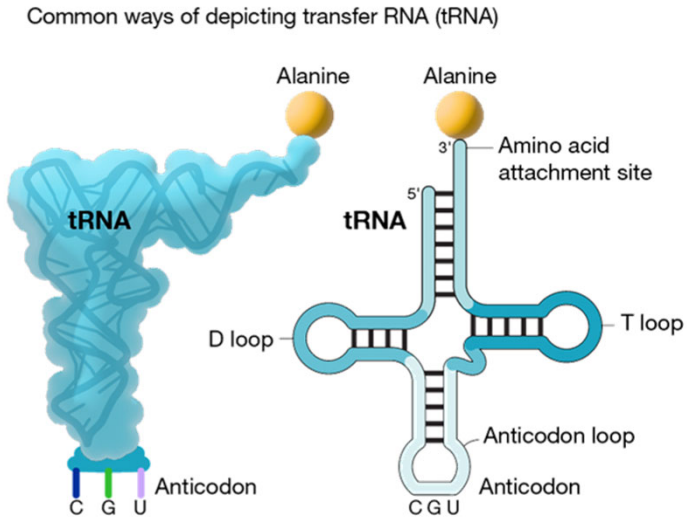
between genotype and phenotype

Triplets of 3 Nucleotides can define 64 possible codons, but only 20 amino acids are used (redundancy)



Figures from Eigen [1992] . *Steps Towards Life*.

- The genetic code maps information stored in the genome into functional proteins
  - Triplet combinations of nucleotides into amino acids



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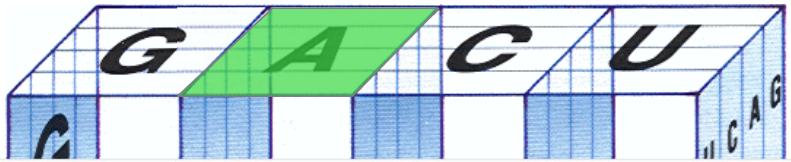
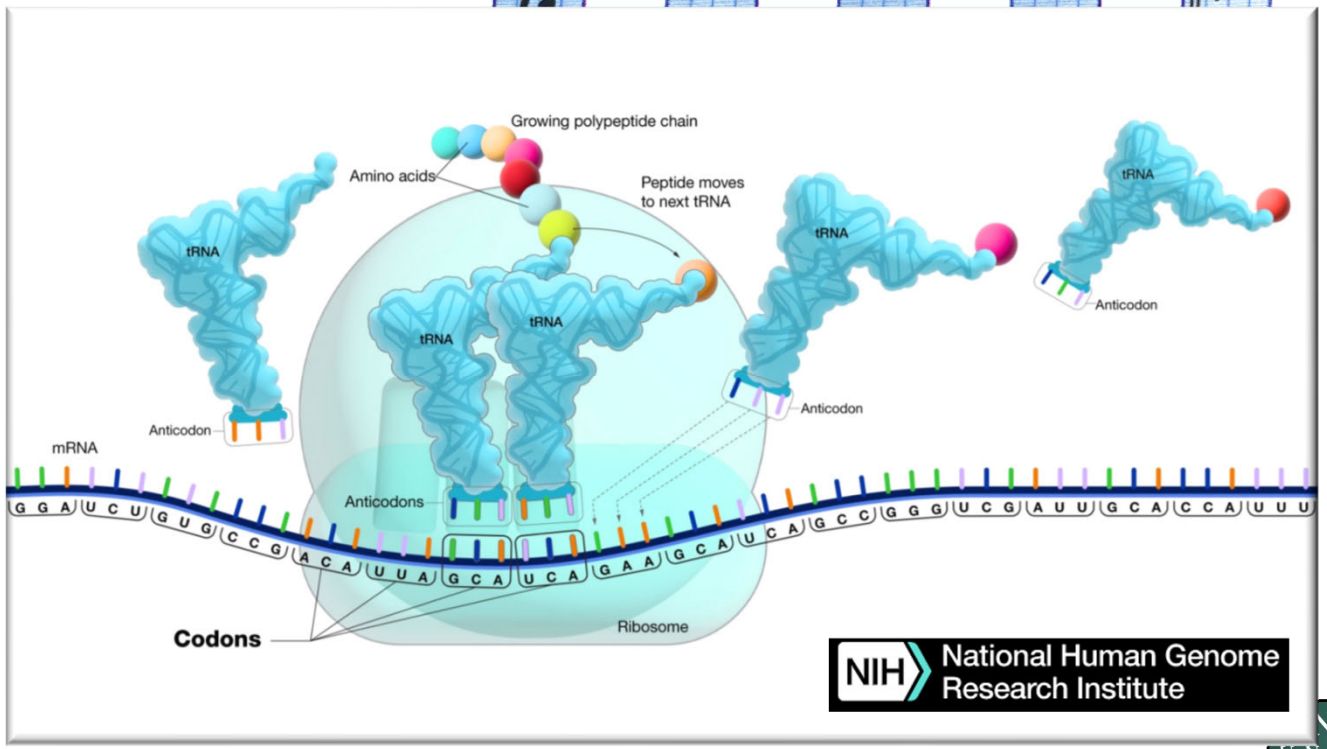


- The genetic code maps information stored in the genome into functional proteins
  - Triplet combinations of nucleotides into amino acids



Purine (R) → Adenine (A), Guanine (G)

Nucleotides

Pyrimidine (Y) → Cytosine (C), Thymine (T), Uracil (U)

4 Letter Alphabet
DNA: A, G, C, T
RNA: A, G, C, U

Linear molecules w phosphate-sugar

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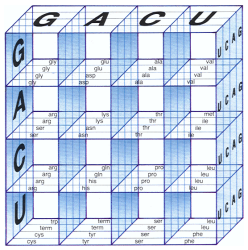
semiotic closure: genetic information at work

genotype/phenotype



Genotype

DNA

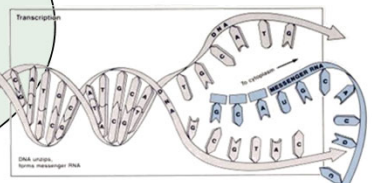
Memory

C

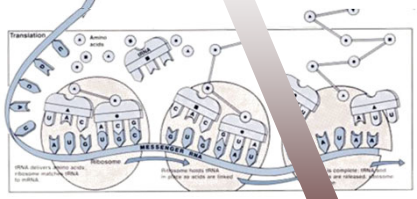
syntax

transcription

RNA

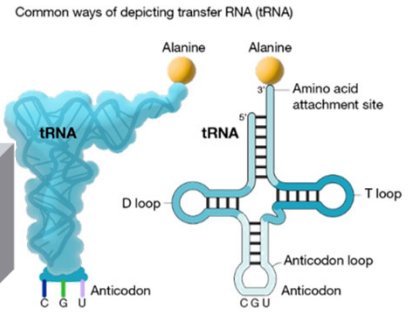


translation



code

A



semantics

C

replication

B

Inherited variation

selection

amino acid chains

Development, regulation

pragmatics

Germ cell line

D

environmental ramifications

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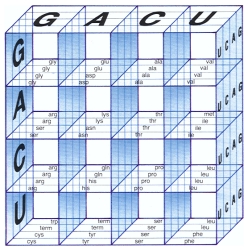

Genotype

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cation

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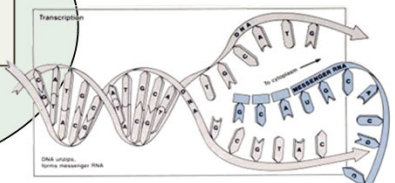
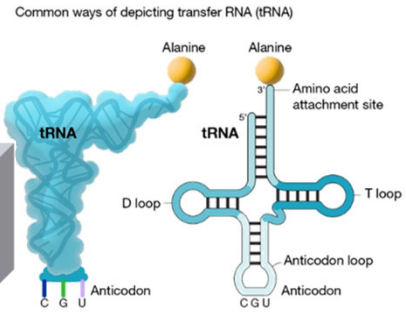


