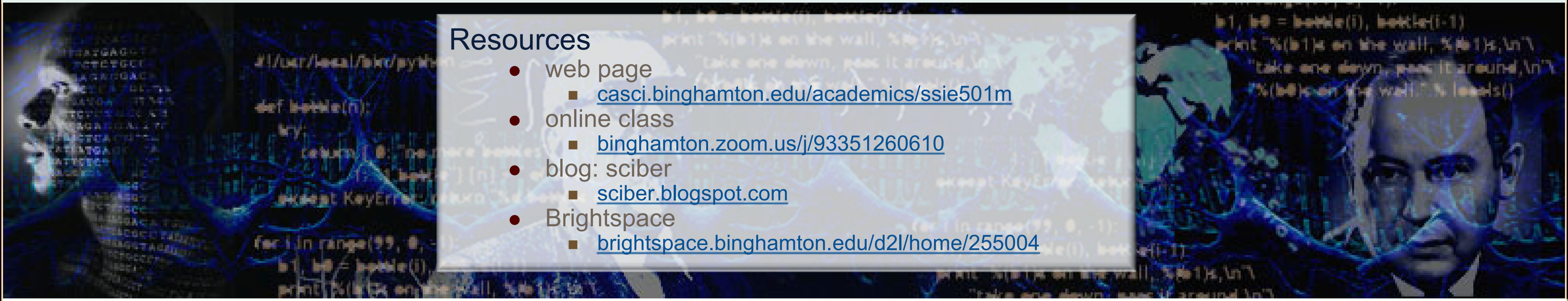


Resources

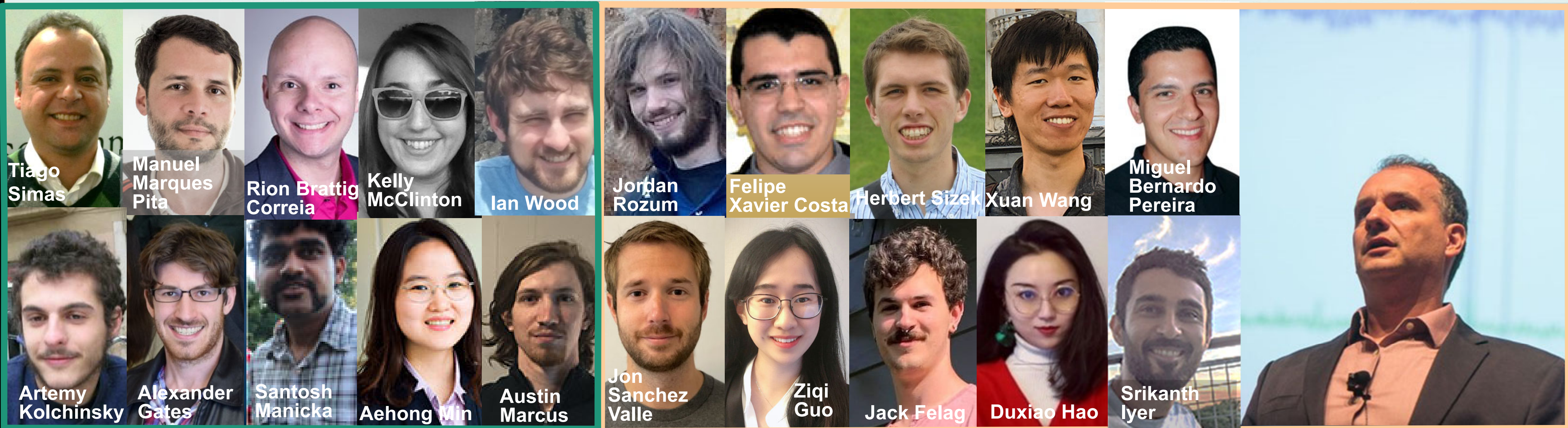
- web page
  - casci.binghamton.edu/academics/ssie501m
- online class
  - binghamton.zoom.us/j/93351260610
- blog: sciber
  - sciber.blogspot.com
- Brightspace
  - brightspace.binghamton.edu/d2l/home/255004

hiroki sayama | SSIE-501 - spring 2025 | **luis m. rocha**

office hours:
Wednesdays: ???
binghamton.zoom.us/my/hirokisayama

office hours:
Thursdays 9-11:30am
binghamton.zoom.us/my/luismrocha

towards extraction of multiscale factors



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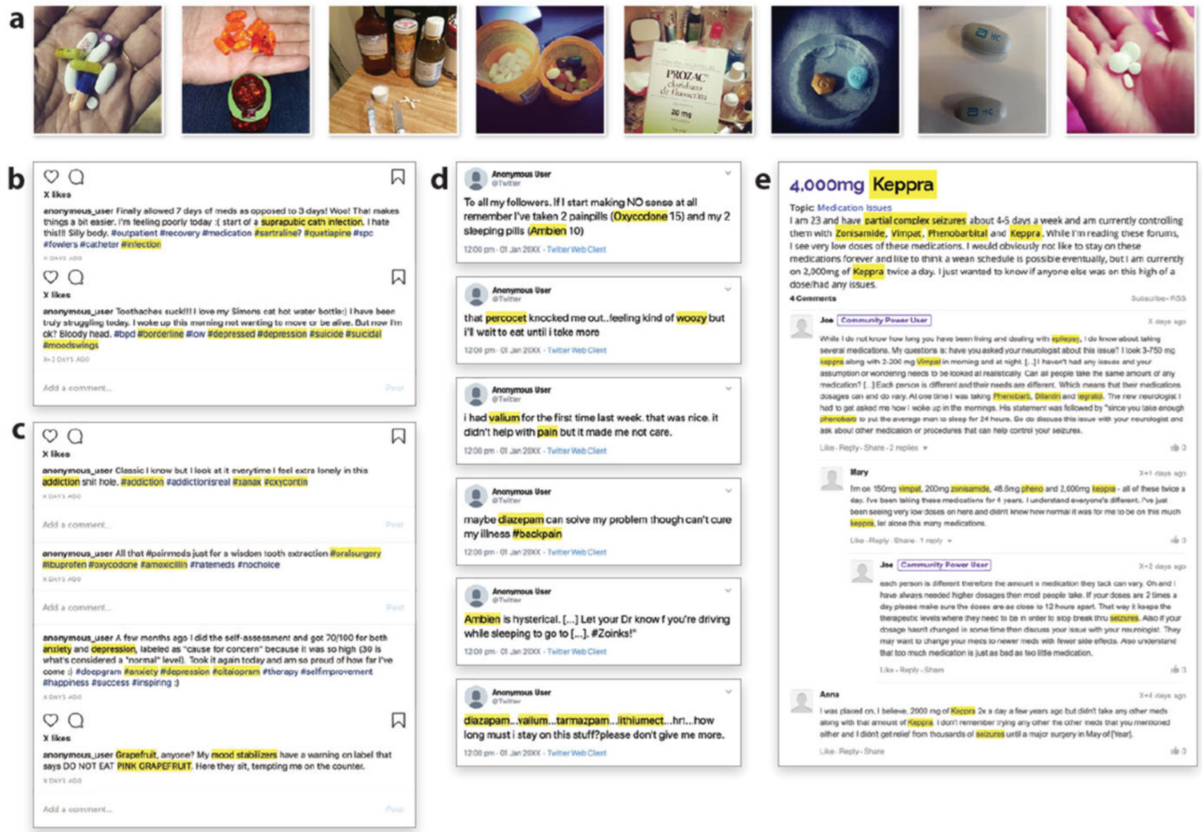
Luanda

social media data pipelines for biomedicine



Min et al [2023]. *CHI 2023*. **32.**
Wood, Correia, Miller, &Rocha [2022]. *Epilepsy & Behavior*. **128**: 108580.
Correia, Wood, Bollen, & Rocha [2020]. *Annual Review of Biomedical Data Science*, 3:1.
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Correia, Li & Rocha [2016]. *PSB*: **21**:492-503.
Ciampaglia, et al [2015]. *PloS ONE*. **10**(6): e0128193.

