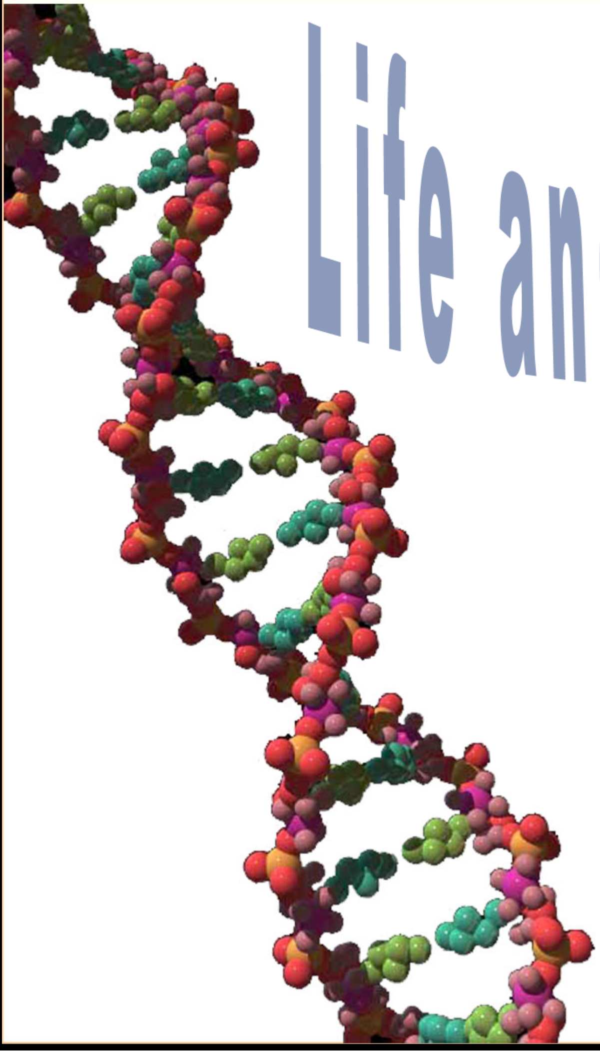
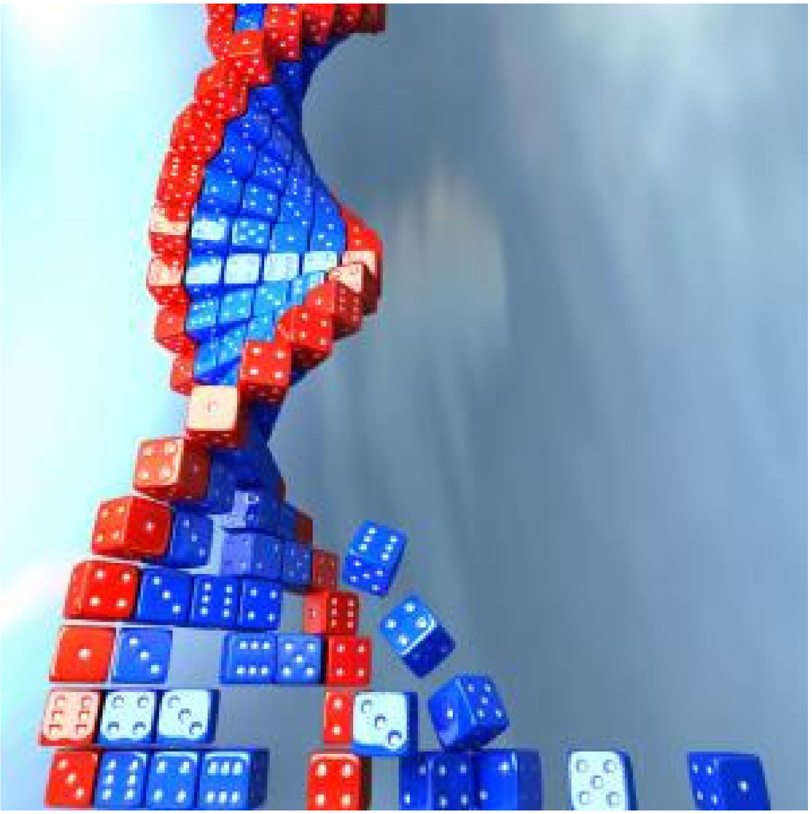


Life and Information



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in the living organization

- organisms act according to information they perceive in an environment
- organisms reproduce and develop from genetic information
  - genetic information is ***transmitted*** "vertically" (inherited) in phylogeny and cell reproduction, and ***expressed*** "horizontally" within a cell in ontogeny and plain functioning
- Self-reference
  - Information relevant to organism/environment: ***function***
    - Only in ***reference*** to an organism/environment does a piece of DNA ***function*** as a gene
  - Biology is contextual and historical, physics is universal
    - How is *purpose/function* generated from processes without purpose?