RNA

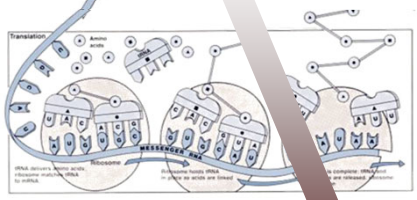
translation

code

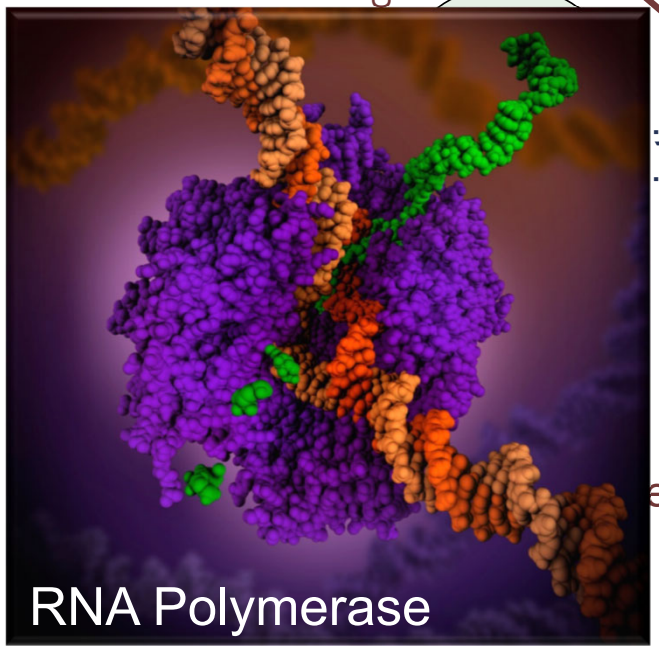
A



semantics



amino acid chains



RNA Polymerase

variation

selection

Development

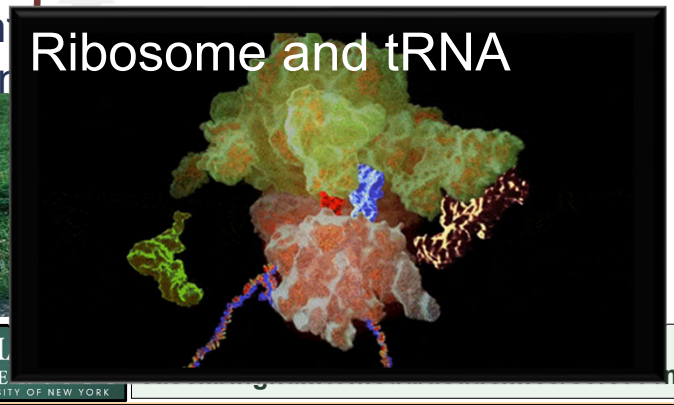
regulation

pragmatics

ell line

D

environmental ramifications



Ribosome and tRNA

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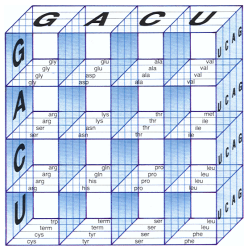
semiotic closure: genetic information at work

genotype/phenotype



C

Genotype

DNA

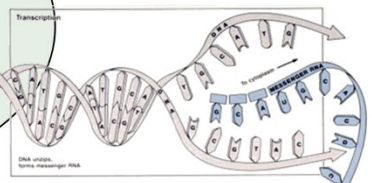
Memory

C

syntax

transcription

RNA



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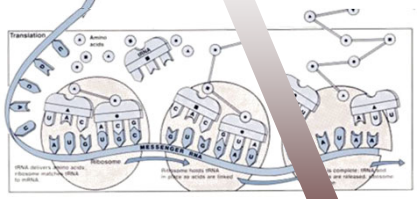

code

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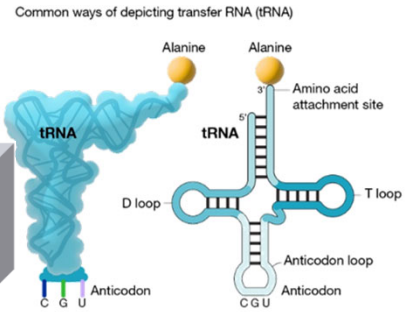

semantics

replication

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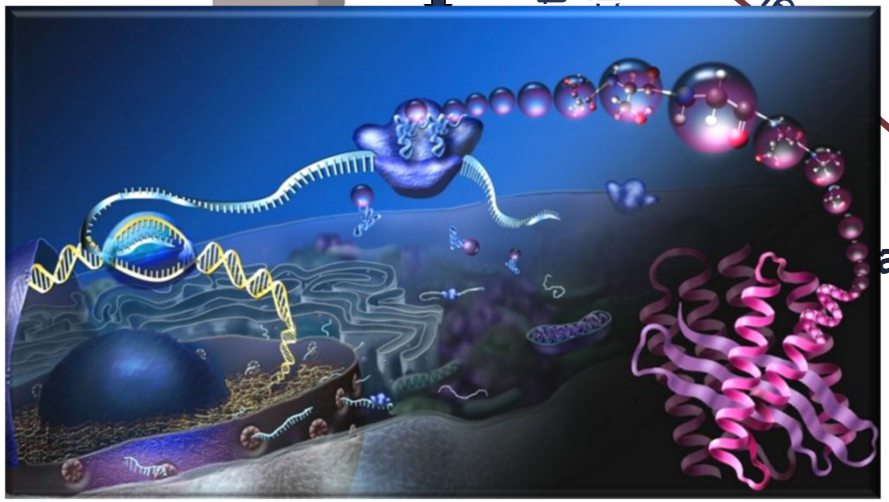

atics

amino acid chains

Development, regulation

D

environmental ramifications

phenotype

organism

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genotype/phenotype

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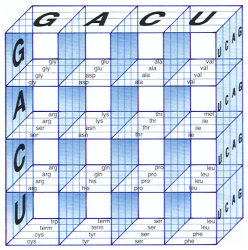

