Using big data to quantify the evolution of language at the micro and macro scale

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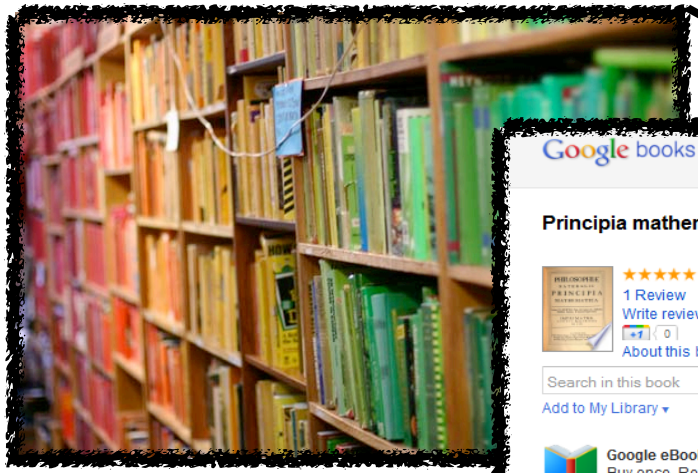
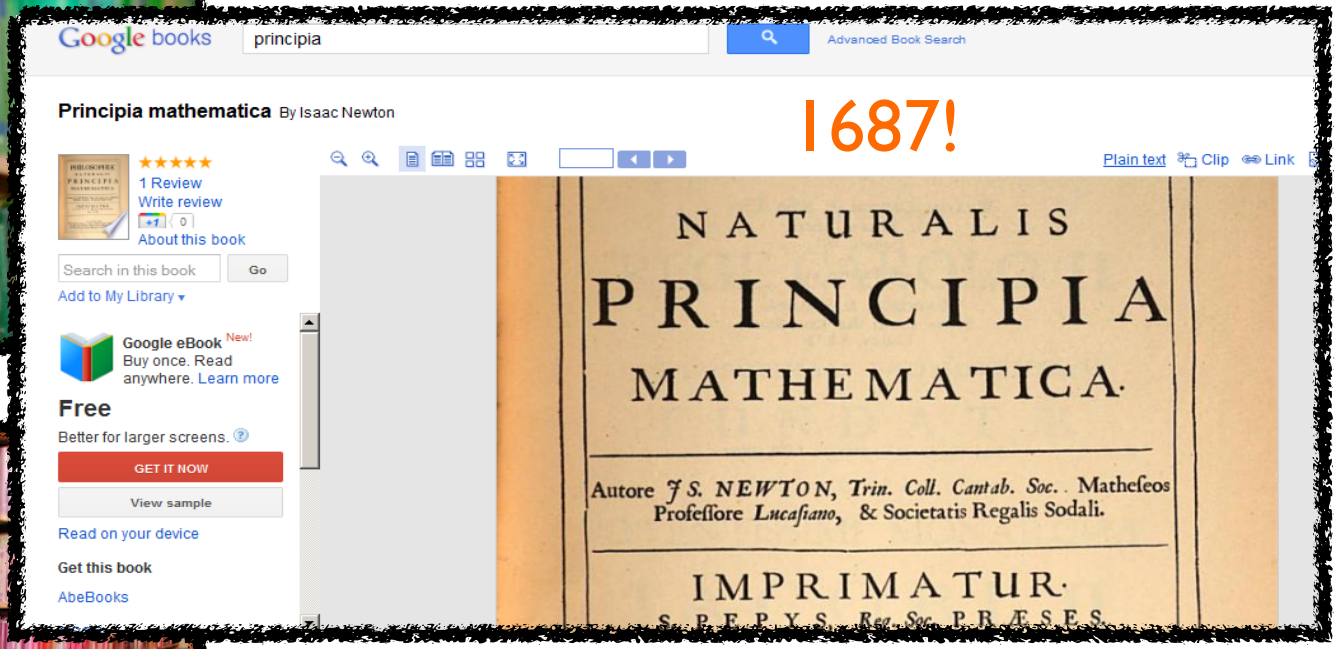
Outline