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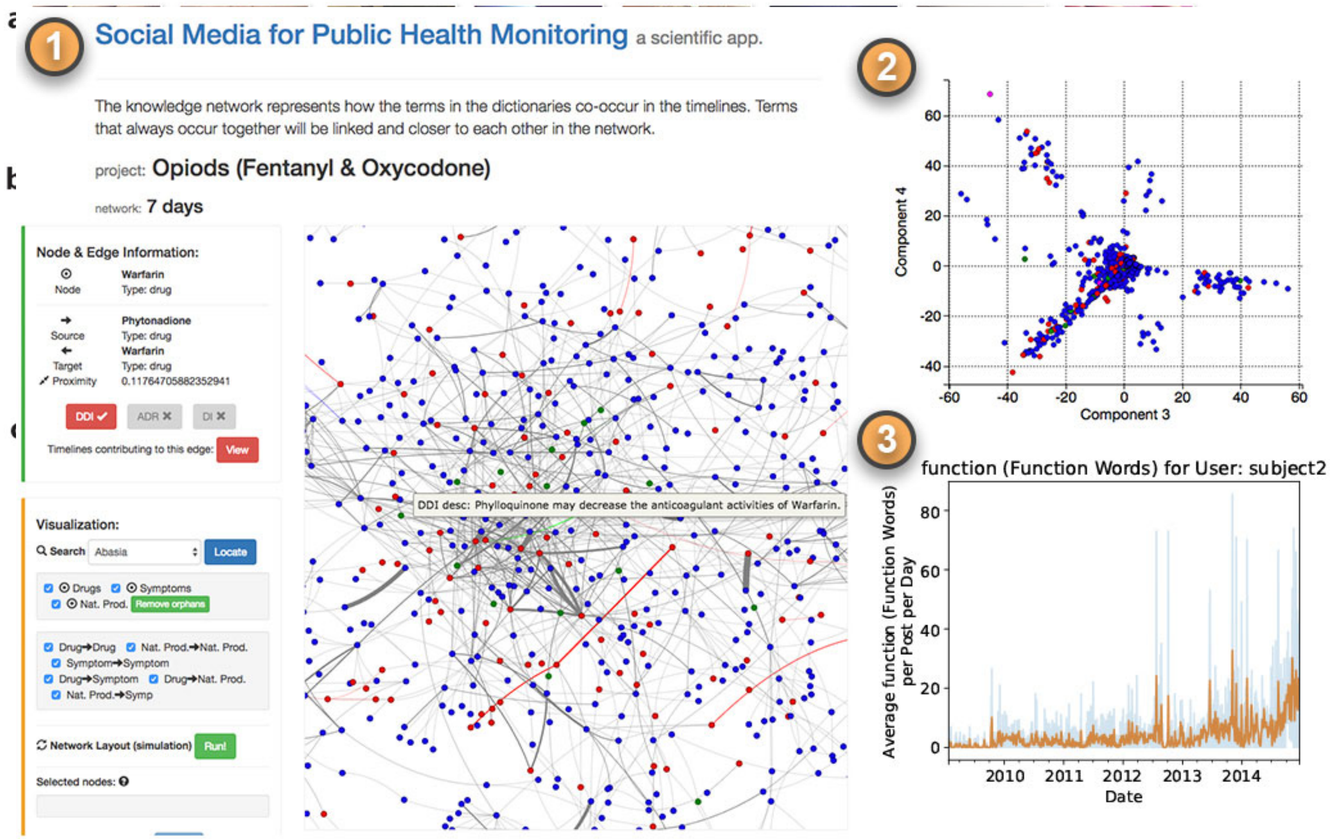
EPILEPSY FOUNDATION



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Wood, Varela, Bollen, Rocha & Sá [2017]. *Scientific Reports. 7: 17973* .

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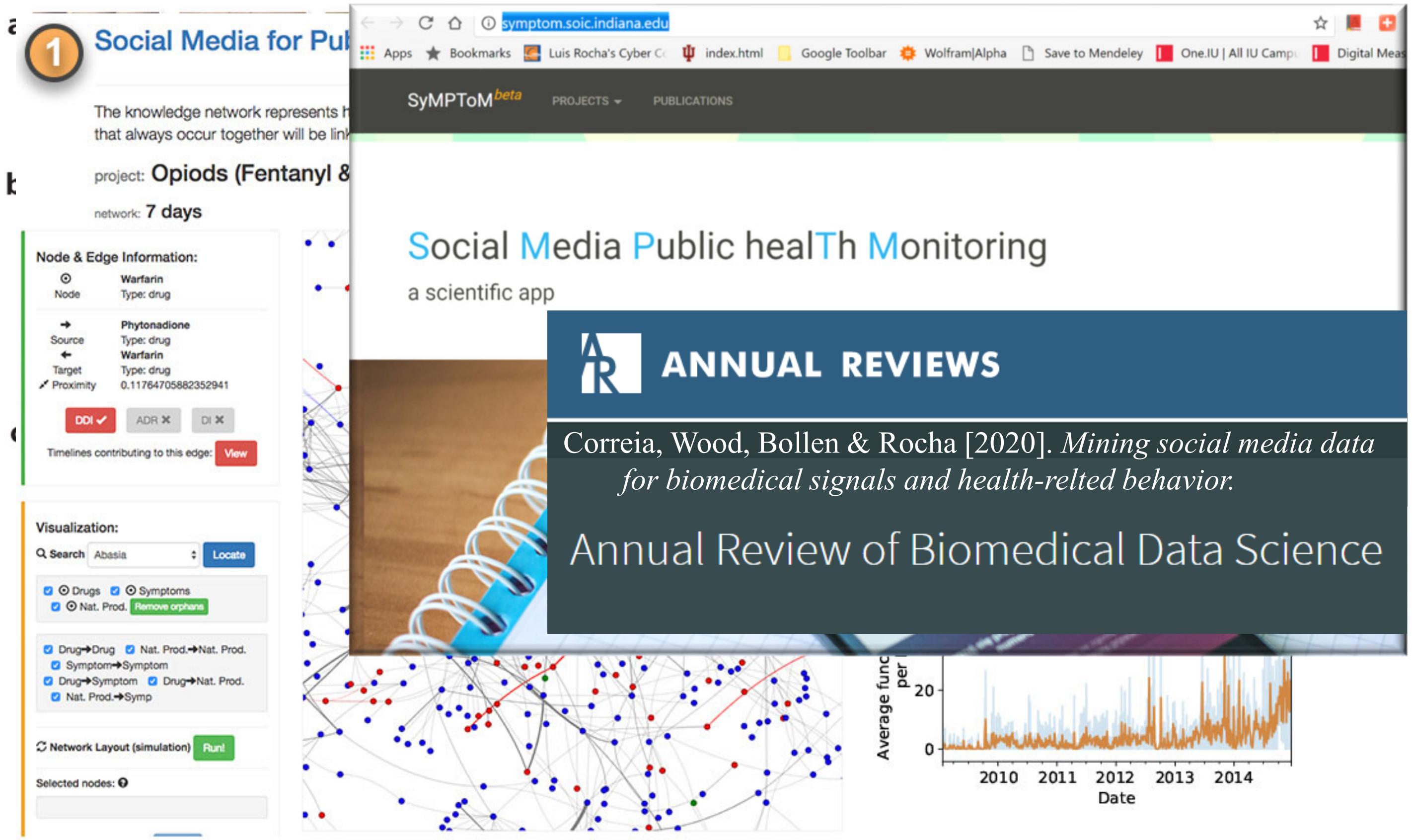