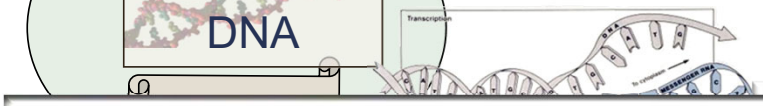

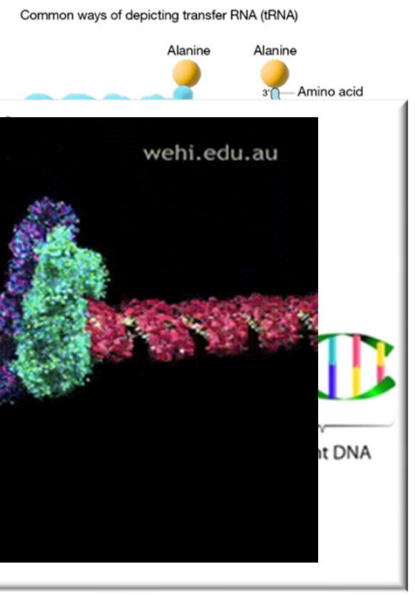

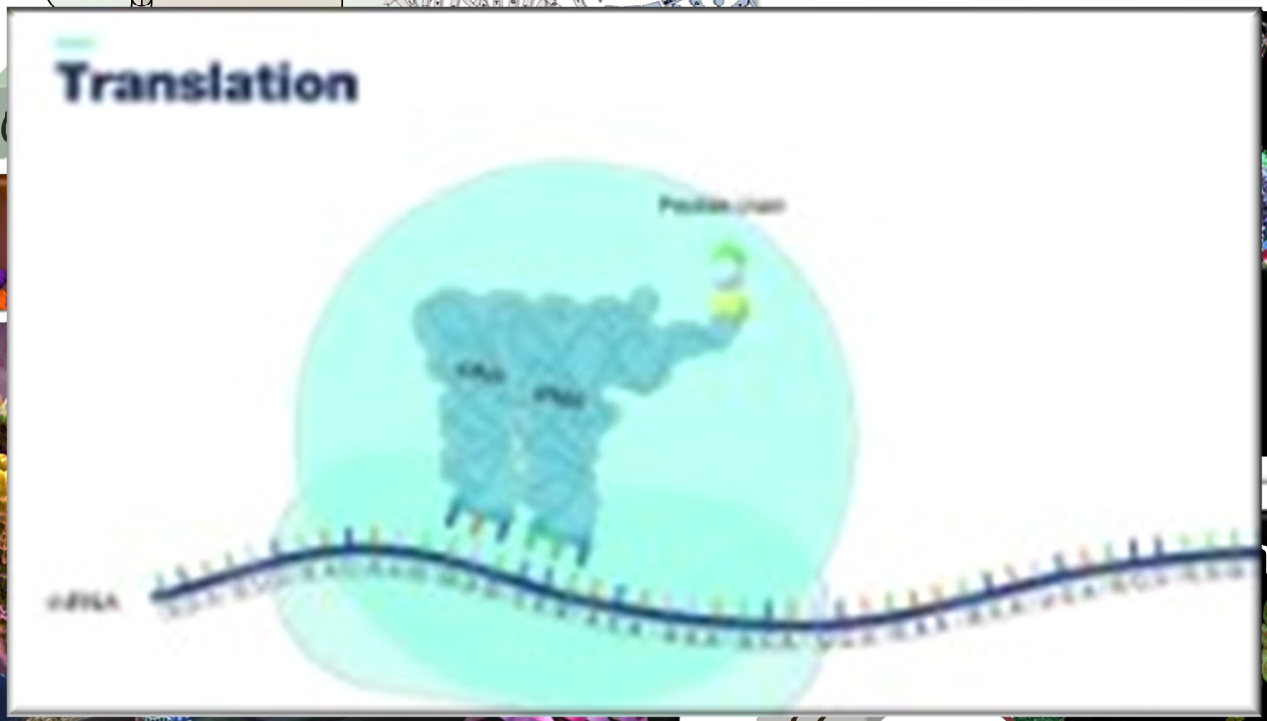

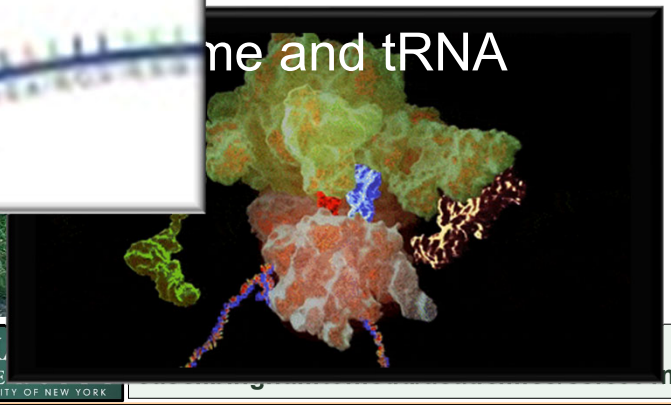

environmental ramifications

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importance of the “external tape”

in biology

- The “information turn”
  - Unlike Schrödinger, Turing and Von Neumann had no direct effect on molecular biology
  - But the “external tape” separated from the constructor (semiotic closure) has become an unavoidable **principle of organization of biocomplexity**
  - A new synthesis?
    - In 1971 Brenner: “in the next twenty-five years we are going to have to teach biologists another language still, […] where a science like physics works in terms of laws, or a science like molecular biology, to now, is stated in terms of mechanisms, maybe now what one has to begin to think of is algorithms. Recipes. Procedures.”

“The concept of the gene as a symbolic representation of the organism — a ***code script*** — is a fundamental feature of the living world and must form the kernel of biological theory. […] at the core of everything are the tapes containing the descriptions to build these special Turing machines.” (Sydney Brenner)

Brenner, Sydney. [2012]. “Life’s code script.” *Nature* **482** (7386): 461-461.

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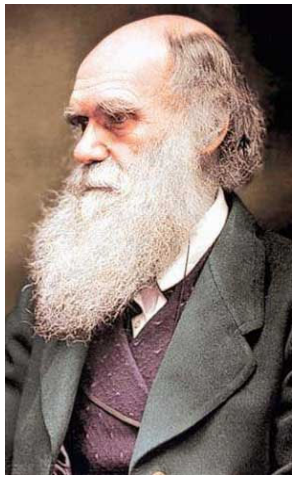
fundamental principle of organisms as *cybernetic mechanisms*



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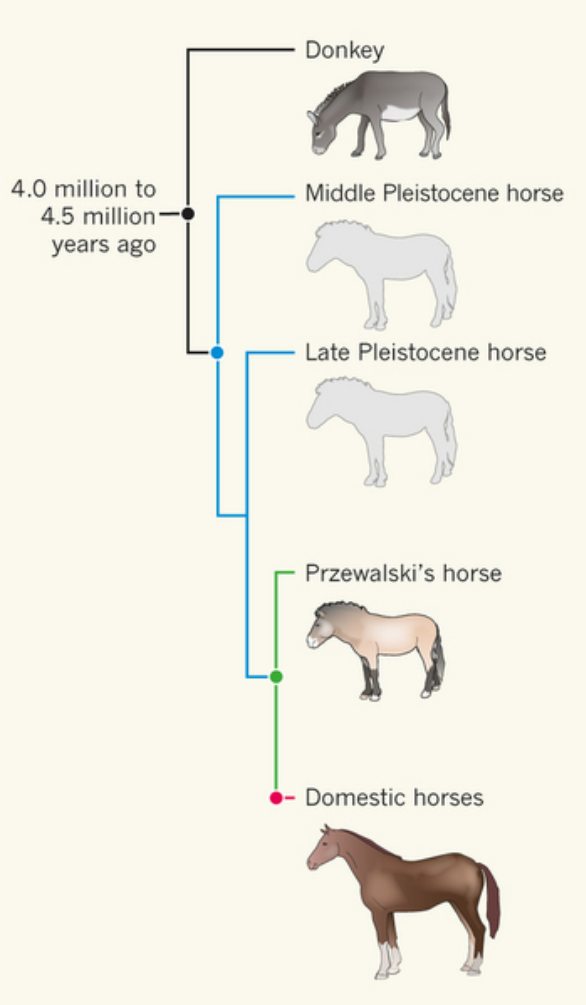
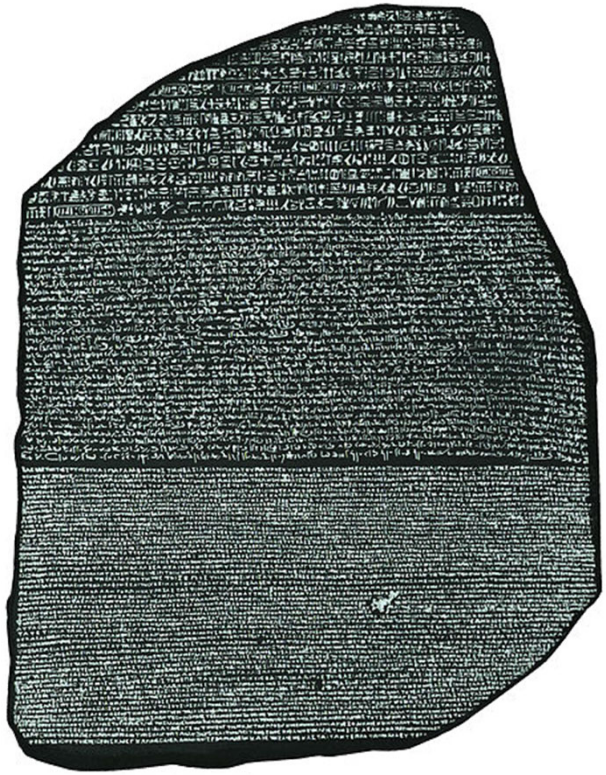
decoupled information



Millar & Lambert [2013]. "Ancient DNA: Towards a million-year-old genome." *Nature*. **doi:10.1038/nature12263**

Orlando, L. et al. [2013] *Nature* **doi.org/10.1038/nature12323**

What other components of life can be ***fossilized*** and ***recovered*** with biochemical reproducibility this way?



