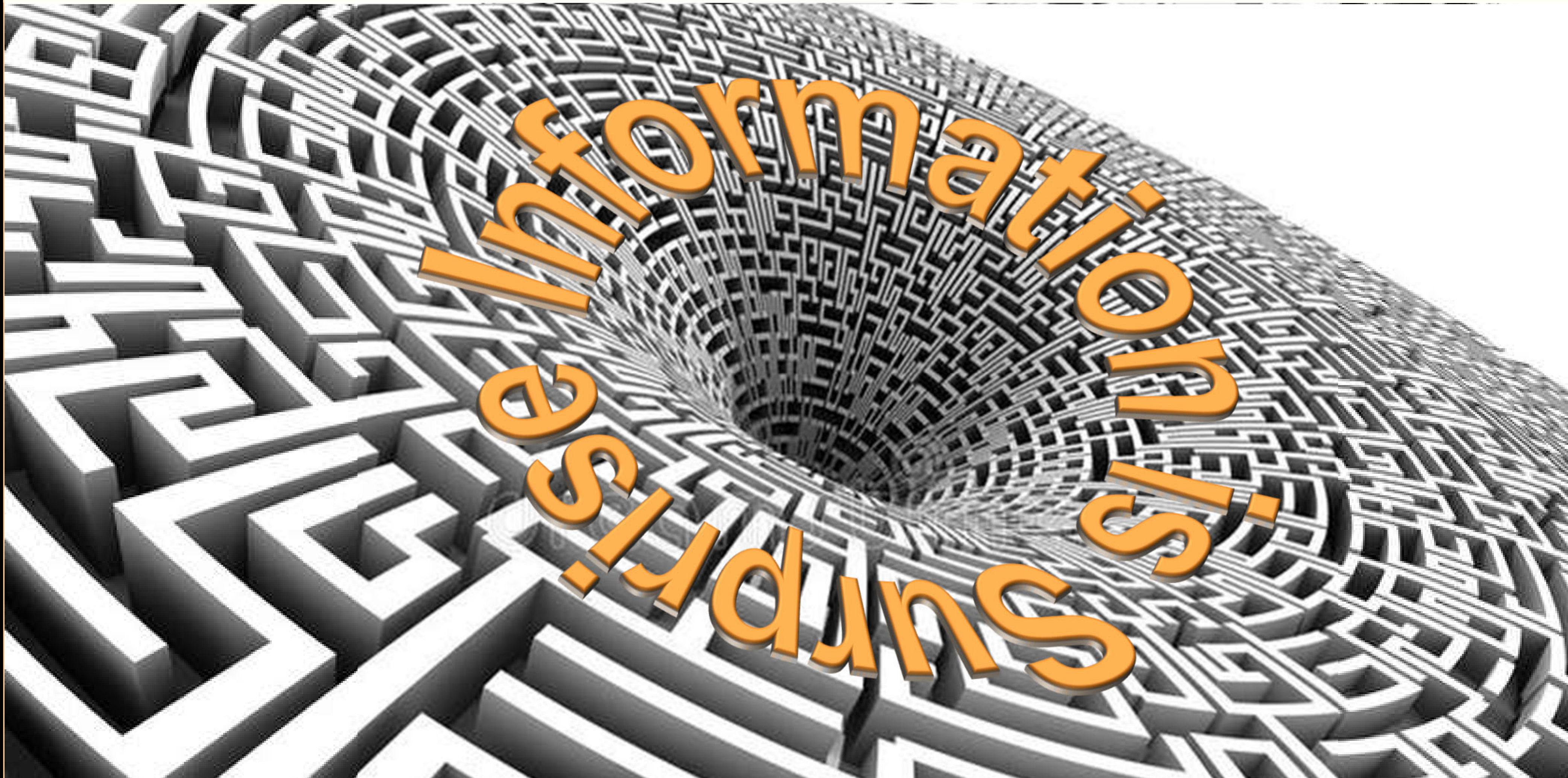
lecture 2: from the garden of forking paths to information as surprise



# Complex adaptive systems and computational intelligence (casci lab)

## Resources

- web page
  - casci.binghamton.edu/academics/ssie501
- online class
  - binghamton.zoom.us/j/93351260610
- blog: sciber
  - sciber.blogspot.com
- Brightspace
  - brightspace.binghamton.edu/d2l/home/255004

SSIE-501/ISE-440 - Fall 2022

**luis m. rocha**

**office hours:**
Tuesdays 9:00- 11:30am
binghamton.zoom.us/my/luismrocha


**office hours:**
Tuesdays: 7:00-8:00pm????
binghamton.zoom.us/my/

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## evaluation

- Participation: 20%.
  - class discussion, everybody reads and discusses every paper
  - engagement in class, including online
- Paper Presentation and Discussion: 20%
  - **SSIE501** students are assigned to papers as lead presenters and discussants
    - all students are supposed to read and participate in discussion of every paper.
    - *section 01* presents in class, *section 20* posts videos on Brightspace (exceptions possible)
  - Presenter prepares short summary of assigned paper (15 minutes)
    - no formal presentations or PowerPoint unless figures are indispensable.
  - Summary should:
    - 1) Identify the key goals of the paper (not go in detail over every section)
    - 2) What discussant liked and did not like
    - 3) What authors achieved and did not
    - 4) Any other relevant connections to other class readings and beyond.
  - **ISE440** students chose one of the presented papers to participate as lead discussant
    - not to present the paper, but to comment on points 2-3) above
  - Class discussion is opened to all
    - lead discussant ensures we important paper contributions and failures are addressed
- Black Box: 60%
  - Group Project (2 parts)
    - Assignment I (25%) and Assignment II (35%)