"Life is a dynamic state of matter **organized** by **information**". Manfred Eigen [1992]

"Biology and physics have nothing to do with each other because biological evolution is essentially historical, and physical laws must be independent of history". Ernst Mayer

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how to best *understand* life?

- Genetic System
  - Construction (expression, development, maintenance, and response) ontogenetically: ***horizontal*** transmission
  - Heredity (reproduction) of cells and phenotypes: ***vertical*** transmission
- Immune System
  - Internal response based on accumulated experience (information)
- Nervous and Neurological system
  - Response to external cues based on memory
- Language, Social, Ecological, Eco-social, etc.

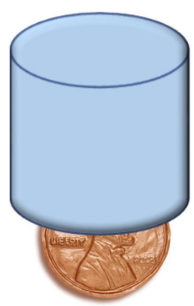
"Life is a complex system for information storage and processing". Minoru Kanehisa [2000]

observer and choice

- ***Information*** is defined as "a measure of the freedom from ***choice*** with which a message is *selected* from the set of all possible messages"
- Bit (short for *binary digit*) is the most elementary **choice** one can make
  - Between two items: "0' and "1", "heads" or "tails", "true" or "false", etc.
  - Bit is equivalent to the choice between two equally likely alternatives
    - Example, if we know that a coin is to be tossed, but are unable to see it as it falls, a message telling whether the coin came up heads or tails gives us one bit of information

1 Bit of *information*

uncertainty ***removed***, information gained



1 Bit of uncertainty

H,T?

choice between 2 symbols recognized by an observer

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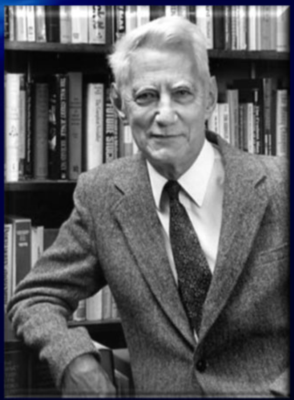
- Information is transmitted through noisy communication channels
  - Ralph Hartley and Claude Shannon (at Bell Labs), the fathers of Information Theory, worked on the problem of efficiently transmitting information; i. e. ***decreasing the uncertainty*** in the transmission of information.

Hartley, R.V.L., "Transmission of Information", *Bell System Technical Journal*, July 1928, p.535.

C. E. Shannon [1948], "A mathematical theory of communication". *Bell System Technical Journal*, **27**:379-423 and 623-656

C. E. Shannon, "A Symbolic analysis of relay and switching circuits" .*MS Thesis*, (unpublished) MIT, 1937.

C. E. Shannon, "An algebra for theoretical genetics." *Phd Dissertation*, MIT, 1940.



Let’s talk about choices

- **Multiplication Principle**
  - “If some choice can be made in M different ways, and some subsequent choice can be made in N different ways, then there are M x N different ways these choices can be made in succession” [Paulos]
    - 3 shirts and 4 pants = 3 x 4 = 12 outfit choices

Combinations quickly grow with long sequences of variables (and state choices)

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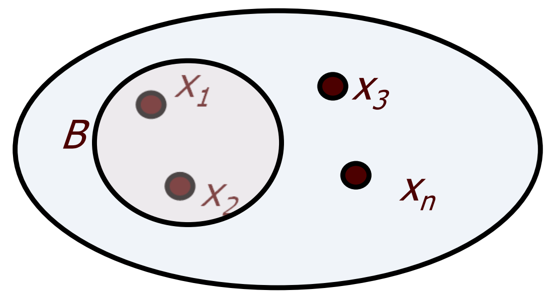
- Nonspecificity
  - Hartley measure
    - The amount of uncertainty associated with a set of alternatives (e.g. messages) is measured by the **amount of information needed to <u>remove</u> the uncertainty**