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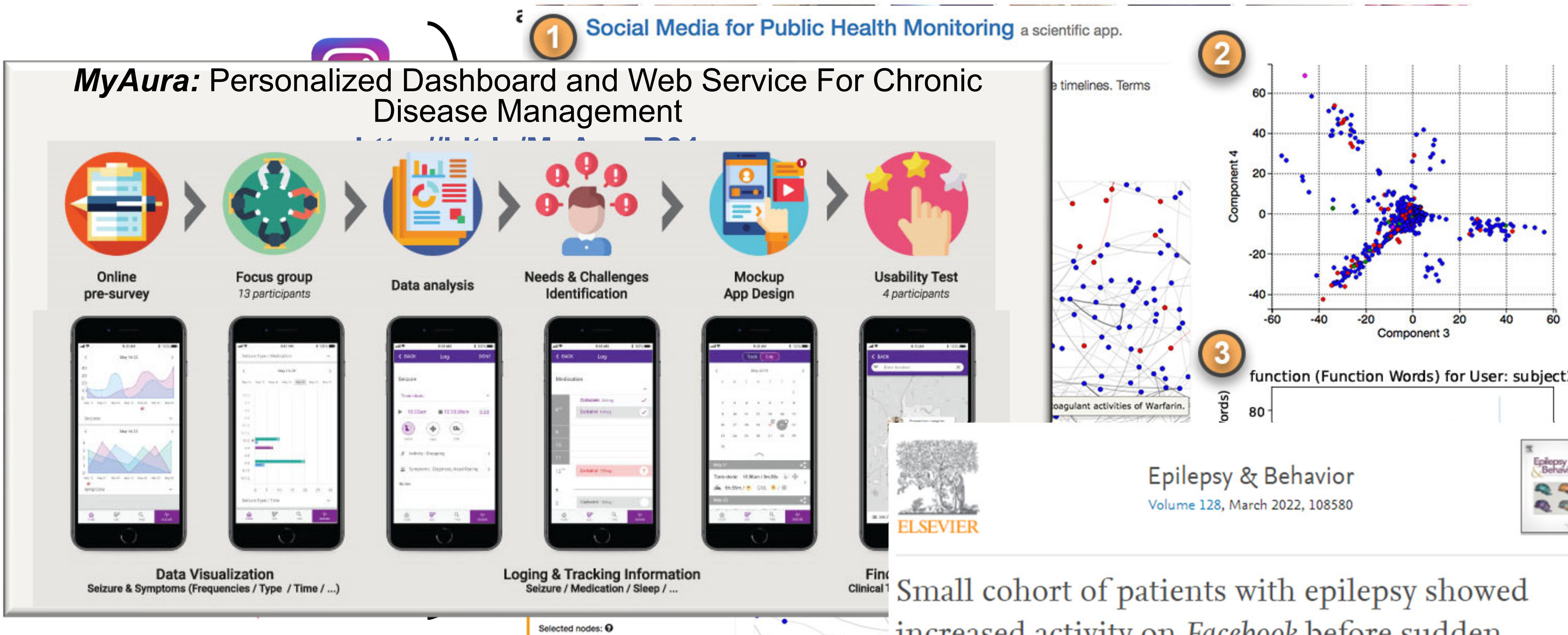

Epilepsy & Behavior

Volume 128, March 2022, 108580

ELSEVIER

Small cohort of patients with epilepsy showed increased activity on *Facebook* before sudden unexpected death

Ian B. Wood [a, 1], Rion Brattig Correia [b, c, a, 1], Wendy R. Miller [d], Luis M. Rocha [e, a, b]

Min et al [2023]. *CHI 2023*. **32.**

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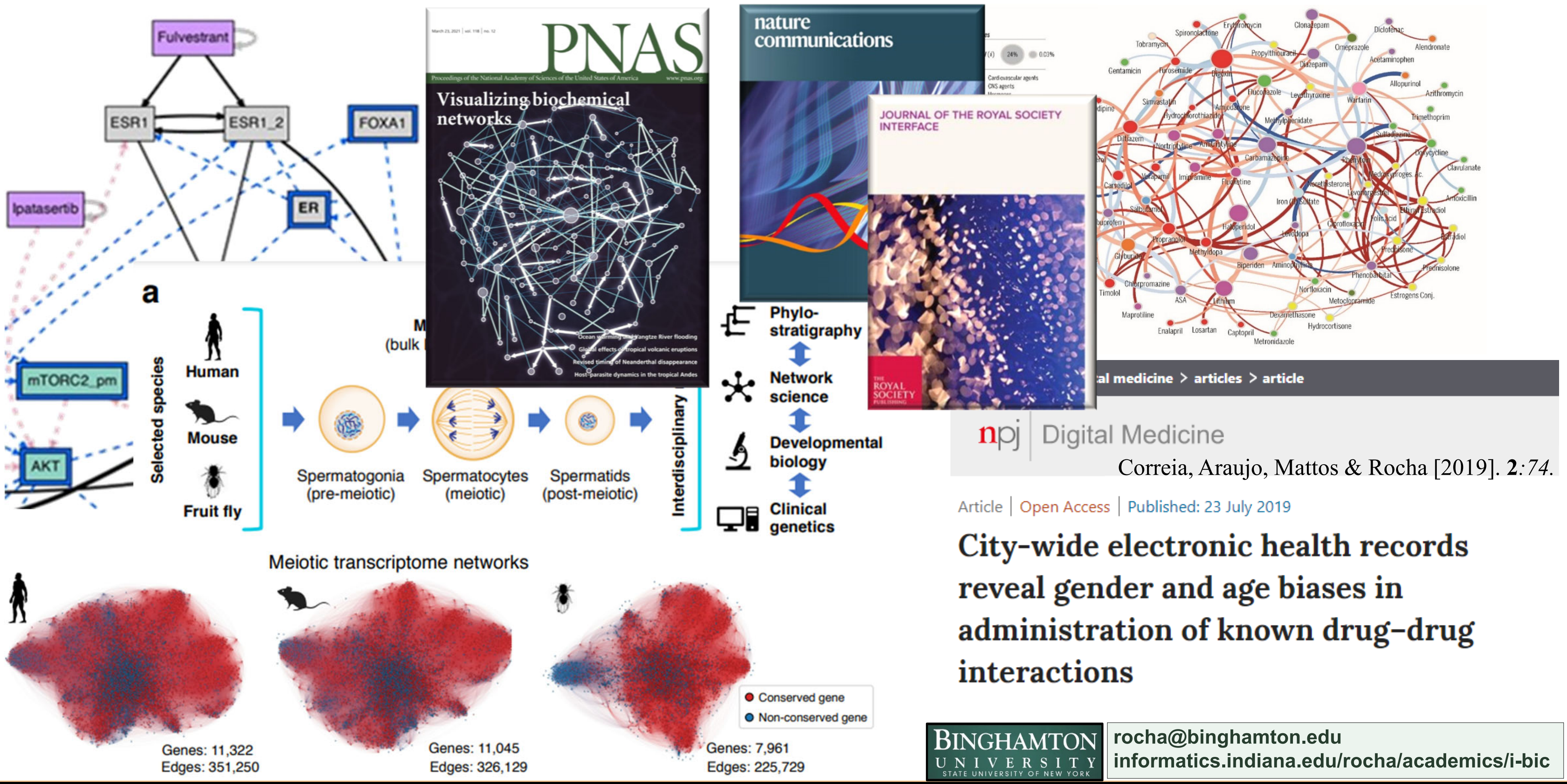
integrating and analyzing multiomic electronic health records with network science

to predict comorbidity & drug interaction networks, disease factors & interventions



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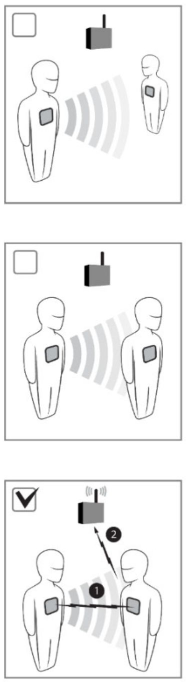
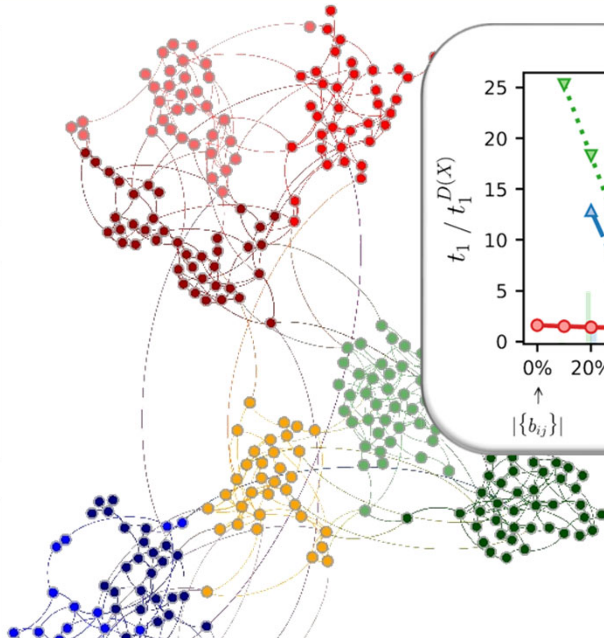
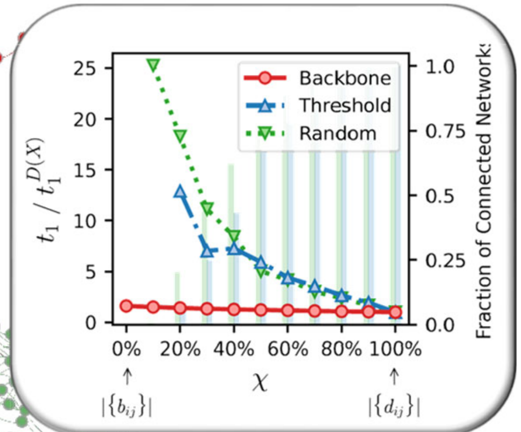
integrating and analyzing multilevel data sources with network science