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## key events coming up

- Paper Presentation: 20%
  - Present (501) and lead (501&440) the discussion of an article related to the class materials
  - *section 01* presents in class, *section 20* (Enginet) posts videos on Brightspace (exceptions possible)
- Module 1: Cybernetics and the Information Turn
- Today
  - Borges, Jorge Luis. [1941]. *The Library of Babel*.
  - Borges, Jorge Luis. [1941]. *The Garden of Forking Paths* .
- Thursday, August 31st
  - Negin Esmaeili:
    - Heims, S.G. [1991]. *The Cybernetics Group*. MIT Press. Chapters: 1 - 2.
      - Optional: Chapters 11-12.
      - Optional: McCulloch, W. and W. Pitts [1943], "A Logical Calculus of Ideas Immanent in Nervous Activity". *Bulletin of Mathematical Biophysics* **5**:115-133.
  - Amahury Lopez Diaz:
    - Gleick, J. [2011]. *The Information: A History, a Theory, a Flood*. Random House. Chapter 8.
      - Optional: Prokopenko, Mikhail, Fabio Boschetti, and Alex J. Ryan. "An information theoretic primer on complexity, self-organization, and emergence." *Complexity* **15**.1 (2009): 11-28.
      - Kline, Ronald R [2015]. *The cybernetics moment, or, why we call our age the information age*. Johns Hopkins University Press. Chapters 1-2.
  - **Discussion by all**


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more upcoming readings (check brightspace)

- Paper Presentation: 20%
  - Present (501) and lead (501&440) the discussion of an article related to the class materials
    - Enginet students post/send video or join by Zoom synchronously
- Thursday, September 7th
  - Savannah Sidoti
    - Brenner, Sydney. [2012]. "History of Science. The Revolution in the Life Sciences". *Science* **338** (6113): 1427-8.
    - Brenner, Sydney. [2012]. "Turing centenary: Life's code script. *Nature* **482** (7386) (February 22): 461-461.
    - Cobb, Matthew. [2013]. "1953: When Genes Became 'Information'." *Cell* **153** (3): 503-506.
      - Optional: Searls, David B. [2010]. "The Roots of Bioinformatics". *PLoS Computational Biology* **6**(6): e1000809.
  - Akshay Gangadhar
    - Weaver, W. [1948]. "Science and Complexity". *American Scientist*, **36**(4): 536-44. Also available in Klir, G.J. [2001]. *Facets of systems Science*. Springer, pp: 533-540.
- Future Modules
  - See brightspace