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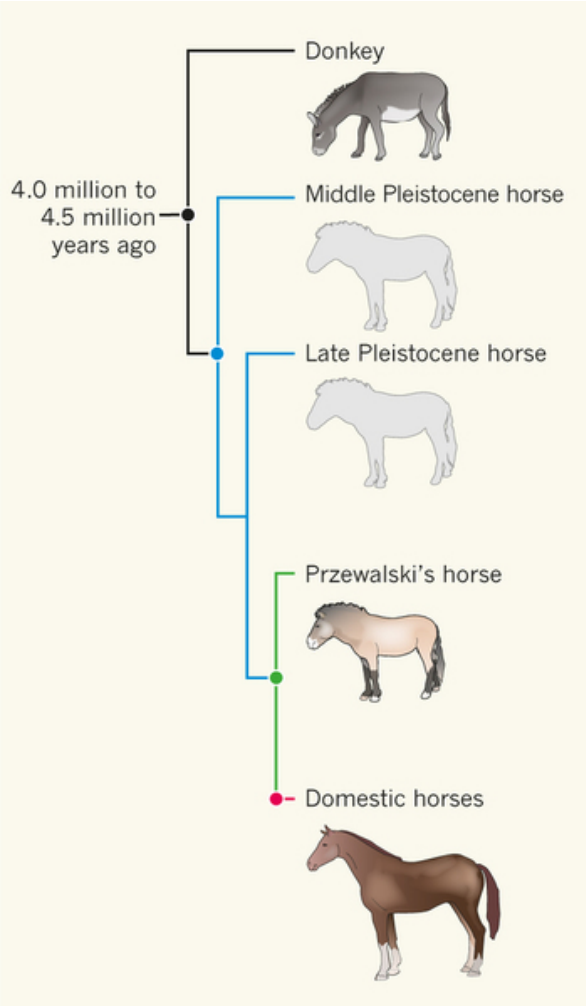
decoupled information



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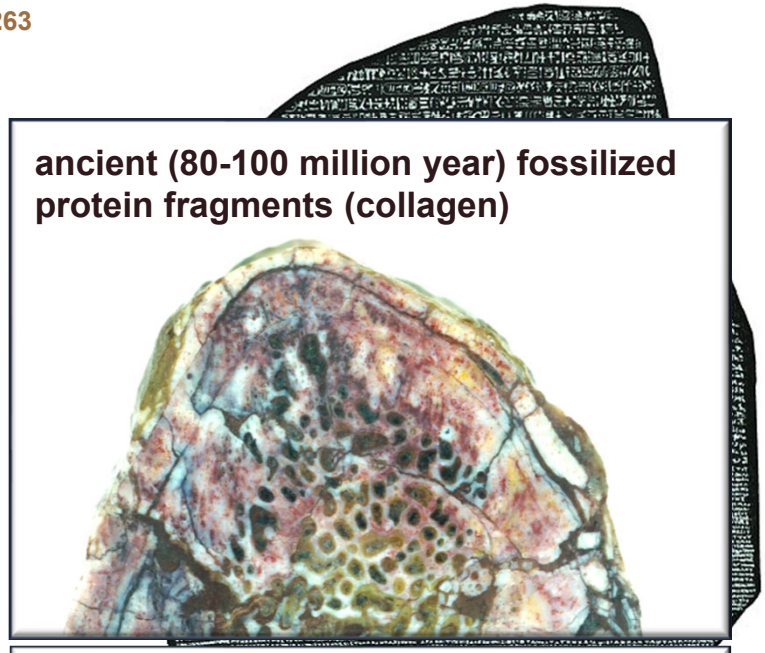

Schweitzer et al [2007] *Science*. **316** (5822): 277-280
Schweitzer et al [2009] *Science*. **324** (5927): 626-631.
Schroeter et al [2017] *J. Proteome Res.***16** (2):920–932
Lee et al [2017] *Nature Communications* **8**: 1422.
Service, R. [2017] *Science*. DOI: 10.1126/science.aal0679

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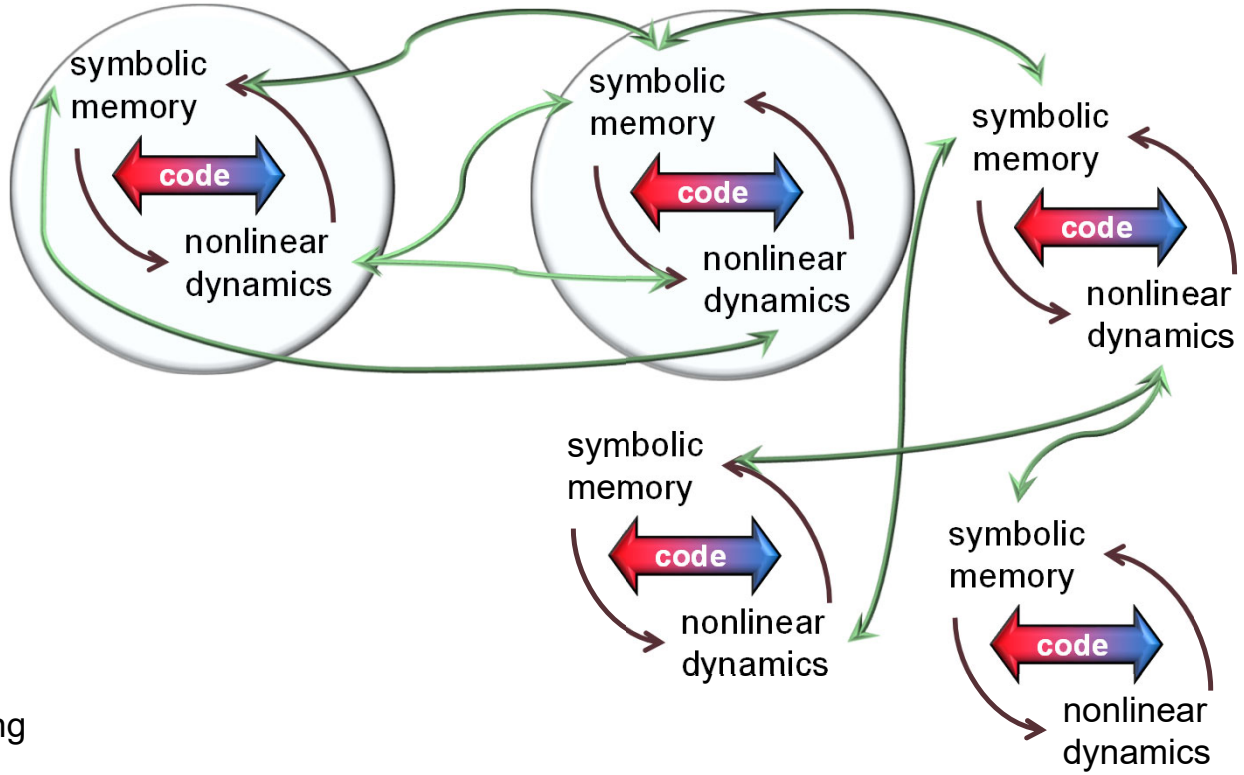
the tape is not necessarily self-contained in cells, brains, or machines

decoupling and externalization enable collective behavior

two roles of information
data/program (Turing)
passive/active (Von Neumann)
description/construction-function (Pattee)
genotype/phenotype (Biology)

"Let the whole outside world consist of a long paper tape". —John von Neumann, 1948

semiotic closure → **semiotic control networks**



Rocha, L.M. [2000] *Annals N.Y. Acad. Sci.* **901**(1): 207-223.
Rocha, L.M. & W. Hordijk [2005] *Artificial Life* **11**:189 - 214.