to predict disease spread, information integration



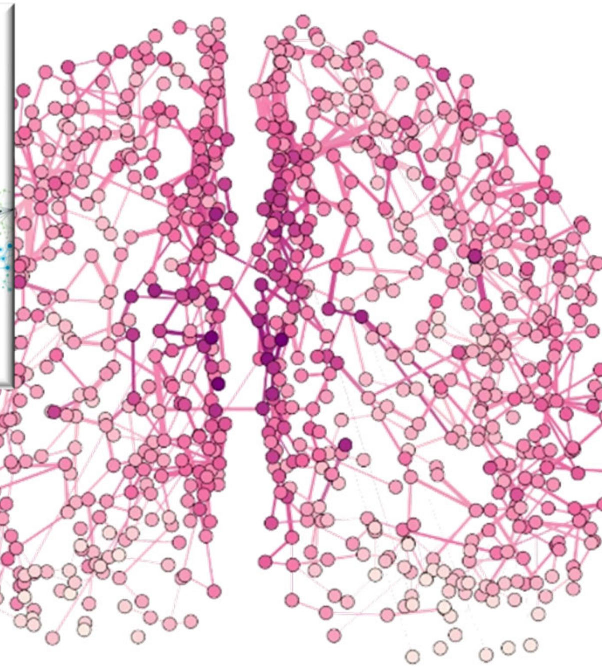




frontiers in NEUROINFORMATICS

ORIGINAL RESEARCH ARTICLE
published: 24 July 2014
doi: 10.3389/fninf.2014.00066

Multi-scale integration and predictability in resting state brain activity



PLOS COMPUTATIONAL BIOLOGY

OPEN ACCESS PEER-REVIEWED

RESEARCH ARTICLE

Contact networks have small metric backbones that maintain community structure and are primary transmission subgraphs

Rion Brattig Correia, Alain Barrat, Luis M. Rocha

Simas & Rocha [2015]. *Network Science*. doi:10.1017/nws.2015.11

Simas, Correia & Rocha [2021]. *J Complex Networks*. **9** (6), cnab021.

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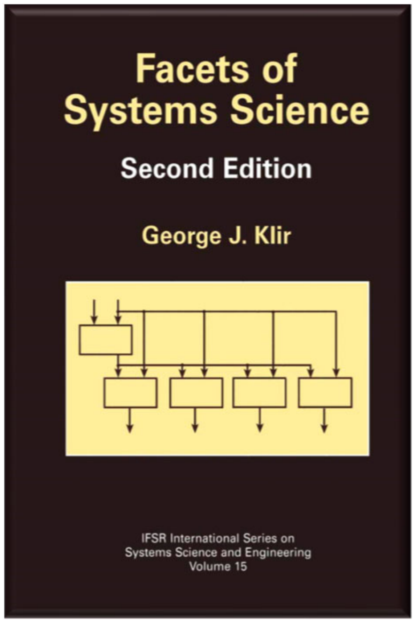
E-TRASH
LIVE IN LISBO
TikTok
@djetrash
TikTok
@djetrash
TikTok
@djetrash
PM - NO COVER
FRIDAY, AUGUST 19: 1AM (BASEMENT)

what about you?

- Background
- Interests
- Course expectations

course materials



- Lecture slides and notes
  - See course web page and brightspace
- Web links and general materials
  - Blog (**sciber.blogspot.com**) and brightspace
- Class Book
  - Klir, G.J. [2001]. *Facets of systems science*. Springer.
    - Available in electronic format for SUNY students.
- Various literature for discussion
  - Course web site and brightspace

Overview and aims

- The course deals with the foundations of Systems Science, as well as current advances in Complex Networks and Systems which is the modern expression of this interdisciplinary field.
- Aims
  - Introduce and discuss the history, methodology and impact of complex systems science.
  - key literature, recent advances, and computational techniques in the field.
  - study concepts such as
    - Information, General Systems Theory, Networks, Modeling, Multi-Level Complexity, as well as their impact on science and society.
  - The course will also attempt to define and understand what systems thinking can bring to science and society.

evaluation

- Participation and Discussion: 15%.
  - class discussion, everybody reads and discusses every paper
  - engagement in class
- Lead Discussions: 25%
  - Students are assigned to papers as lead discussants
    - all students are supposed to read and participate in discussion of every paper.
  - Lead discussant prepares short summary of assigned paper (10 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.
  - Class discussion is opened to all
    - lead discussant ensures we important paper contributions and failures are addressed
- Python Homework: 25%
  - From Python workshop (3rd Session Prof. Sayama)
- Term Paper/Project proposal: 35%
  - A paper with an overview of the topics and literature covered, or a proposal for a project that uses complex systems thinking in your domain of expertise