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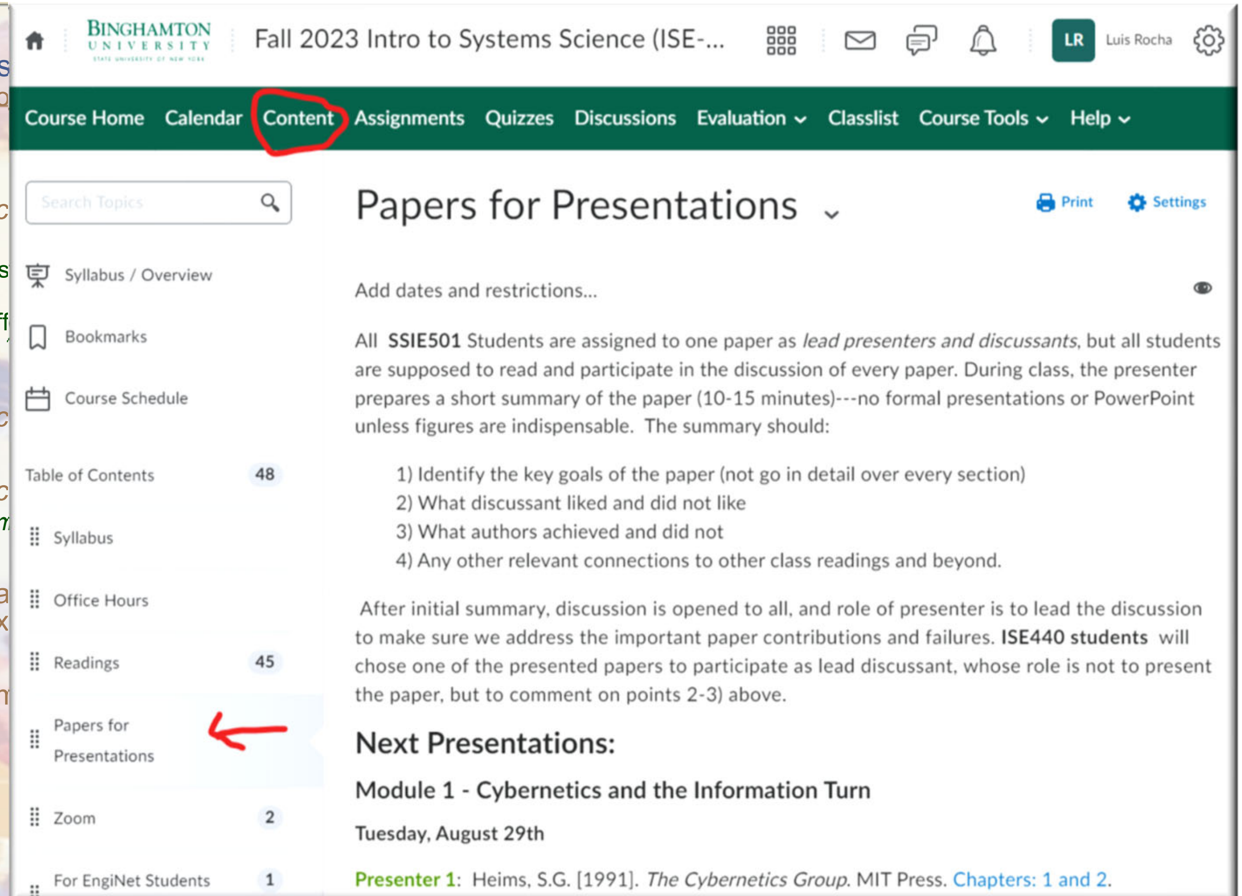
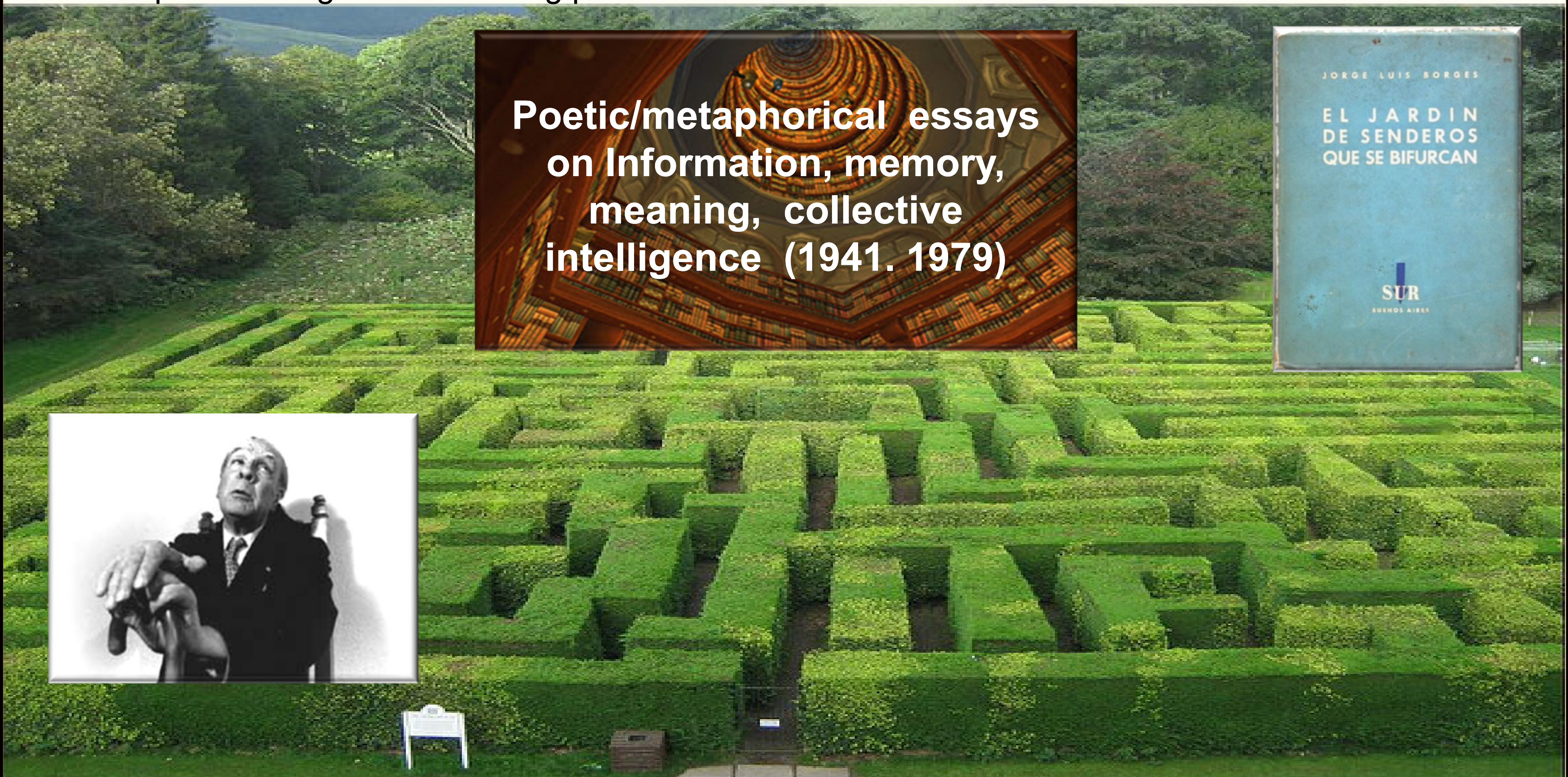
# more upcoming readings (check brightspace)