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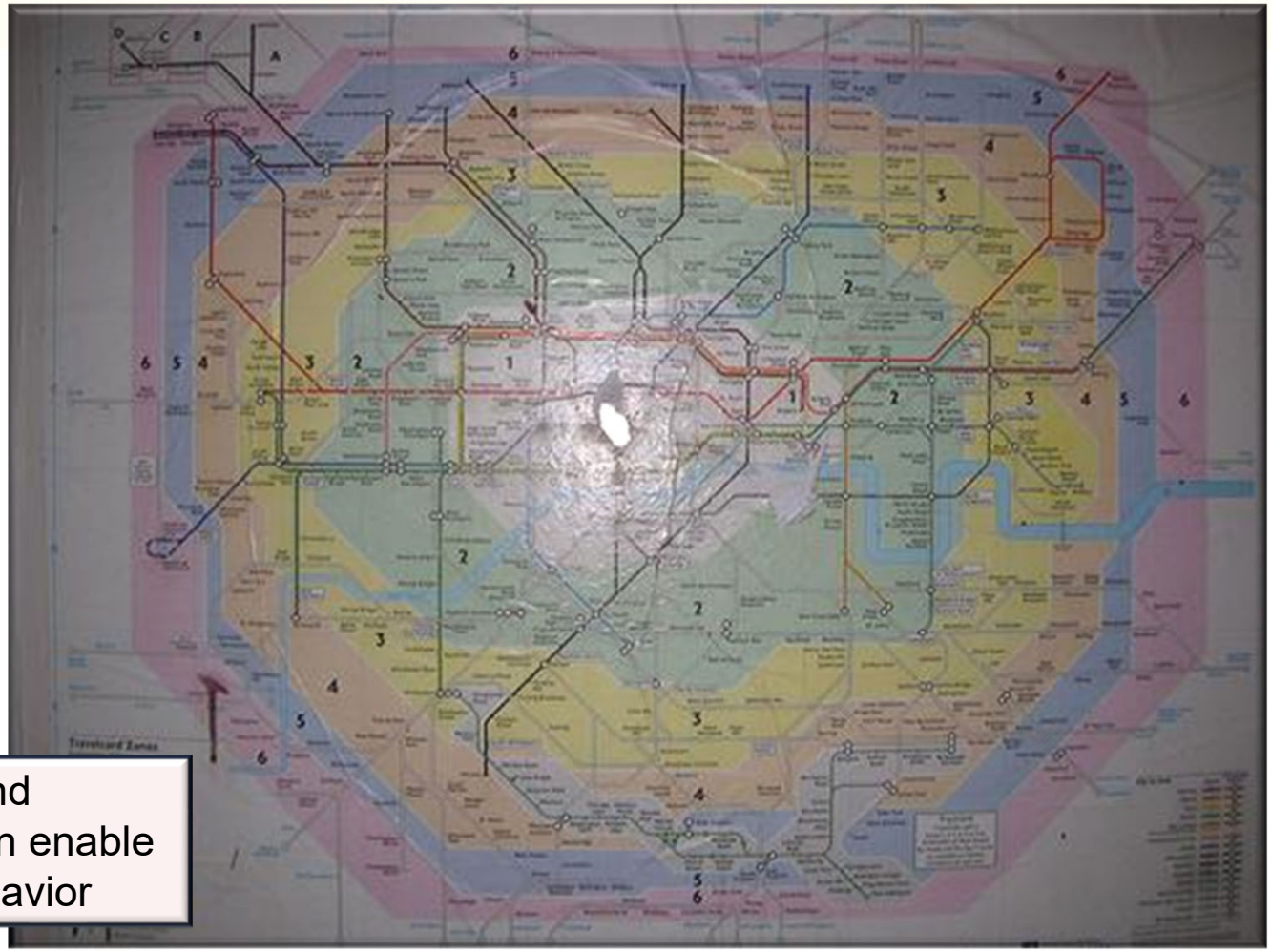
stigmergy



decoupling and externalization enable collective behavior

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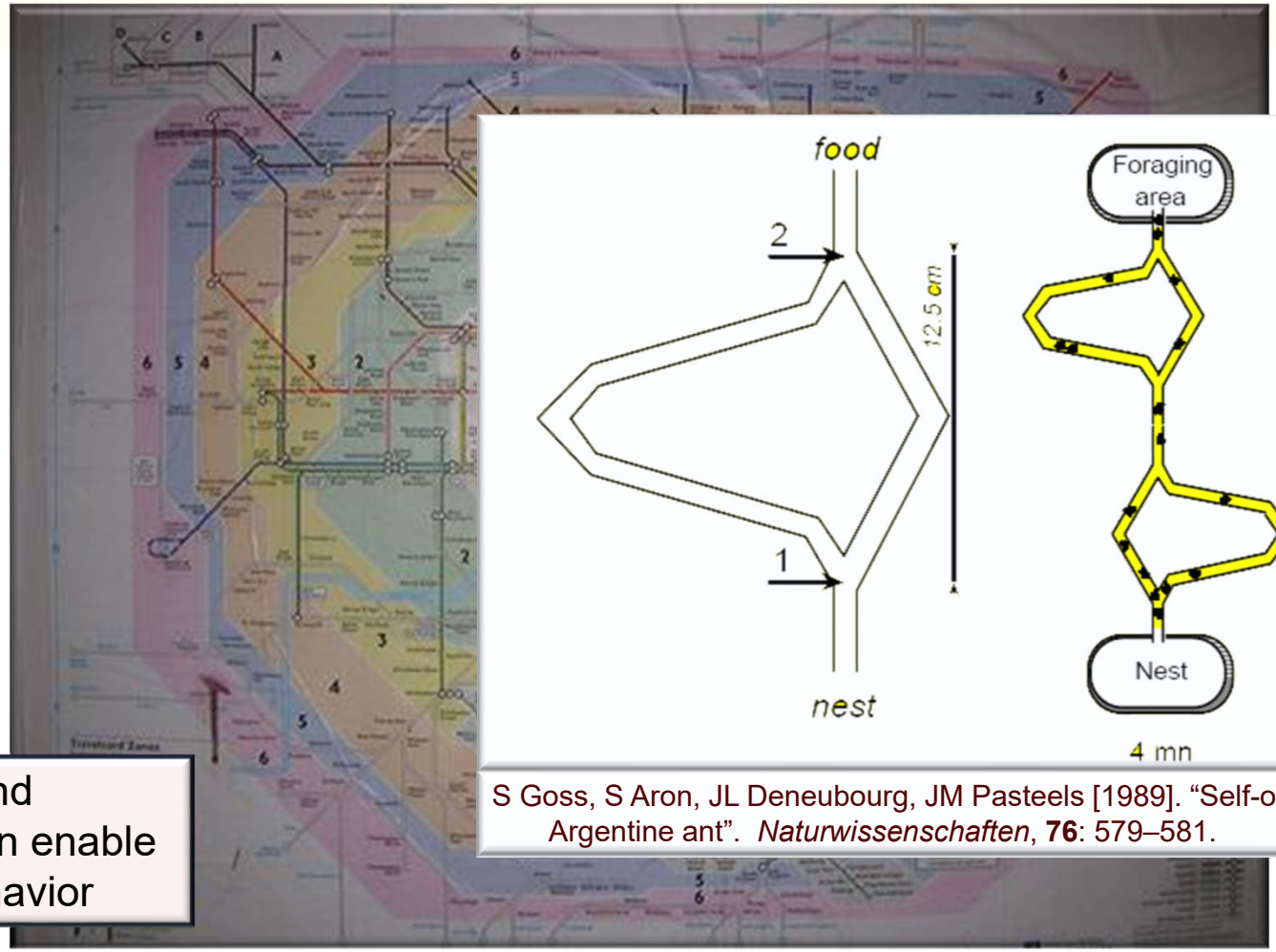

S Goss, S Aron, JL Deneubourg, JM Pasteels [1989]. "Self-organized shortcuts in the Argentine ant". *Naturwissenschaften*, **76**: 579–581.