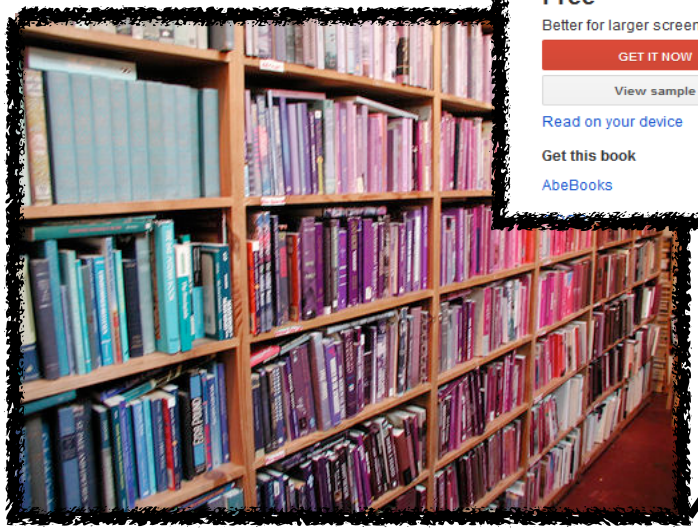
- "Digital Humanities" and "Culturomics":
  new science made possible by "crowd-sourced" "Big data"
- Google digital books: 5 million books and 500 billion word uses
  - Competition (for limited use, attention)
  - Geographic variation: the role of socio-political shocks
  - Tipping points in the life-cycle of new words
  - Languages become "colder as they expand"
  - Uncovering an enormous hidden "Dark language"

Historical crowd-sourced data



Google Inc. digital books repository





Corpus of 5,195,769 digitized books from 1520-present, containing ~4% of all books ever published

Quantitative Analysis of Culture Using Millions of Digitized Books

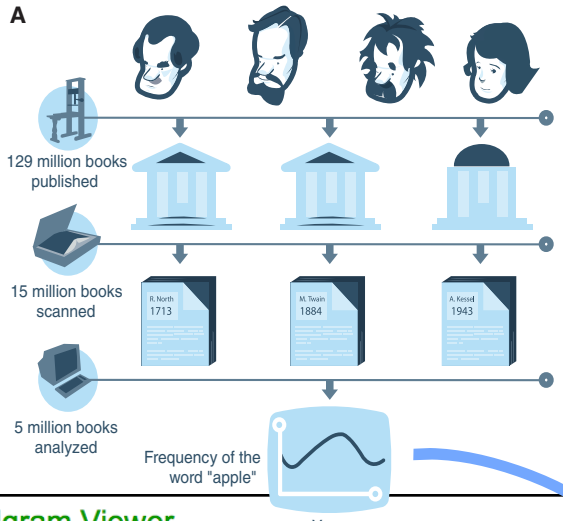
14 JANUARY 2011 VOL 331 **SCIENCE**

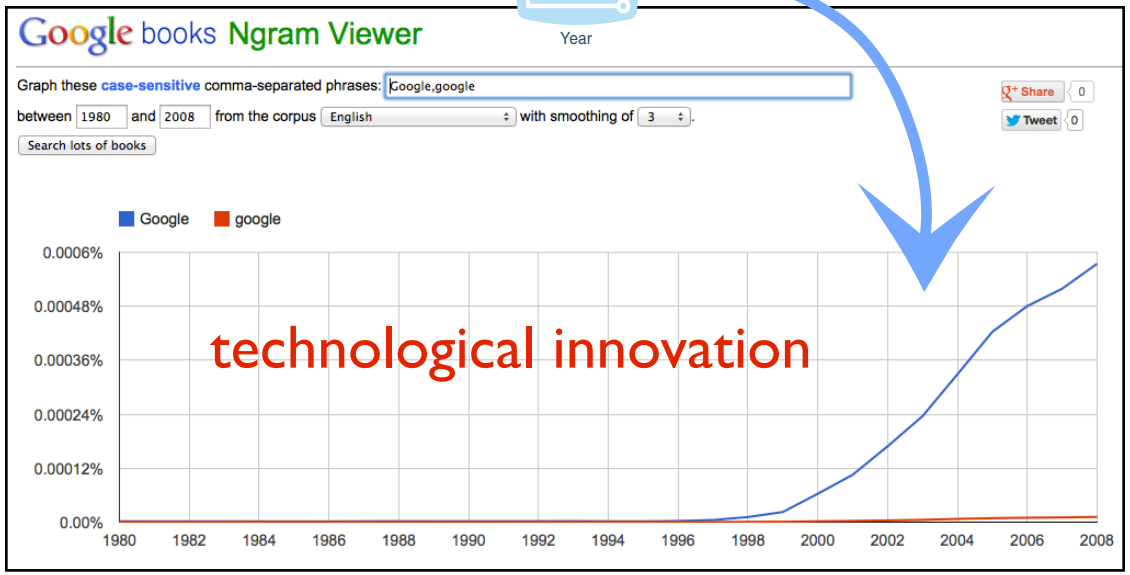
Time series constructed from billions of word counts from books

https://books.google.com/ngrams

Michel, J.-B. et al. Quantitative analysis of culture using millions of digitized books. Science (2011).