- Paper Presentation: 20%
  - Present (501) and lead (501&440) the discus
    - Enginet students post/send video or join by Zo
- Module 2: Systems Science
  - Sarah Donovan:
    - Klir, G.J. [2001]. *Facets of systems Scienc*
      - Optional:
      - Rosen, R. [1986]. "Some comments on sys *systems Science*. Springer. pp: 241-243.
      - Wigner, E.P. [1960], "The unreasonable eff delivered at New York University, May 11,
  - Emma Bachyrycz:
    - Klir, G.J. [2001]. *Facets of systems Scienc*
  - Nicole Dates:
    - Klir, G.J. [2001]. *Facets of systems Scienc*
      - Optional: Klir, G.J. [2001]. *Facets of system*
  - Presenter 8:
    - Schuster, P. (2016). The end of Moore's la *Complexity*. **21**(S1): 6-9. DOI 10.1002/cplx
  - Presenter 9:
    - Von Foerster, H., P. M. Mora and L. W. Am
- Future Modules
  - See brightspace



Personal path in the garden of forking paths



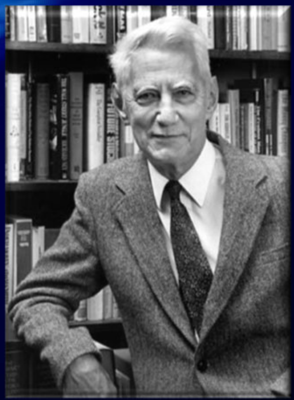
- Information is transmitted through noisy communication channels
  - Ralph Hartley and Claude Shannon (at Bell Labs), the fathers of Information Theory, worked on the problem of efficiently transmitting information; i. e. ***decreasing the uncertainty*** in the transmission of information.

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

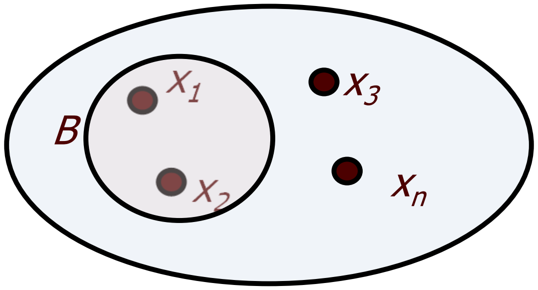
C. E. Shannon, "A Symbolic analysis of relay and switching circuits" .*MS Thesis*, (unpublished) MIT, 1937.

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



- 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

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

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

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

$$\log_2(1) = 0$$

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

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

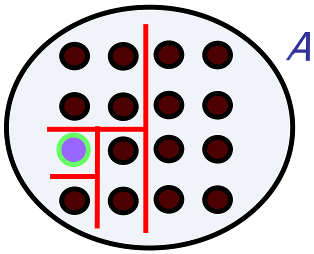
$$H(A) = \log_2 |A|$$

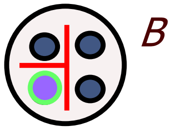
Measured in bits

Number of Choices

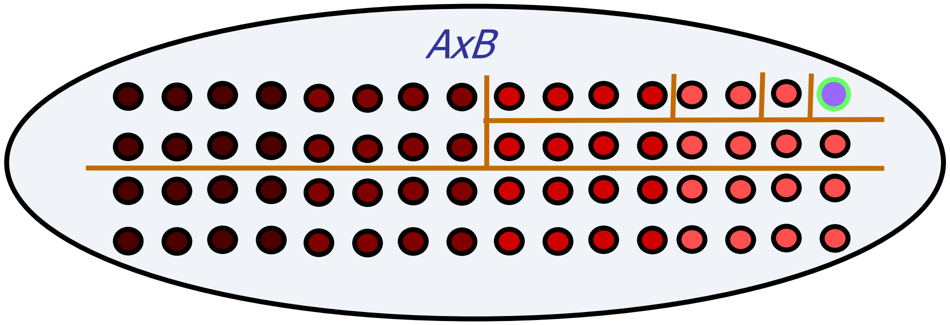
Quantifies how many yes-no questions need to be asked to establish what the correct alternative is

- 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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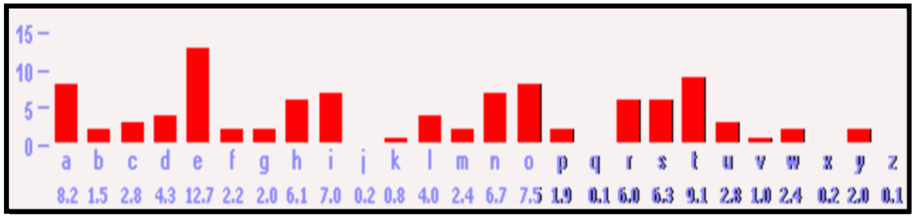
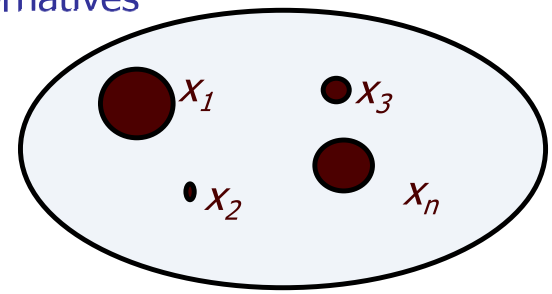
uncertainty-based information




*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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## 5-letter “english”

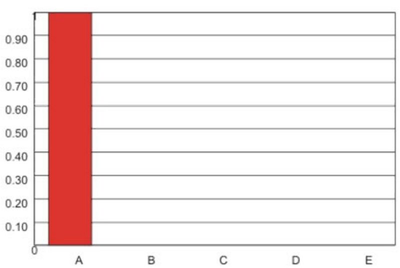
- Given a symbol set {A,B,C,D,E}
  - And occurrence probabilities $P_A$, $P_B$, $P_C$, $P_D$, $P_E$,
- The Shannon entropy is
  - The average minimum number of bits needed to represent a symbol