A = Set of Alternatives



Quantifies how many yes-no questions need to be asked to establish what the correct alternative is

$$H(A) = \log_2 |A|$$

Measured in bits

Number of Choices

Elementary Choice is between 2 alternatives: 1 bit

$$H(B) = \log_2(2) = 1$$

$$\log_2(4) = 2 \qquad 2^2 = 4$$

$$\log_2(16) = 4 \qquad 2^4 = 16$$

$$\log_2(1) = 0$$

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$$H(A) = \log_2(16) = 4$$

$$H(B) = \log_2(4) = 2$$

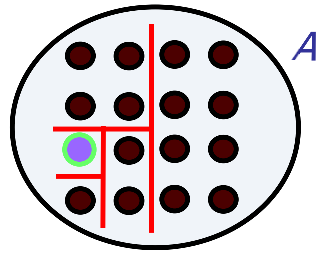
$$H(A) = \log_2 |A|$$

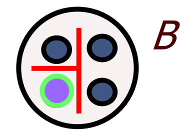
Measured in bits

Number of Choices

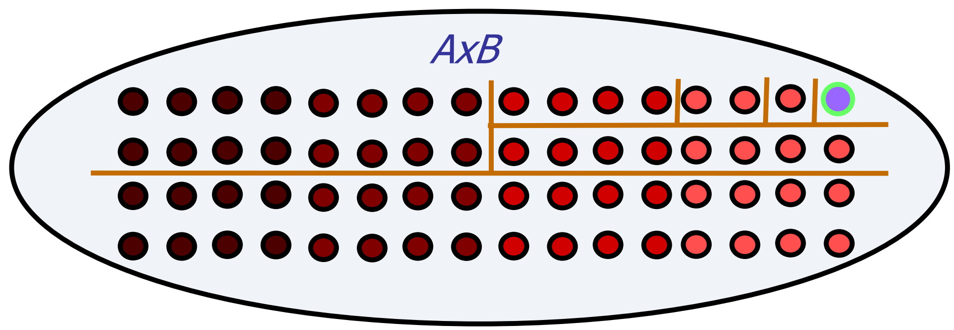
Quantifies how many yes-no questions need to be asked to establish what the correct alternative is

- Example
  - Menu Choices
    - A = 16 Entrees
    - B = 4 Desserts
  - How many dinner combinations?
    - 16 x 4 = 64





$$H(A \times B) = \log_2(16 \times 4) =$$
$$= \log_2(16) + \log_2(4) = 6$$



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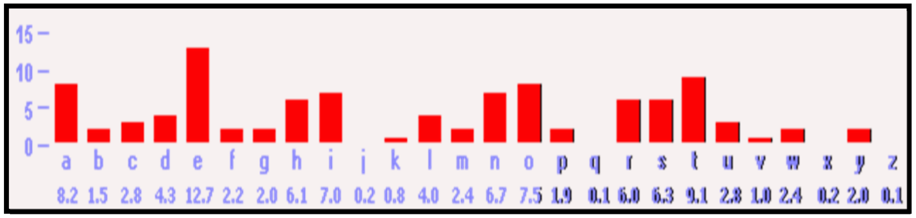
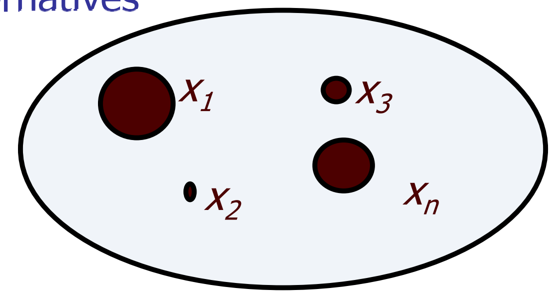
uncertainty-based information



A = Set of weighted Alternatives



- Shannon's measure
  - The ***average*** amount of uncertainty associated with a set of ***weighted*** alternatives (e.g. messages) is measured by the ***average*** amount of information needed to remove the uncertainty

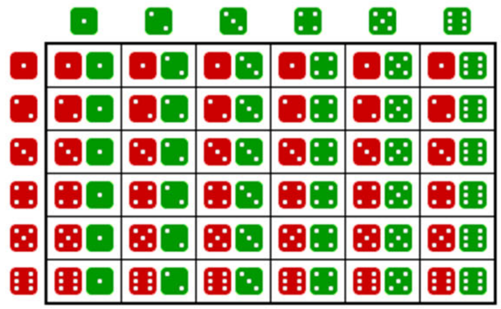
$$H_S(A) = -\sum_{i=1}^{n} p(x_i)\log_2\big(p(x_i)\big)$$