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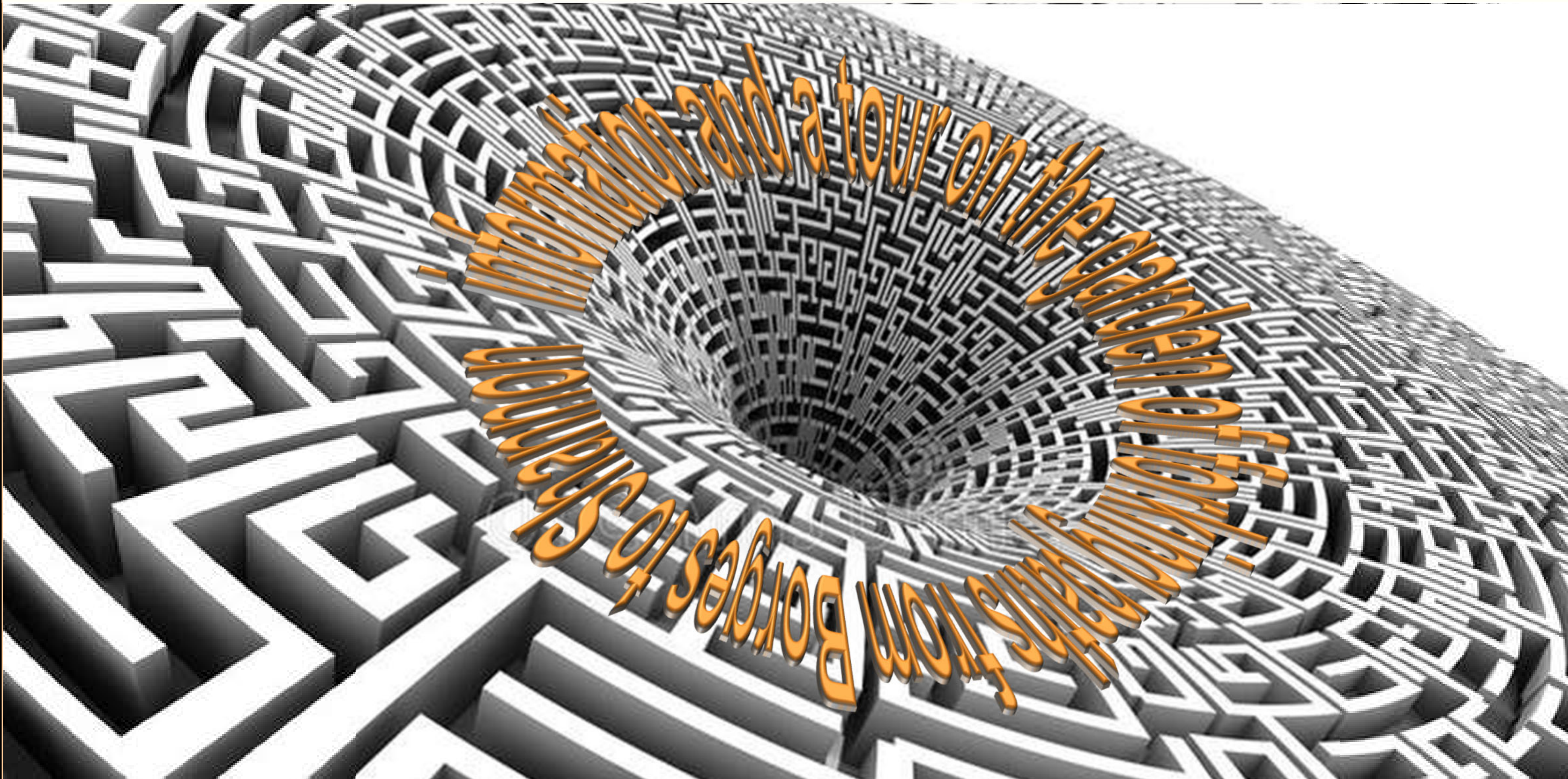
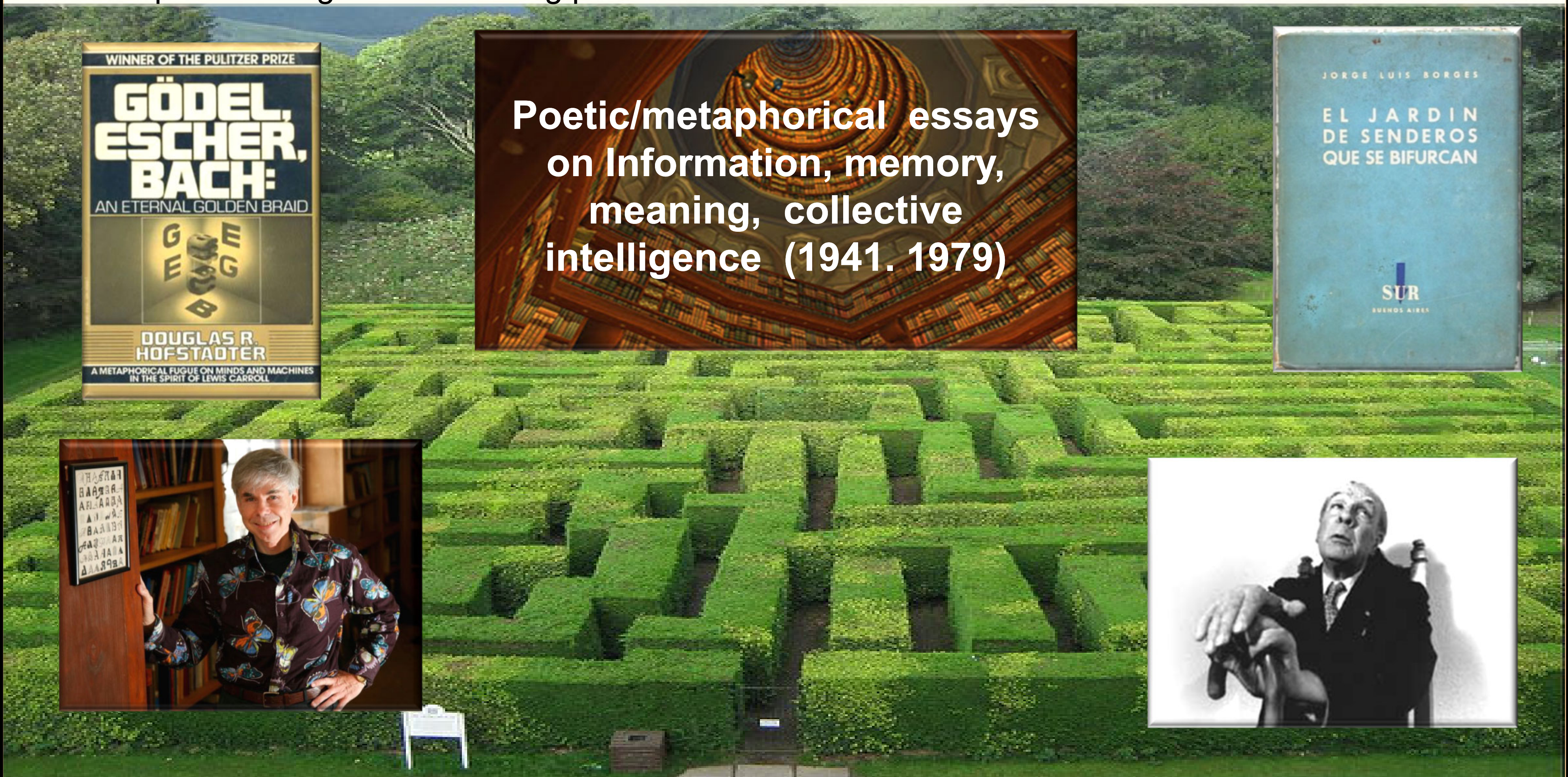
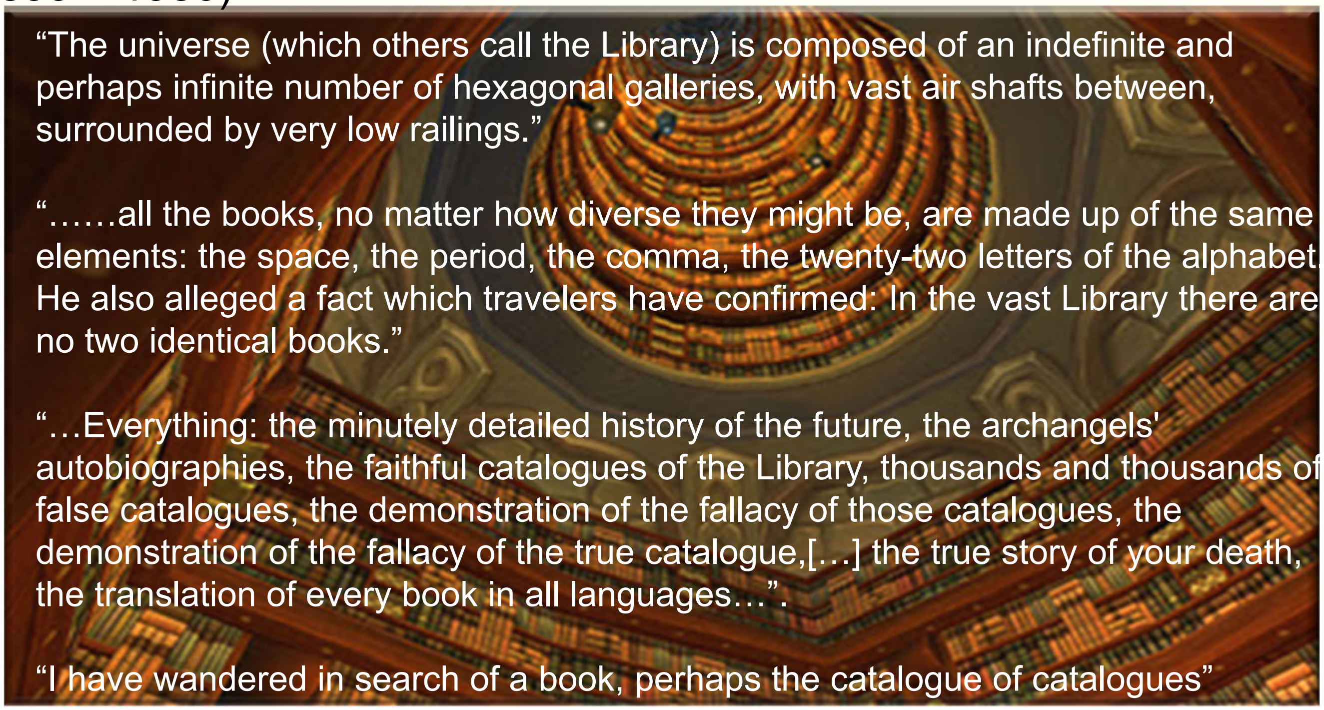
lecture 1: information and a tour on the garden of forking paths from Borges to Shannon



Personal path in the garden of forking paths



Jorge Luis Borges (1899 – 1986)

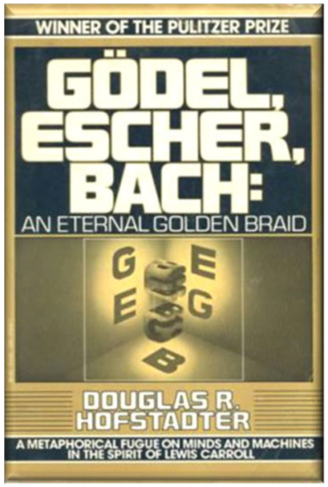


"The universe (which others call the Library) is composed of an indefinite and perhaps infinite number of hexagonal galleries, with vast air shafts between, surrounded by very low railings."