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

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

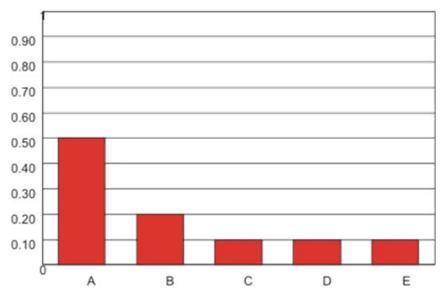
$$H_S = -5.\left(\frac{1}{5}\right).\log_2\left(\frac{1}{5}\right) = -(\log_2(1) - \log_2(5)) = \log_2(5)$$

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



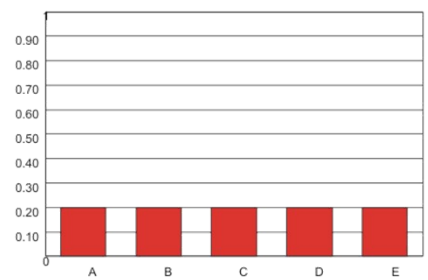

$H_S$ = 0 bits

0 questions




$H_S$ = 1.96

≈2 questions




$H_S$ = 2.32 bits

**information is surprise**



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# Shannon’s entropy formula

## what it measures

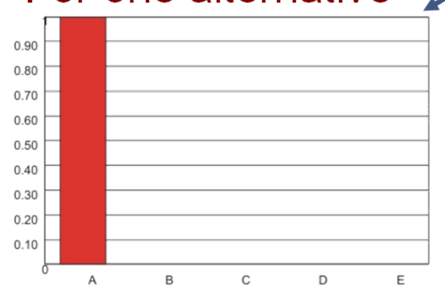
*uncertainty*, about outcome. How much information is gained when symbol is known

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

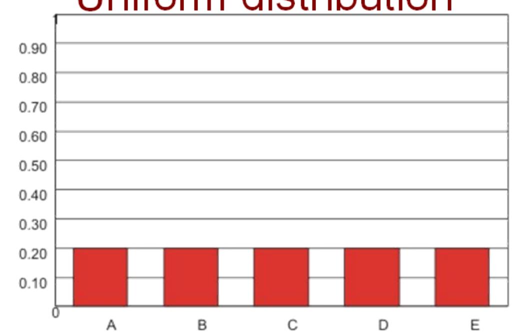
$$H_S \in = -\sum_{i=1}^{n} p(x_i)\log_2\big(p(x_i)\big)$$

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

For one alternative




Uniform distribution

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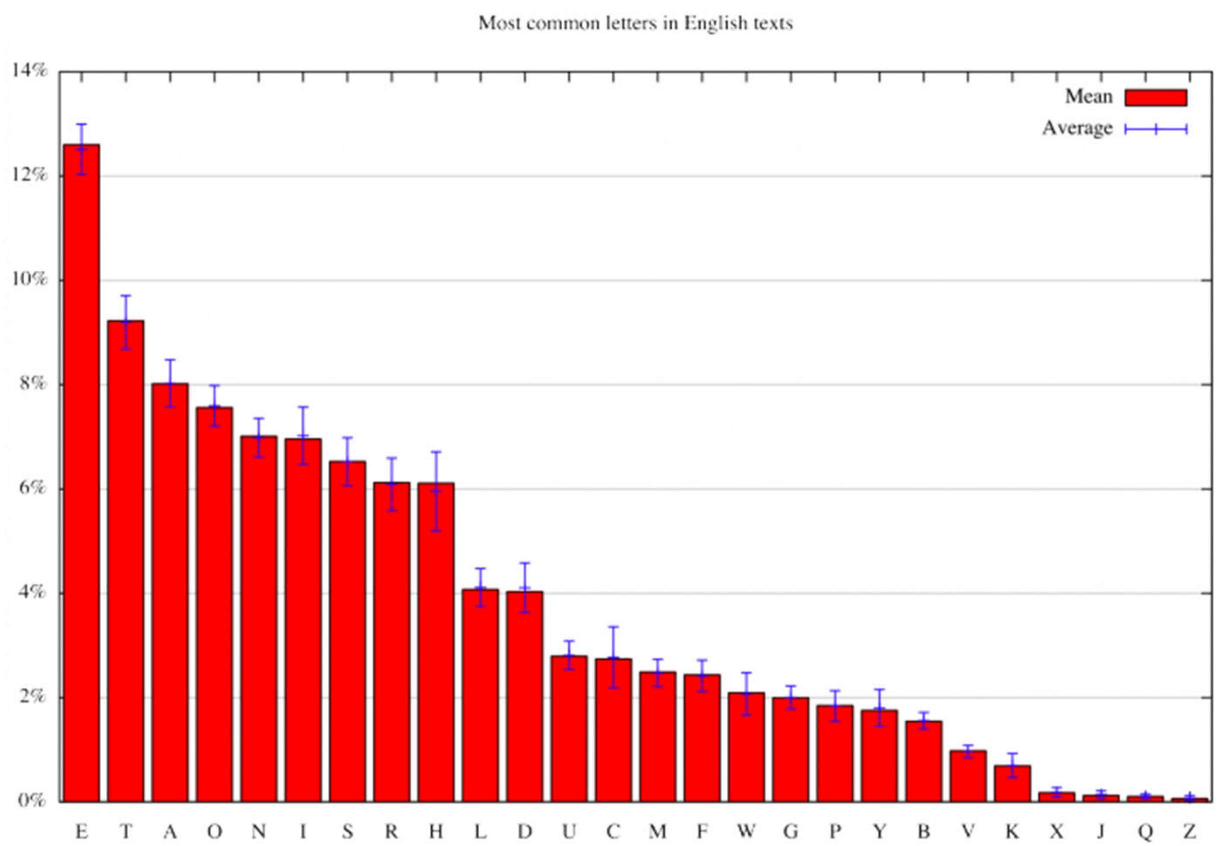
## from letter frequency