Google Inc. digital books repository

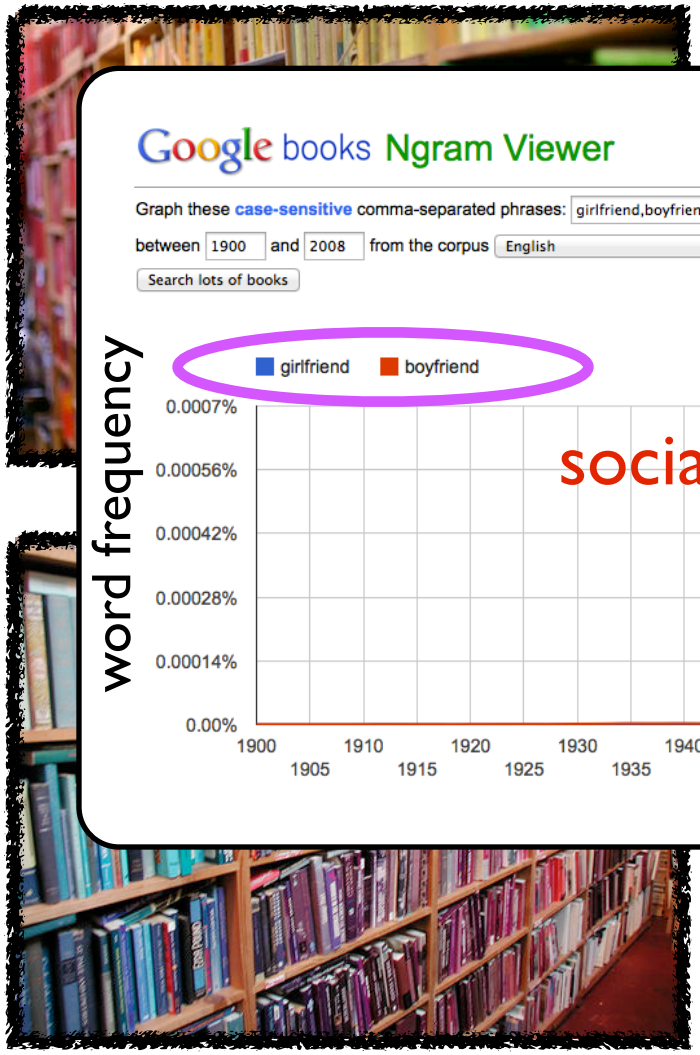




Time series constructed from word counts in books: aggregated at multiple levels

Michel, J.-B. et al. Quantitative analysis of culture using millions of digitized books. Science (2011).

Google Inc. digital books repository



Google books Ngram Viewer

Graph these case-sensitive comma-separated phrases: girlfriend,boyfriend

between 1900 and 2008 from the corpus English with smoothing of 3.

Search lots of books

Share 0 Tweet 0

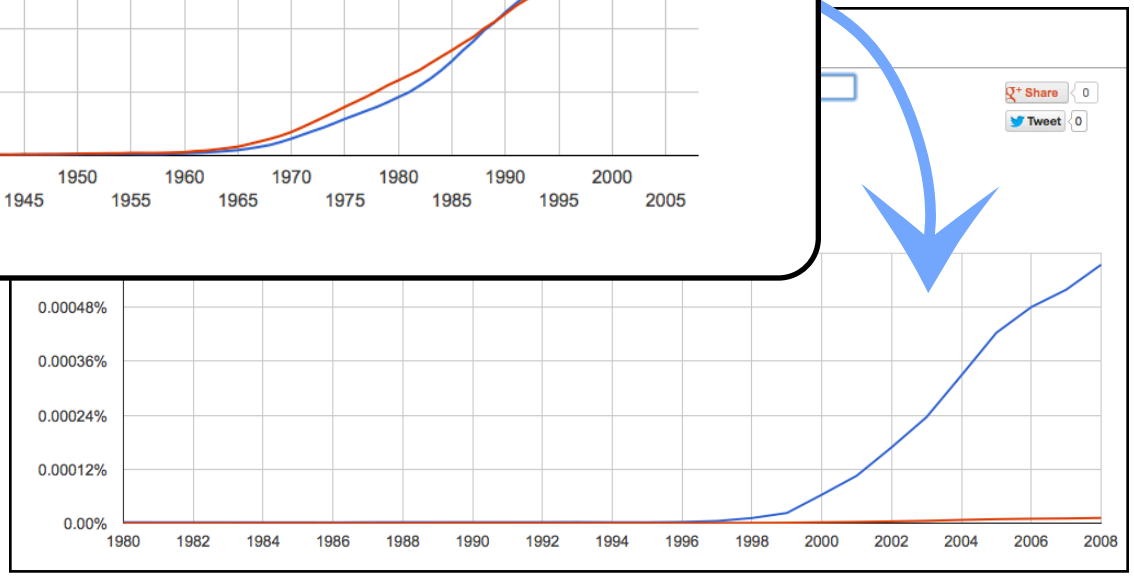
girlfriend boyfriend

word frequency

0.0007%
0.00056%
0.00042%
0.00028%
0.00014%
0.00%

1900 1905 1910 1915 1920 1925 1930 1935 1940 1945 1950 1955 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005