"……all the books, no matter how diverse they might be, are made up of the same elements: the space, the period, the comma, the twenty-two letters of the alphabet. He also alleged a fact which travelers have confirmed: In the vast Library there are no two identical books."

"…Everything: the minutely detailed history of the future, the archangels' autobiographies, the faithful catalogues of the Library, thousands and thousands of false catalogues, the demonstration of the fallacy of those catalogues, the demonstration of the fallacy of the true catalogue,[…] the true story of your death, the translation of every book in all languages…".

"I have wandered in search of a book, perhaps the catalogue of catalogues"



Poetic essays on information and memory (1941)

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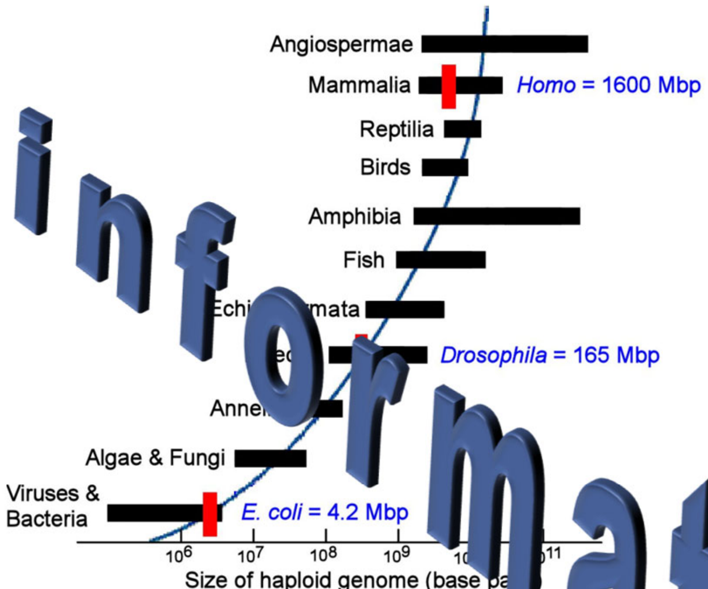
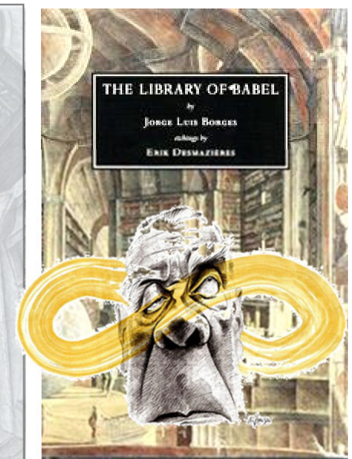
numbers



information

- Each book
  - 25 characters, written in any sequence for 410 pages of 40 lines of 80 characters
  - 410*40*80 = sequence of ≈ $10^{6.1}$ characters
    - ≈ $10^{7.2}$ base pairs (10 Mbp)
    - ≈ 1 book to store E.Coli genotype, 10 for drosophila, and 100 for human
- How many possible books?
  - = $25^{(410*40*80)}$ combinations = $25^{1,312,000}$ books!
    - ≈ 1.956 x $\mathbf{10^{1,834,097}}$ books
  - Total number of atoms in the current, observable universe is about 10^{80}
    - If each book were the size of an atom, library would hold $10^{1,834,017}$ **universes**!
  - Yet finite!
    - Can also be reproduced with just two symbols (cf Quine, Turing, Leibniz)



Information Space Is finite but larger than Physical space

"the Library is so enormous that any reduction of human origin is infinitesimal."
"every copy is unique, irreplaceable, but (since the library is total) there are always several hundred thousand imperfect facsimiles: works which differ only in a letter or a comma."

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What to do in such information spaces to avoid becoming a Quixotic wanderer?

Are there principles of organization?

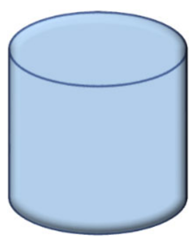

How did we get here?
MEDIA
NETWORK SEARCH
WORLD
BUSINESS

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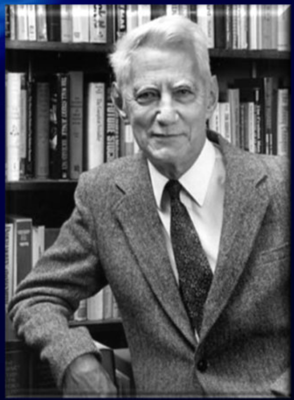
Hartley, R.V.L., "Transmission of Information", *Bell System Technical Journal*, July 1928, p.535.

- 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.

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.



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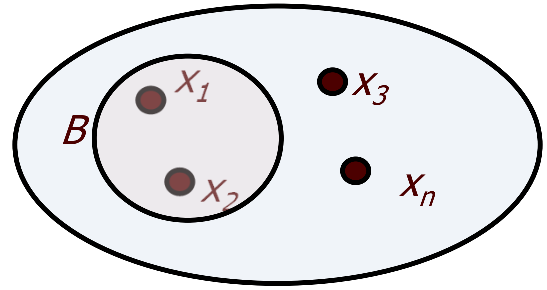
- Nonspecificity
  - Hartley measure
    - The amount of uncertainty associated with a set of alternatives (e.g. messages) is measured by the **amount of information needed to <u>remove</u> the uncertainty**

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

A = Set of Alternatives



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

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

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

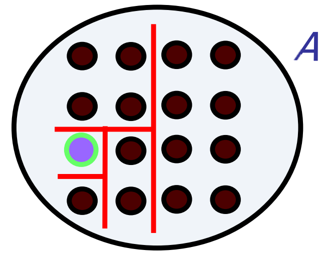
$$H(A) = \log_2 |A|$$

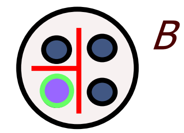
Measured in bits

Number of Choices

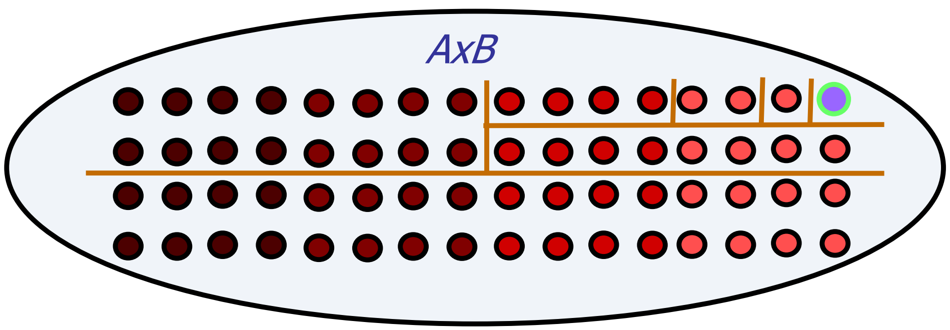
Quantifies how many yes-no questions need to be asked to establish what the correct alternative is

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

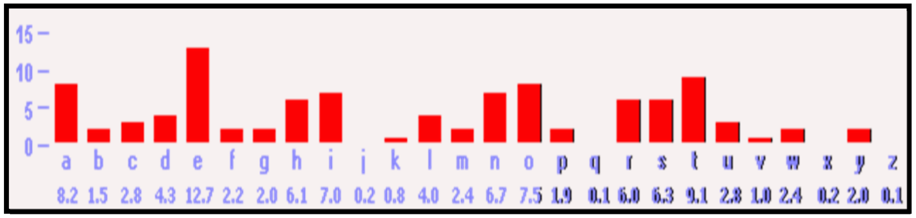




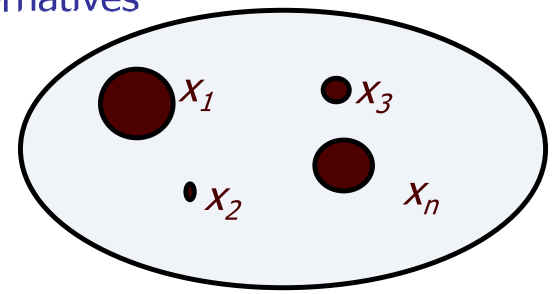
$$H(A \times B) = \log_2(16 \times 4) =$$
$$= \log_2(16) + \log_2(4) = 6$$



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.