decoupling and externalization enable collective behavior

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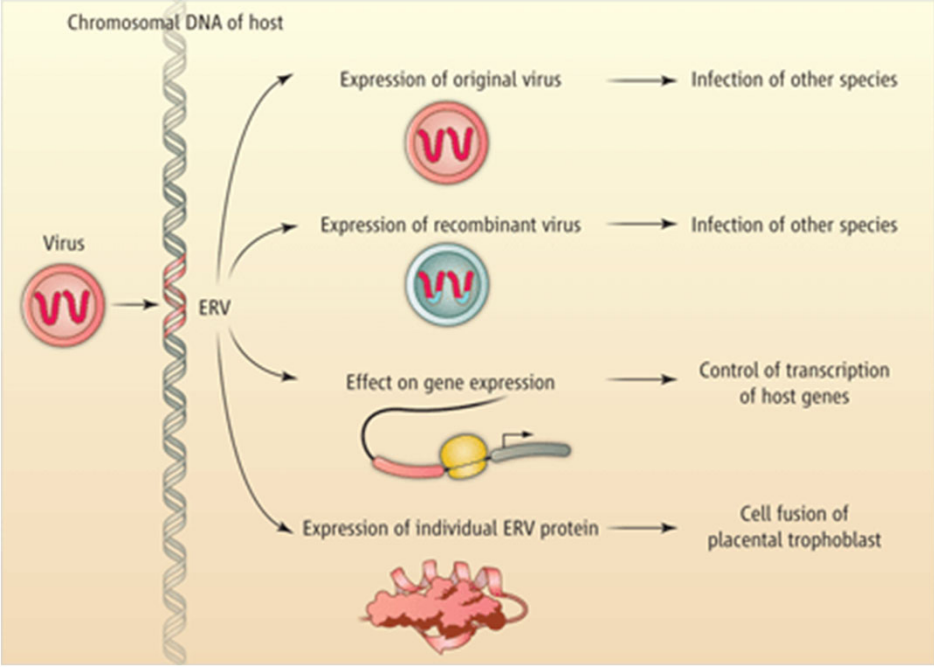
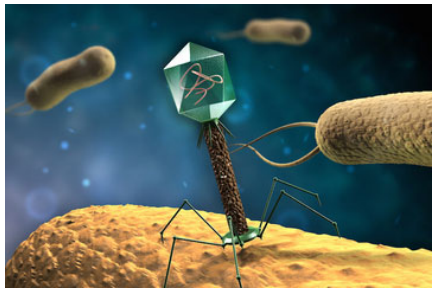
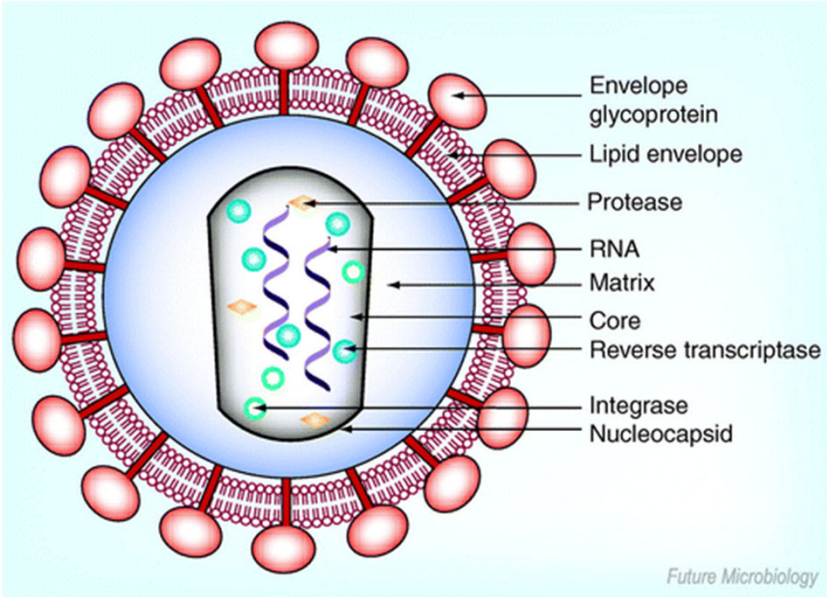
Turing machines written on other Turing machines (naturally)







Sequences from RNA and DNA viruses found in host genomes Retroviral genomes, account **for 6 to 14% of host genomes**

~8% of human DNA.

endogenous retroviruses (ERVs) comprise more DNA than host proteome.

Weiss & Stoye [2013]. "Our Viral Inheritance." *Science*.**340** (6134): 820-821.

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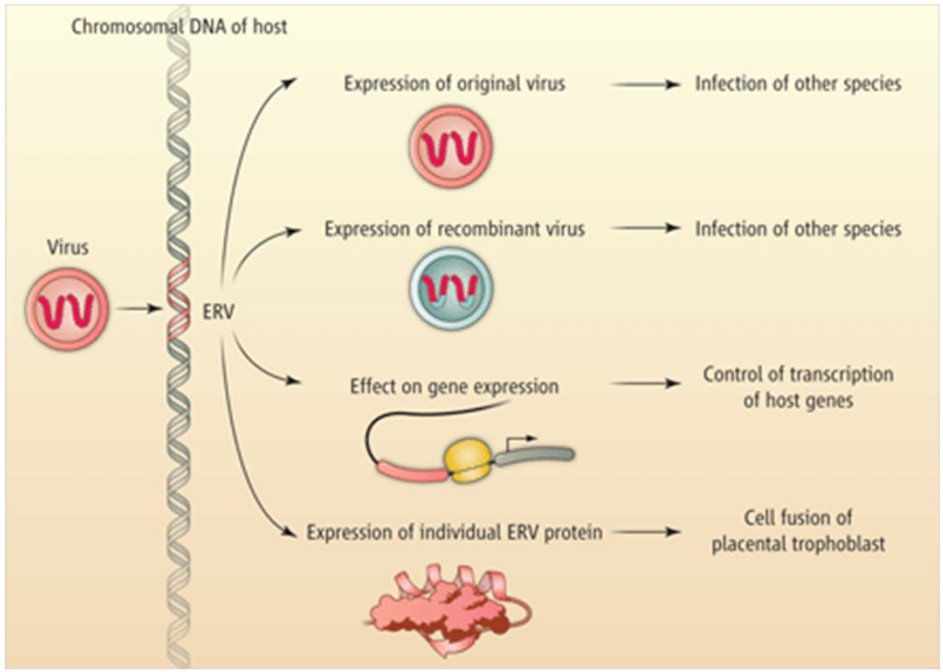

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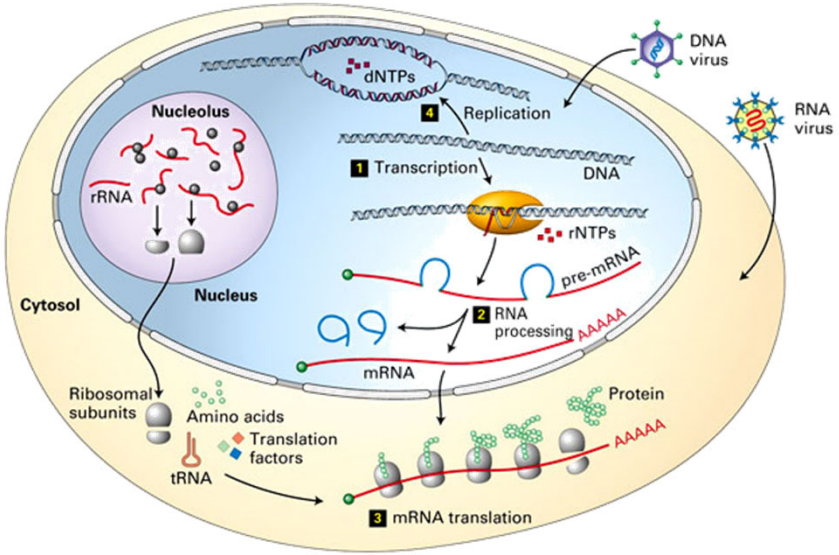
The social symbiome

semiotic control networks enable new, interacting levels of organization and selection, which take control of genes, organisms, and even societies.



Mercer et al. [2012] Targeted RNA sequencing reveals the deep complexity of the human transcriptome. *Nat. Biotech*. **30**, 99–104.