http://www.macfreek.nl/memory/Letter_Distribution



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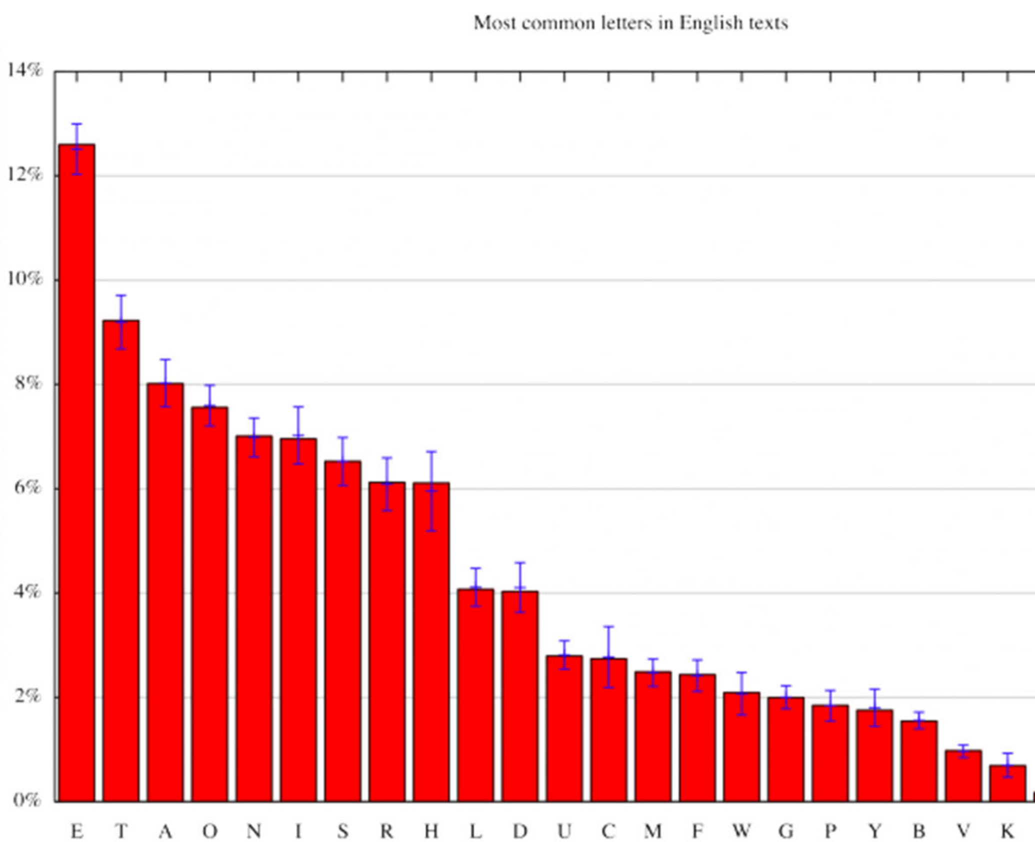
# from letter frequency

| | p(x) | log2(p(x)) | -p(x).log2(p(x)) |
|---|---|---|---|
| e | 0.124167 | -3.0096463 | 0.373698752 |
| t | 0.096923 | -3.3670246 | 0.326340439 |
| a | 0.082001 | -3.6082129 | 0.295877429 |
| i | 0.076805 | -3.7026522 | 0.284382943 |
| n | 0.076406 | -3.7101797 | 0.283478135 |
| o | 0.07141 | -3.8077402 | 0.271908822 |
| s | 0.070677 | -3.8226195 | 0.270170512 |
| r | 0.066813 | -3.903723 | 0.260820228 |
| l | 0.044831 | -4.4793659 | 0.200813559 |
| d | 0.036371 | -4.7810716 | 0.173891876 |
| h | 0.035039 | -4.8349111 | 0.169408515 |
| c | 0.034439 | -4.8598087 | 0.167367439 |
| u | 0.028777 | -5.11894 | 0.147307736 |
| m | 0.028[illegible] | [illegible] | [illegible]094755 |
| f | 0.023[illegible] | [illegible] | [illegible]220629 |
| p | 0.020517 | -5.6211617 | 0.114205704 |
| y | 0.018918 | -5.7240814 | 0.108289316 |
| g | 0.018119 | -5.7863688 | 0.104842059 |
| w | 0.013523 | -6.2084943 | 0.083954364 |
| v | 0.012457 | -6.3269343 | 0.078812722 |
| b | 0.010658 | -6.5519059 | 0.069830868 |
| k | 0.00393 | -7.9911852 | 0.031406876 |
| x | 0.002198 | -8.8294354 | 0.019409218 |
| j | 0.001998 | -8.9669389 | 0.017919531 |
| q | 0.000933 | -10.066609 | 0.009387113 |
| z | 0.000599 | -10.705156 | 0.006412389 |
| | | Entropy | **4.14225193** |