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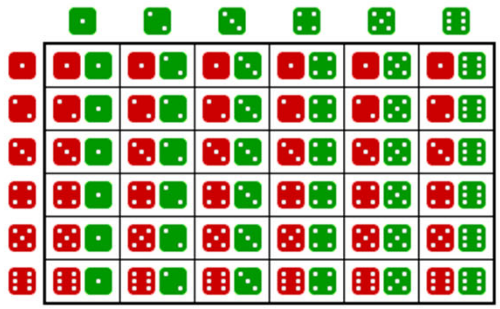
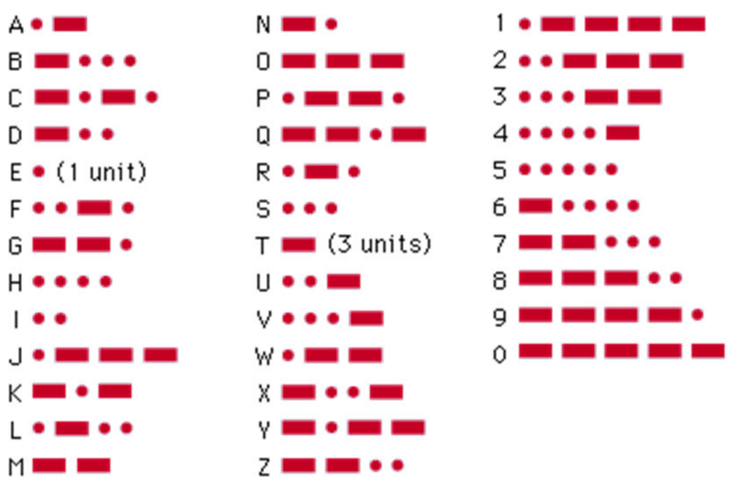
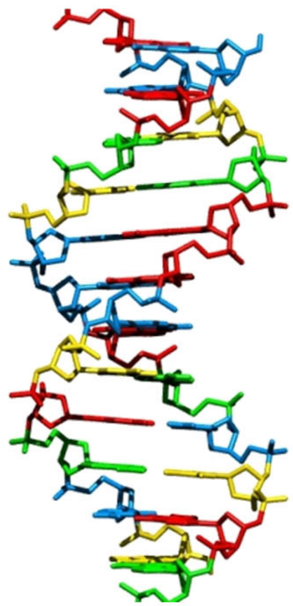
alphabet examples

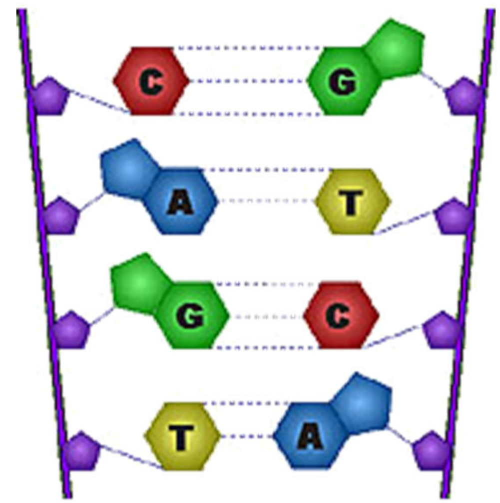


Message encoded in an alphabet of ***n*** symbols, for example:

- 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"

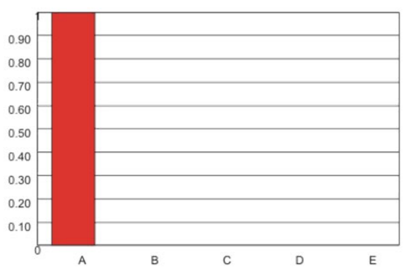
- Given a symbol set {A,B,C,D,E}
  - And occurrence probabilities P_A, P_B, P_C, P_D, P_E,
- The Shannon entropy is
  - The average minimum number of bits needed to represent a symbol

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

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

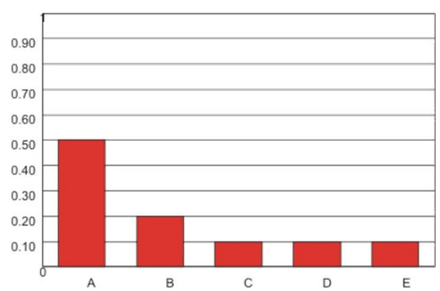
$$H_S = -5.\left(\frac{1}{5}\right).\log_2\left(\frac{1}{5}\right) = -(\log_2(1) - \log_2(5)) = \log_2(5)$$

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



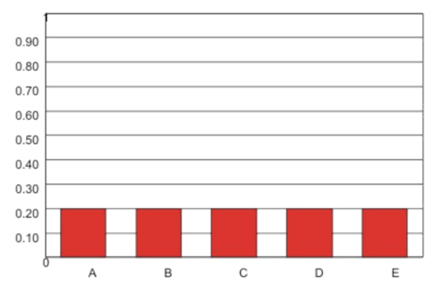
H_S = 0 bits

0 questions



H_S = 1.96

≈2 questions



H_S = 2.32 bits

information is surprise

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what it measures

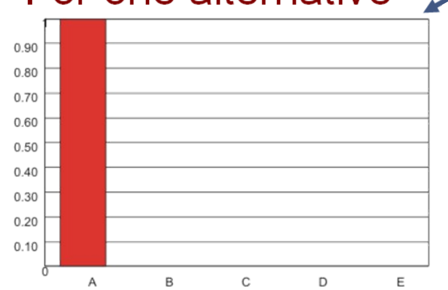
uncertainty, about outcome. How much information is gained when symbol is known

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

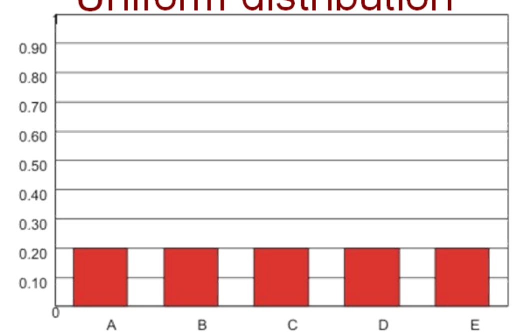
$$H_S \in= -\sum_{i=1}^{n} p(x_i)\log_2\big(p(x_i)\big)$$

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

For one alternative



Uniform distribution



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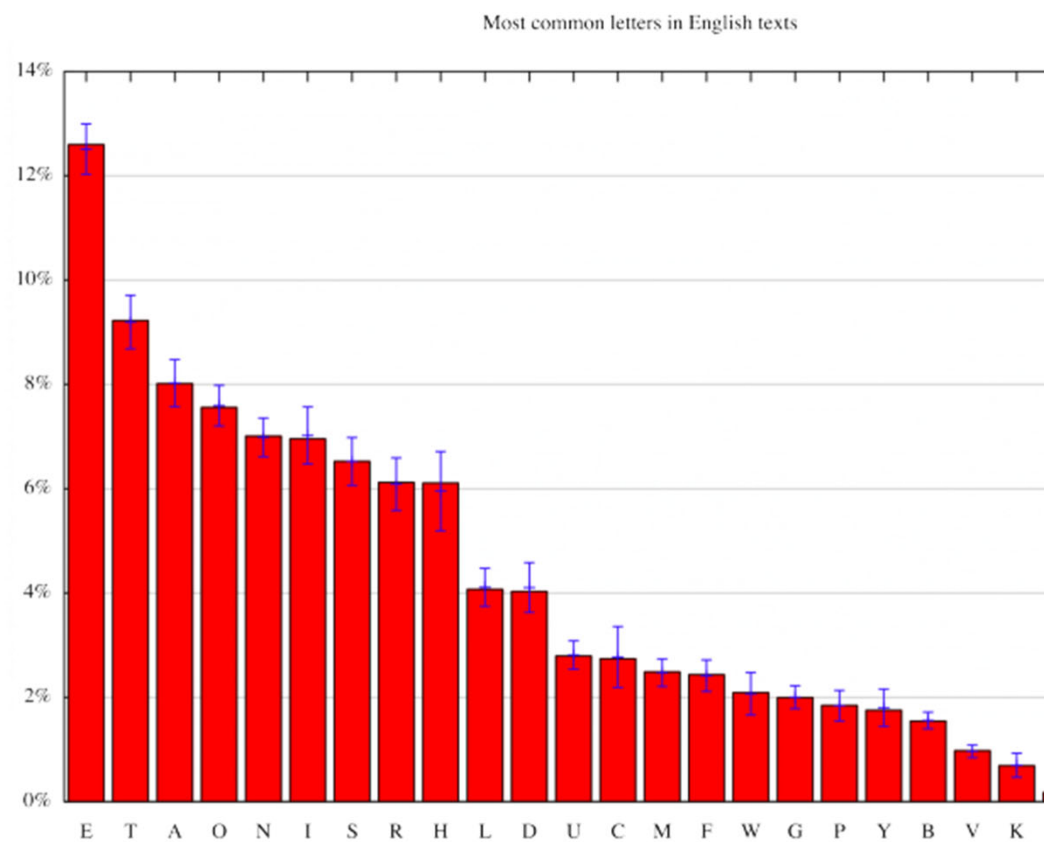
from letter frequency

	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	0.02270	-5.4574854	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

what’s (not) in it?