Measured in bits

Probability of alternative

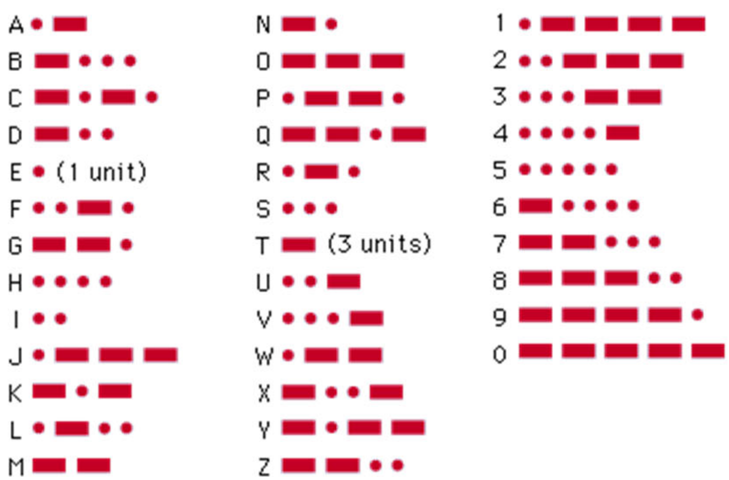
Optional Reading: Aleksander, I. [2002]. "Understanding Information Bit by Bit". In: *It must be beautiful : great equations of modern science*. G. Farmelo (Ed.), Grant.

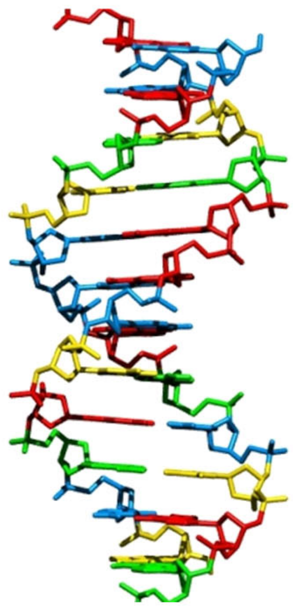
alphabet examples

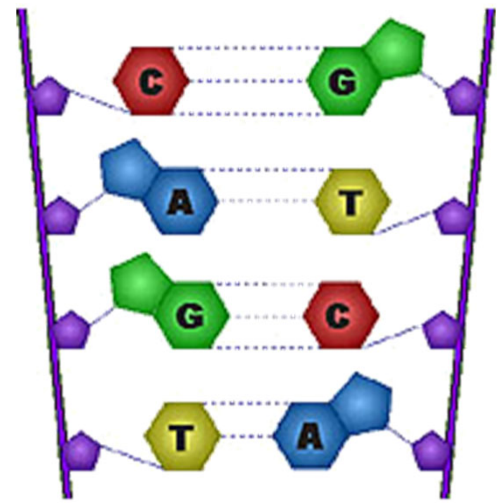


Message encoded in an alphabet of ***n*** symbols, for example:

- English (26 letters + space + punctuations)
- Morse code (dot, dash, space)
- DNA (A, T, G, C)
- Two dice (11 integers)







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5-letter "english"

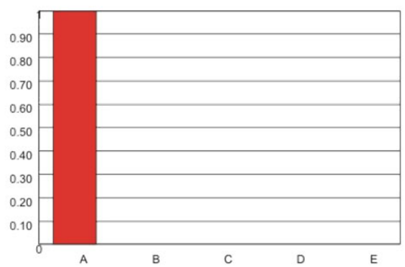
- Given a symbol set {A,B,C,D,E}
  - And occurrence probabilities P_A, P_B, P_C, P_D, P_E,
- The Shannon entropy is
  - The average minimum number of bits needed to represent a symbol

$$H_S = -\left(p_A \log_2(p_A) + p_B \log_2(p_B) + p_C \log_2(p_C) + p_D \log_2(p_D) + p_E \log_2(p_E)\right)$$

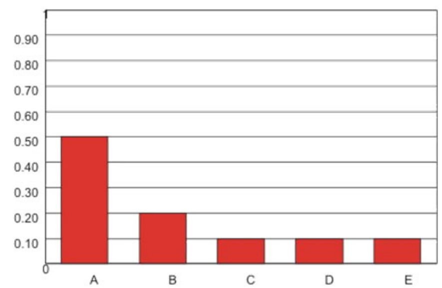
$$H_S = -(1.\log_2(1) + 0.\log_2(0) + 0.\log_2(0) + 0.\log_2(0) + 0.\log_2(0)) = -\log_2(1)$$

$$H_S = -5.\left(\frac{1}{5}\right).\log_2\left(\frac{1}{5}\right) = -(\log_2(1) - \log_2(5)) = \log_2(5)$$