Hartley Measure
H(|26|) 4.7004397




| | p(x) | log2(p(x)) | -p(x).log2(p(x)) |
|---|---|---|---|
| Space | 0.18288 | -2.4509943 | 0.448249175 |
| E | 0.10267 | -3.2839625 | 0.337152952 |
| T | 0.07517 | -3.7336995 | 0.280662128 |
| A | 0.06532 | -3.9362945 | 0.257125332 |
| O | 0.06160 | -4.0210249 | 0.247678132 |
| N | 0.05712 | -4.1298574 | 0.235897914 |
| I | 0.05668 | -4.1409036 | 0.234724772 |
| S | 0.05317 | -4.2332423 | 0.225081718 |
| R | 0.04988 | -4.3254212 | 0.215748053 |
| H | 0.04979 | -4.3281265 | 0.215478547 |
| L | 0.[illegible] | [illegible] | [illegible]63015644 |
| D | 0.[illegible] | [illegible] | [illegible]61811184 |
| U | [illegible] | [illegible] | 0.124201198 |
| C | 0.02234 | -5.4844363 | 0.122504535 |
| M | 0.02027 | -5.6248177 | 0.113990747 |
| F | 0.01983 | -5.6561227 | 0.112164711 |
| W | 0.01704 | -5.8750208 | 0.100104113 |
| G | 0.01625 | -5.9435013 | 0.096576215 |
| P | 0.01504 | -6.0547406 | 0.091082933 |
| Y | 0.01428 | -6.1301971 | 0.087518777 |
| B | 0.01259 | -6.3117146 | 0.079456959 |
| V | 0.00796 | -6.9728048 | 0.055511646 |
| K | 0.00561 | -7.4778794 | 0.041948116 |
| X | 0.00141 | -9.4709063 | 0.013346416 |
| J | 0.00098 | -10.001987 | 0.009754119 |
| Q | 0.00084 | -10.222907 | 0.008554069 |
| Z | 0.00051 | -10.929184 | 0.005604998 |
| | | Entropy | **4.0849451** |

Hartley Measure
H(|27|) 4.7548875

http://www.macfreek.nl/memory/Letter_Distribution

- entropy quantifies information (surprise), but it does not consider information content
  - semantic aspects of information are irrelevant to the engineering problem in Shannon's conception

We were good, we were gold
Kinda dream that can't be sold
We were right 'til we weren't
Built a home and watched it burn

Mm, I didn't wanna leave you
I didn't wanna lie
Started to cry, but then remembered I
I can buy myself flowers
Write my name in the sand
Talk to myself for hours
Say things you don't understand
I can take myself dancing
And I can hold my own hand
Yeah, I can love me better than you can

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

wdeo eog geWl ewr e deorw
aainhmta d rettoeKandl dsbc
eeeier ntw hWttr ewrgliwe
oriaedatmht ndc lwn thuaBeuib

eanm dtal vewdi nl o unMay
al indn nltawde i
cl rettedtebrmSrb reemntuy da oth e
uolrawe blnffmsyylc es
niWe dty ne rsehmntiama
arem Tll ssytrfu fkoooh
nyoh e gdodudtnaraustsi tnynS
atf lk emcnegyn snlicad a
hmhydcndAwannoo n dl l a
tlhl eatta nom Ybrueny h ee oaavn cce

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## entropy according to probabilistic model

0th order model: equiprobable symbols

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

Hartley Measure
H(|27|) 4.7548875

XFOML RXKHRJFFJUJ ZLPWCFWKCYJ FFJEYVKCQSGXYD QPAAMKBZAACIBZLHJQD

1st order model: frequency of symbols

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

$H_S$ =4.08

OCRO HLI RGWR NMIELWIS EU LL NBNESBEYA TH EEI ALHENHTTPA OOBTTVA NAH BRL

2nd order model: frequency of digrams

Most common *digrams*: th, he, in, en, nt, re, er, an, ti, es, on, at, se, nd, or, ar, al, te, co, de, to, ra, et, ed, it, sa, em, ro.

ON IE ANTSOUTINYS ARE T INCTORE ST BE S DEAMY ACHIN D ILONASIVE TUCOOWE AT TEASONARE FUSO TIZIN ANDY TOBE SEACE CTISBE

3rd order model: frequency of trigrams

Most common *trigrams*: the, and, tha, ent, ing, ion, tio, for, nde, has, nce, edt, tis, oft, sth, men

IN NO IST LAT WHEY CRATICT FROURE BERS GROCID PONDENOME OF DEMONSTURES OF THE REPTAGIN IS REGOACTIONA OF CRE

4th order model: frequency of tetragrams

$H_S$ = 2.8

THE GENERATED JOB PROVIDUAL BETTER TRAND THE DISPLAYED CODE ABOVERY UPONDULTS WELL THE CODERST IN THESTICAL IT DO HOCK BOTHE MERG INSTATES CONS ERATION NEVER ANY OF PUBLE AND TO THEORY EVENTIAL CALLEGAND TO ELAST BENERATED IN WITH PIES AS IS WITH THE