- 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

Something's got a hold of me lately
No, I don't know myself anymore
Feels like the walls are all closin' in
And the devil's knockin' at my door, whoa

Out of my mind, how many times
Did I tell you I'm no good at bein' alone?
Yeah, it's takin' a toll on me, tryin' my best to keep
From tearin' the skin off my bones, don't you know

I lose control
When you're not next to me (when you're not here with me)
I'm fallin' apart right in front of you, can't you see?
I lose control
When you're not next to me, mm-hm
Yeah, you're breakin' my heart, baby
You make a mess of me

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

eo   t ogaohgSmtos hmefdei'ltlnya l
l Nymlwafs onmn oed ,'orktn oey
lan ell isecli'lao l askelniteFrewsh
a mnkd kni eds h''tywviroleno,oa hAdt oc

i mO ywt ynoefhmdmmia ous tn,
a bdIoo nit o ludel yt'e' ooiaemnlnlDg?
y htmtaoyi Y e'e, bt'ltnnak' stkei,a orotmns eepli
trtdn ns hu o''fye ea   nnofrFeoitb ,msonoikomykw

tonI eors ollc
ienm w' t ot)tortee nhW'e(ronu he
eenexrhneotmhoyyuw
oi'au,If rternlclt an'to ?i af pmy uytf rna onigsheo'
olrlc o slnote
ue e,no ot ht 'yhtm-Wmnnr ome emx
ebhe yb' ntYy,,eihbaa 'eamku rray ro
o e mmsfmY sea aoe uk

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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

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)
  - ...nd q,
  - ... represent q (model approximation) as it
- ...ses in time
  - ..., in knowing future values of Y, knowing the past values of X and Y.

Whdglqlv?Lrodq1#Fp rv#dqg#Orkq#Mduh3#Nqirup dwlrq#wkhru|?F#
irxqgdwlrq#ru#frp sch{lw|#vflhqfh3'#Urfhhglqlv#ri#wkh#Sdwlrqdo#
Ffdghp |#ri#Xflhqfhv#66>388#7577.#h766>5=>66>3

Tswlrqdo#Whdglql?#Odp hv1#W3#dqg#Hxwfkilhog1#D3#756<.3#R xolydulduh#
Ihshqghqfh#gh|rqg#Kdqqrq#Nqirup dwlrq'#Jqwurs|1#5>-65.1#:863

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

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

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

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

Tswlrqdo#Whdglql?#Jurnrshqnr1#R hkdlb#Kdglr#Grvfkhwl#dqg#Fdn{#D3#W|dq3#
'Fq#lqirup dwlrq#wkhruhwlf#sulp hu#rq#frp sch{lw|1#vhoi#ruldql}dwlrq#dqg#
hp hujhqfh3'Hrp sch{lw| 6:36#755>.3#627=3

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information as decrease in uncertainty .

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

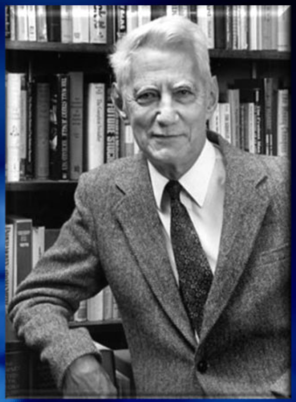
Measured in bits

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

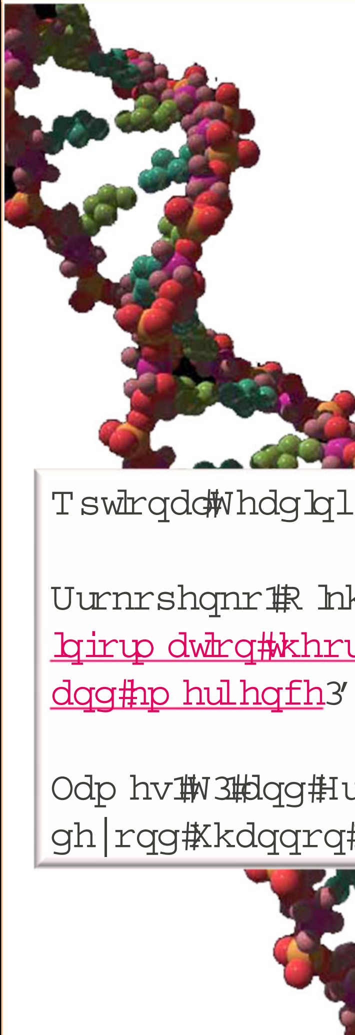


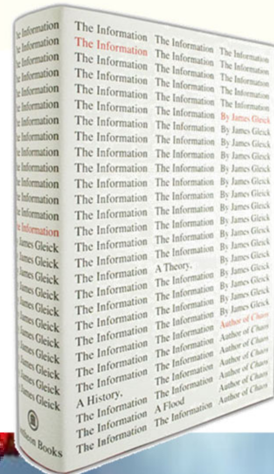
$$H_S(A) = -\sum_{i=1}^{n} p(x_i) \log_2\left(p(x_i)\right)$$

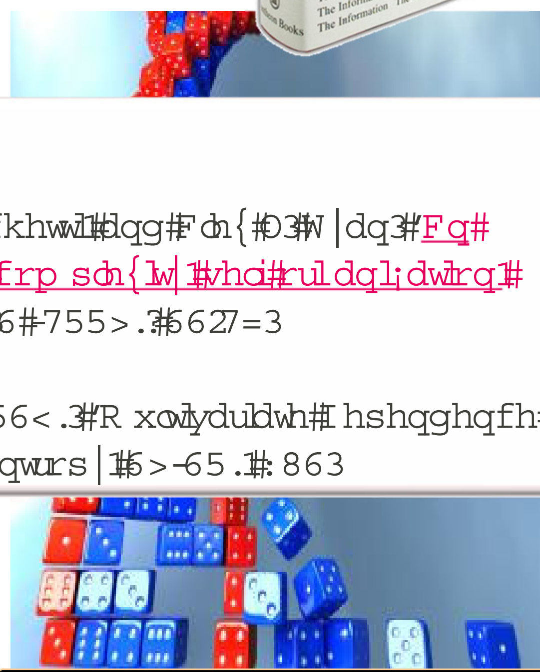
Measured in bits

Probability of alternative

C. E. Shannon [1948], “A mathematical theory of communication”. *Bell System Technical Journal*, **27**:379-423 and 623-656 rate of removing uncertainty of each symbol







Tswlrqdo#Whdglqlv?#

Uurnrshqnr1#R lnkdlo#Kdglr#Grvfkhwl#dqg#Fdn{#03#W|dq3#Fq# lqirup dwlrq#wkhruhwlf#sulp hu#rq#frp sdn{lw|1#vhoi#ruldql;dwlrq1# dqg#hp hulhqfh3'Hrp sdn{lw| 6:36#755>.3#627=3

Odp hv1#W3#dqg#Iuxwfkilhog1#03#756<.3#R xolydudwh#Ihshqghqfh# gh|rqg#Kkdqqrq#Nqirup dwlrq'3#Jqwurs|1#6>-65.1#:863

Something's got a hold of me lately
No, I don't know myself anymore
Feels like the walls are all closin' in
And the devil's knockin' at my door, whoa

Out of my mind, how many times
Did I tell you I'm no good at bein' alone?

I'm fallin' apart right in front of you, can't you see?
I lose control

“syntactic” surprise But what about function and meaning (semantics)?

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