Examples: eukaryotic RNA/DNA complexity, vertebrate immunity, eusociality, cultural constraints on reproduction, GMOs (including via CRISPR), viral pandemics, etc.

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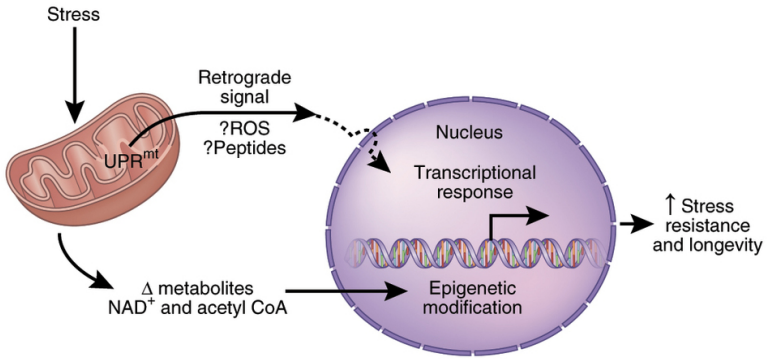

Eukaryote **complexity in regulation**: regulatory components larger than coding, genome size is secondary: 10-100K times more energy per gene than bacteria (# proteins expressed)
Lane & Martin [2010] *Nature* **467**(7318):929–934.

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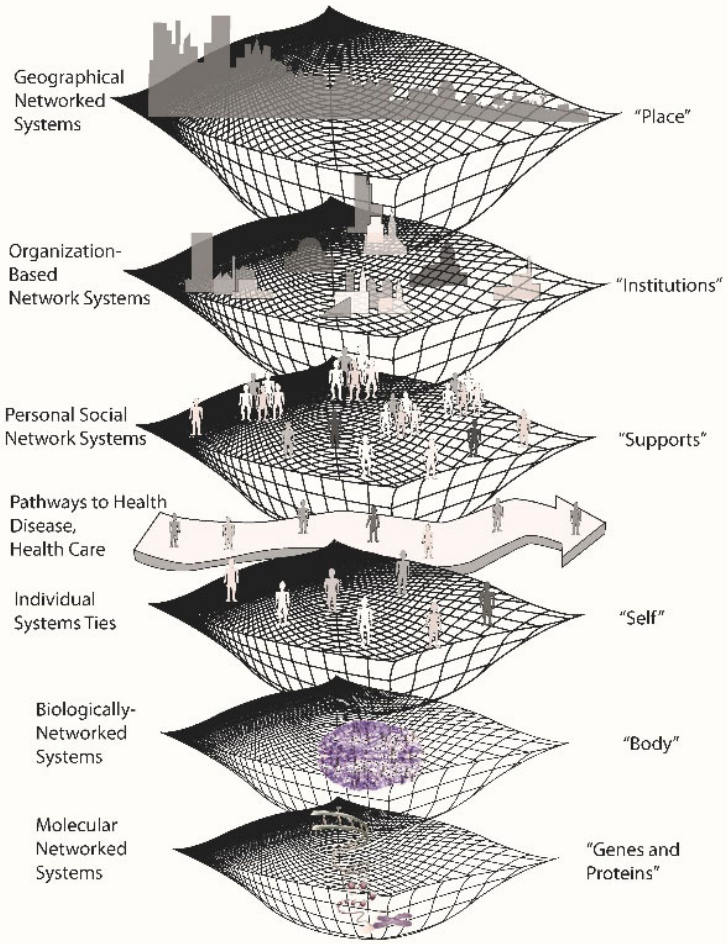
Pescosolido et al [2017] ***The Social Symbiome*** Framework: Linking genes-to-global cultures in public health using network science, in The Handbook of Applied Systems Science.



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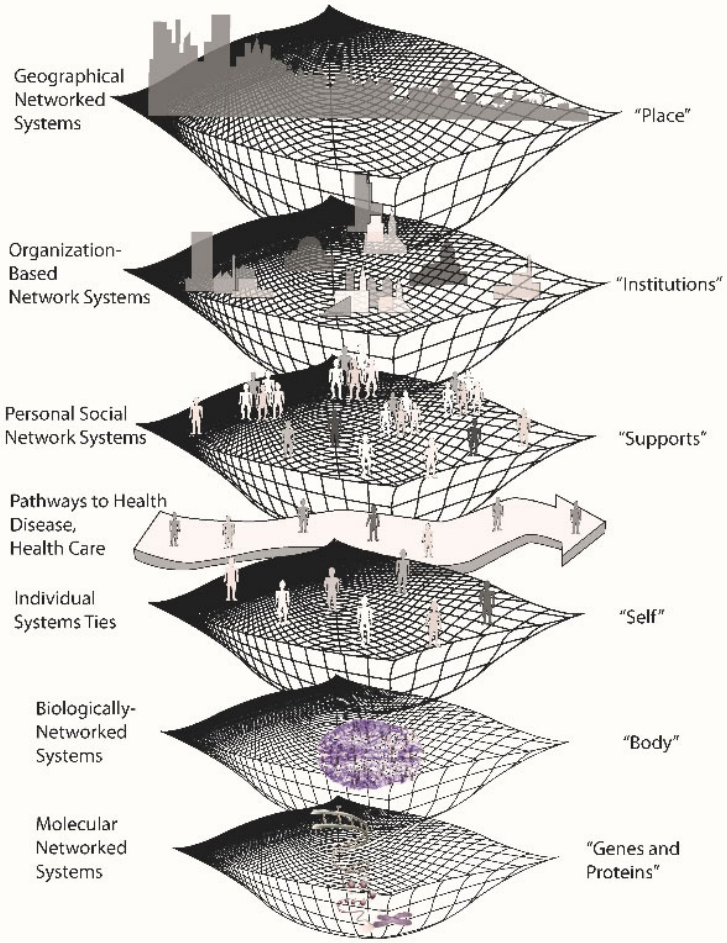

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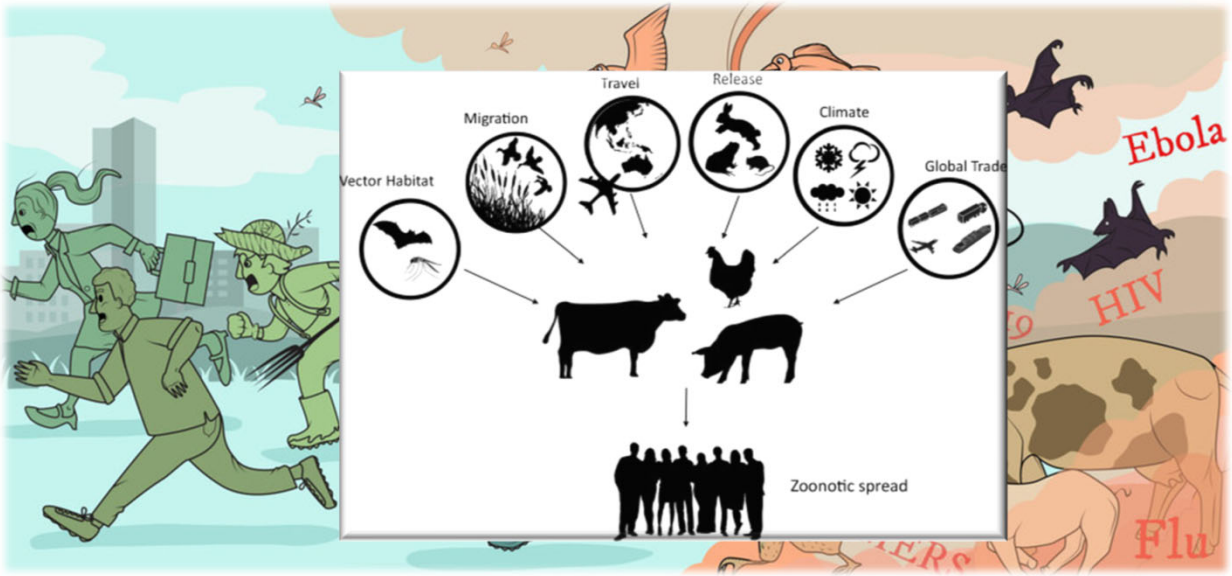