**including more structure reduces surprise**

**http://pages.central.edu/emp/LintonT/classes/spring01/cryptography/letterfreq.html**

**http://everything2.com/title/entropy+of+English**

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## other measures to infer structure and organization in nature and society

- **Mutual Information**
  - Amount of information about one variable that can be gained (uncertainty reduced) by observing another variable
- **Information Gain (Kullback-Leibler Divergence)**
  - Difference between two probability distributions *p* and *q*,
    - average number of bits per data point needed in order to represent *q* (model approximation) as it deviates from *p* ("true" or theoretical distribution)
- **Transfer Entropy**
  - transfer of information between two random processes in time
    - Amount of information (in bits) gained, or uncertainty lost, in knowing future values of Y, knowing the past values of X and Y.

$$I(X;Y) = \sum_{i=1}^{n}\sum_{j=1}^{m} p(x_i, y_j)\log_2 \frac{p(x_i, y_j)}{p(x_i)p(y_j)}$$

$$IG(p(X), q(X)) = \sum_{i=1}^{n} p(x_i)\log_2 \frac{p(x_i)}{q(x_i)}$$

$$I(X;Y) = H(X) + H(Y) - H(X,Y)$$

$$T_{X\rightarrow Y} = H(Y_t | Y_{t-1:t-L}) - H(Y_t | Y_{t-1:t-L}, X_{t-1:t-L})$$

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# other measures to infer structure and organization in nature and society

- Mutual Information
  - Amount of information about one variable that can be gained (uncertainty reduced) by observing another variable
- Information Gain (Kullback-Leibler Divergence)
  - [...]ons *p* and *q*,
    - [...] order to represent *q* (model approximation) as it
    - [...])
- [...] processes in time
  - [...]ainty lost, in knowing future values of Y, knowing the past values of X and Y.

Zuhtr nsl%Wjfinslx?%Ltqfs1%Fr tx1%fsi%Otms%Mfwyj3%Nsktwr fyts%
ymjtw~?%F%ktzsifyts%ktw%htr ugj}ny~%xhnjshj3'%Uwthjjinslx%tk%ymj%
Sfyntsfq%Fhfijr ~%tk%Xhnjshjx%66>3%8%-7577.?%j766>5=>66>3

Ofr jx1%W3%fsi%Hwzyhmknjqi1%O3%-756<.3%R zqyn{fwnfyj%Ijujsijshj%
gj~tsi%Xmfssts%Nsktwr fyts'3%Jsywtu~1%6>-65.1%:863

$$I(X;Y) = \sum_{i=1}^{n} \sum_{j=1}^{m} p(x_i, y_j) \log_2 \frac{p(x_i, y_j)}{p(x_i)p(y_j)}$$

$$IG(p(X), q(X)) = \sum_{i=1}^{n} p(x_i) \log_2 \frac{p(x_i)}{q(x_i)}$$

$$I(X;Y) = H(X) + H(Y) - H(X,Y)$$

$$T_{X \to Y} = H(Y_t | Y_{t-1:t-L}) - H(Y_t | Y_{t-1:t-L}, X_{t-1:t-L})$$

Tuyntsfq%Wjfinsl?%Uwtptujspt1%R npmfnq%Kfgnt%Gtxhmjyyn1%fsi%Fgj}%O3%W~fs3%
'Fs%nsktwr fynts%ymjtwjynh%uwr jw%ts%htr uqj}ny~1%xjqk%twlfsn{fynts1%fsi%
jr jwljshj3' Htr uqj}ny~ 6:36%-755>.%662=3

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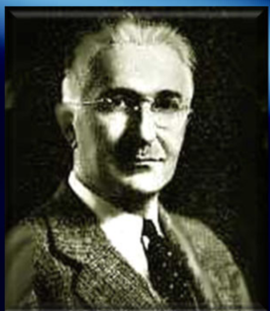
## information as decrease in uncertainty .



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

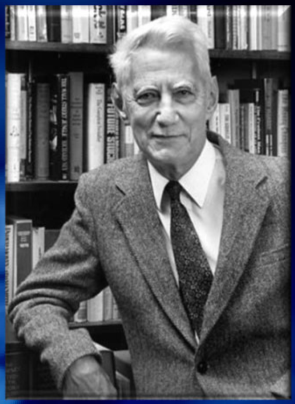
Measured in bits

Number of Choices

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

including more structure reduces surprise

information is surprise



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

Measured in bits

Probability of alternative

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

- Class Book
  - Klir, G.J. [2001]. *Facets of systems science*. Springer.
- Papers and other materials
  - Negin Esmaeili:
    - Heims, S.G. [1991]. *The Cybernetics Group*. MIT Press. Chapters: 1 - 2.
      - Optional: Chapters 11-12.
      - Optional: McCulloch, W. and W. Pitts [1943], "A Logical Calculus of Ideas Immanent in Nervous Activity". *Bulletin of Mathematical Biophysics* **5**:115-133.
  - Amahury Lopez Diaz:
    - Gleick, J. [2011]. *The Information: A History, a Theory, a Flood*. Random House. Chapter 8.
      - Optional: Prokopenko, Mikhail, Fabio Boschetti, and Alex J. Ryan. "An information theoretic primer on complexity, self-organization, and emergence." *Complexity* **15**.1 (2009): 11-28.
      - Kline, Ronald R [2015]. *The cybernetics moment, or, why we call our age the information age*. Johns Hopkins University Press. Chapters 1-2.