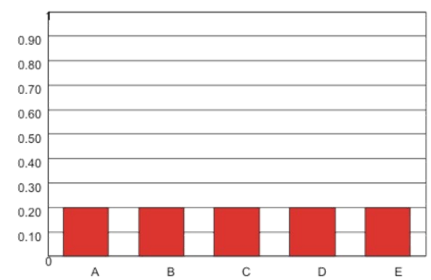
$$H_S = -(\tfrac{1}{2}.\log_2\left(\tfrac{1}{2}\right) + \tfrac{1}{5}.\log_2\left(\tfrac{1}{5}\right) + 3.\left(\tfrac{1}{10}\right).\log_2\left(\tfrac{1}{10}\right))$$



H_S = 0 bits
0 questions



H_S = 1.96
≈2 questions



H_S = 2.32 bits

information is surprise

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what it measures

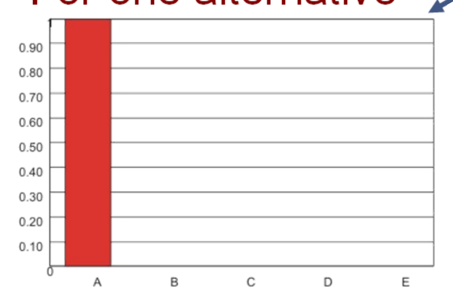
uncertainty, about outcome. How much information is gained when symbol is known

- ***on average***, how many *yes-no* questions need to be asked to establish what the symbol is
- “structure” of uncertainty in situations

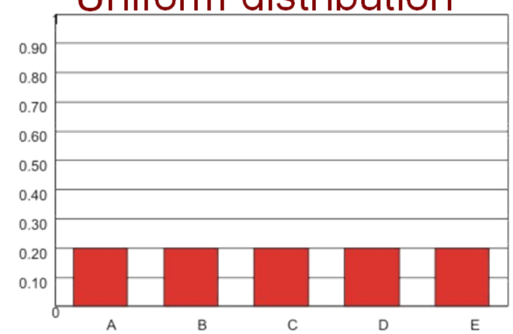
$$H_S \in= -\sum_{i=1}^{n} p(x_i)\log_2\big(p(x_i)\big)$$

$$H_S \in [0, \log_2|X|]$$

For one alternative



Uniform distribution



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readings

- Class Book
  - Floreano, D. and C. Mattiussi [2008]. *Bio-Inspired Artificial Intelligence: Theories, Methods, and Technologies*. MIT Press. **Preface**.
    - Nunes de Castro, Leandro [2006]. *Fundamentals of Natural Computing: Basic Concepts, Algorithms, and Applications*. Chapman & Hall. **Chapter 1**, pp. 1-23.
- Lecture notes
  - Chapter 1: "What is Life?"
    - posted online @ http://informatics.indiana.edu/rocha/i-bic
- Papers for Presentations
  - Logical mechanisms of life (optional for SSIE 483)
    - Langton, C. [1989]. "Artificial Life" In *Artificial Life*. C. Langton (Ed.). Addison-Wesley. pp. 1-47.
      - Pattee, H. [1989], "Simulations, Realizations, and Theories of Life". In Artificial Life. C. Langton (Ed.). pp. 63-77
- Other Readings
  - Life and Information
    - Dennet, D.C. [2005]. "Show me the Science". *New York Times*, August 28, 2005
    - Polt, R. [2012]. "Anything but Human". *New York Times*, August 5, 2012
  - Optional
    - Gleick, J. [2011]. *The Information: A History, a Theory, a Flood*. Random House. **Chapter 8**.
    - Cobb, Matthew. [2013]. "1953: When Genes Became 'Information'." *Cell* **153** (3): 503-506.
    - Aleksander, I. [2002]. "Understanding Information Bit by Bit". In: *It must be beautiful : great equations of modern science*. G. Farmelo (Ed.), Grant
    - James, R., and Crutchfield, J. (2017). Multivariate Dependence beyond Shannon Information. Entropy, 19(10), 531.
    - Prokopenko, Mikhail, Fabio Boschetti, and Alex J. Ryan. "An information-theoretic primer on complexity, self-organization, and emergence." Complexity 15.1 (2009): 11-28.

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