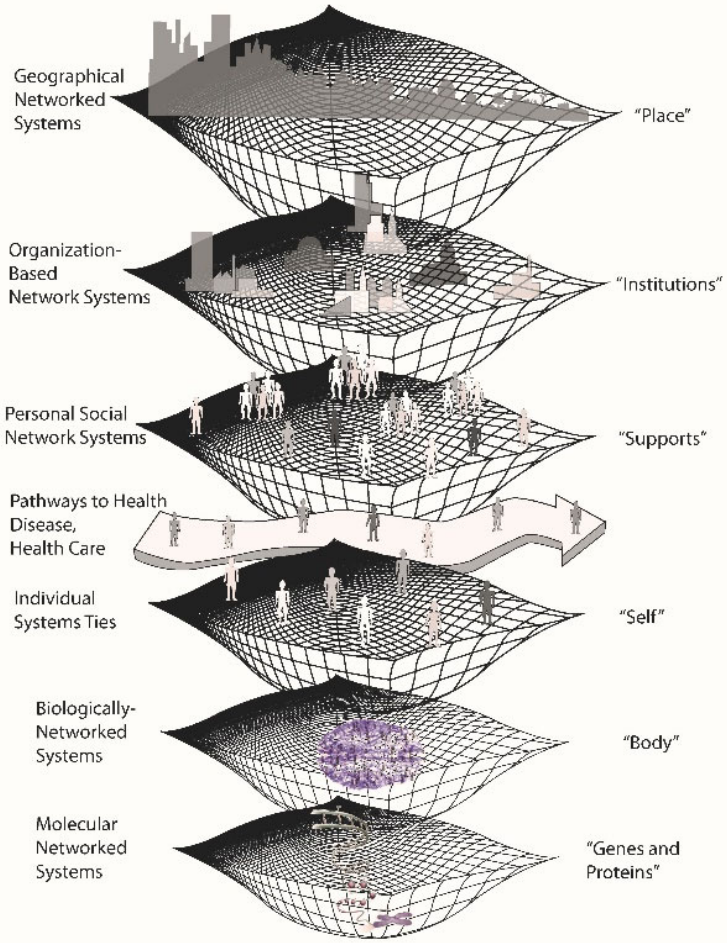

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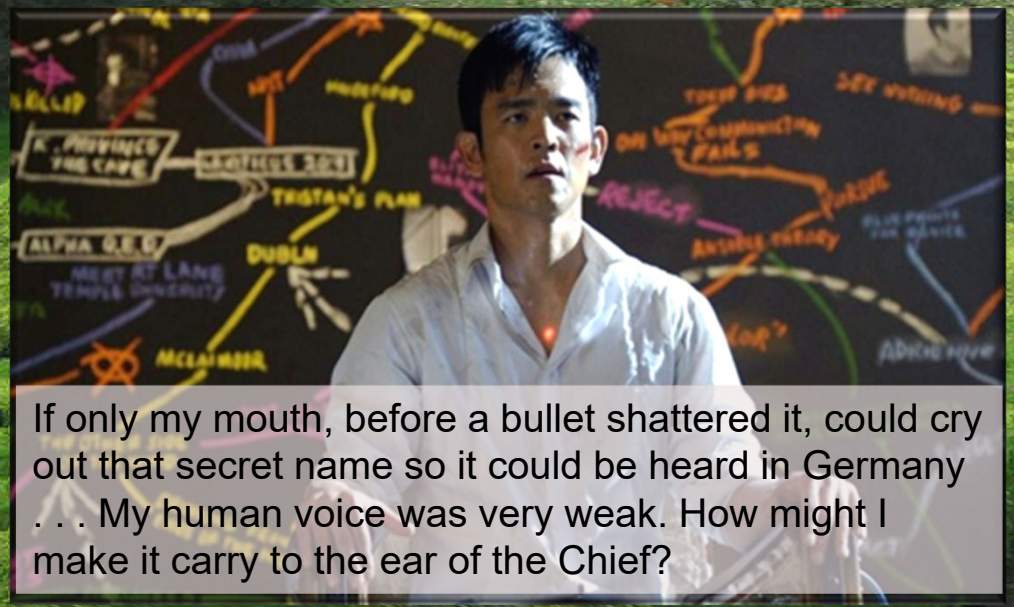
symbolic control

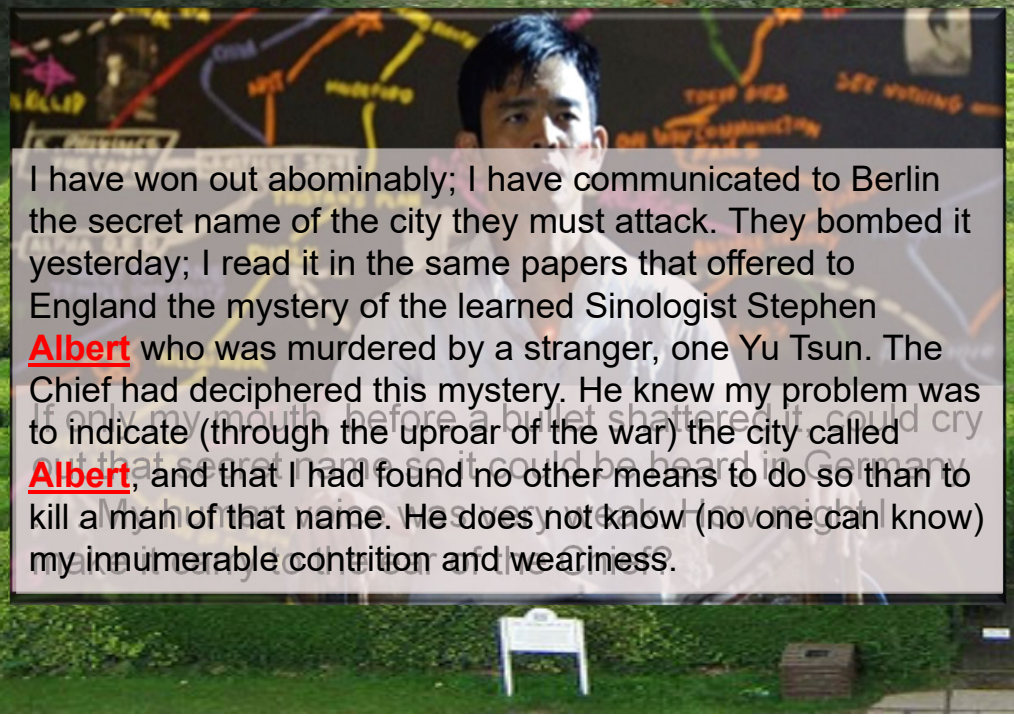
collective behavior via the external tape

- In the presence of semiotic closure
  - Details of cells, brains, and culture can easily become irrelevant
  - Borges' garden of forking paths
    - All the knowledge on the labyrinth, but Albert is just a symbol for **control**
    - things that have (local) meaning, can easily become **irrelevant** in the intertwined semiotic control networks of collective behavior (the ***garden of forking paths***)



collective behavior via the external tape

- In the presence of semiotic closure
  - Details of cells, brains, and culture can easily become irrelevant
  - Borges' garden of forking paths
    - All the knowledge on the labyrinth, but Albert is just a symbol for **control**
    - things that have (local) meaning, can easily become **irrelevant** in the intertwined semiotic control networks of collective behavior (the ***garden of forking paths***)



I have won out abominably; I have communicated to Berlin the secret name of the city they must attack. They bombed it yesterday; I read it in the same papers that offered to England the mystery of the learned Sinologist Stephen **Albert** who was murdered by a stranger, one Yu Tsun. The Chief had deciphered this mystery. He knew my problem was to indicate (through the uproar of the war) the city called **Albert**, and that I had found no other means to do so than to kill a man of that name. He does not know (no one can know) my innumerable contrition and weariness.