social innovation



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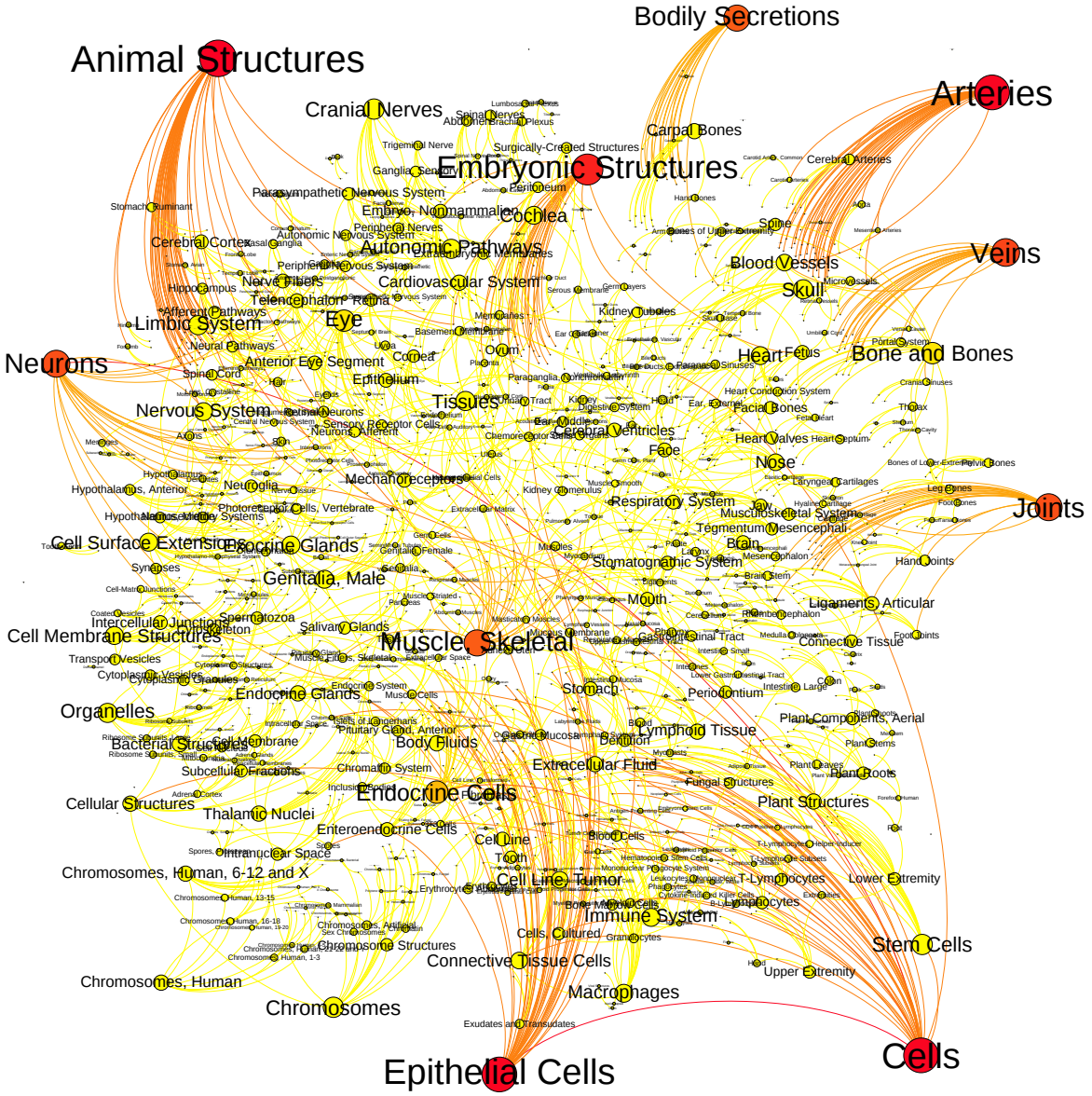
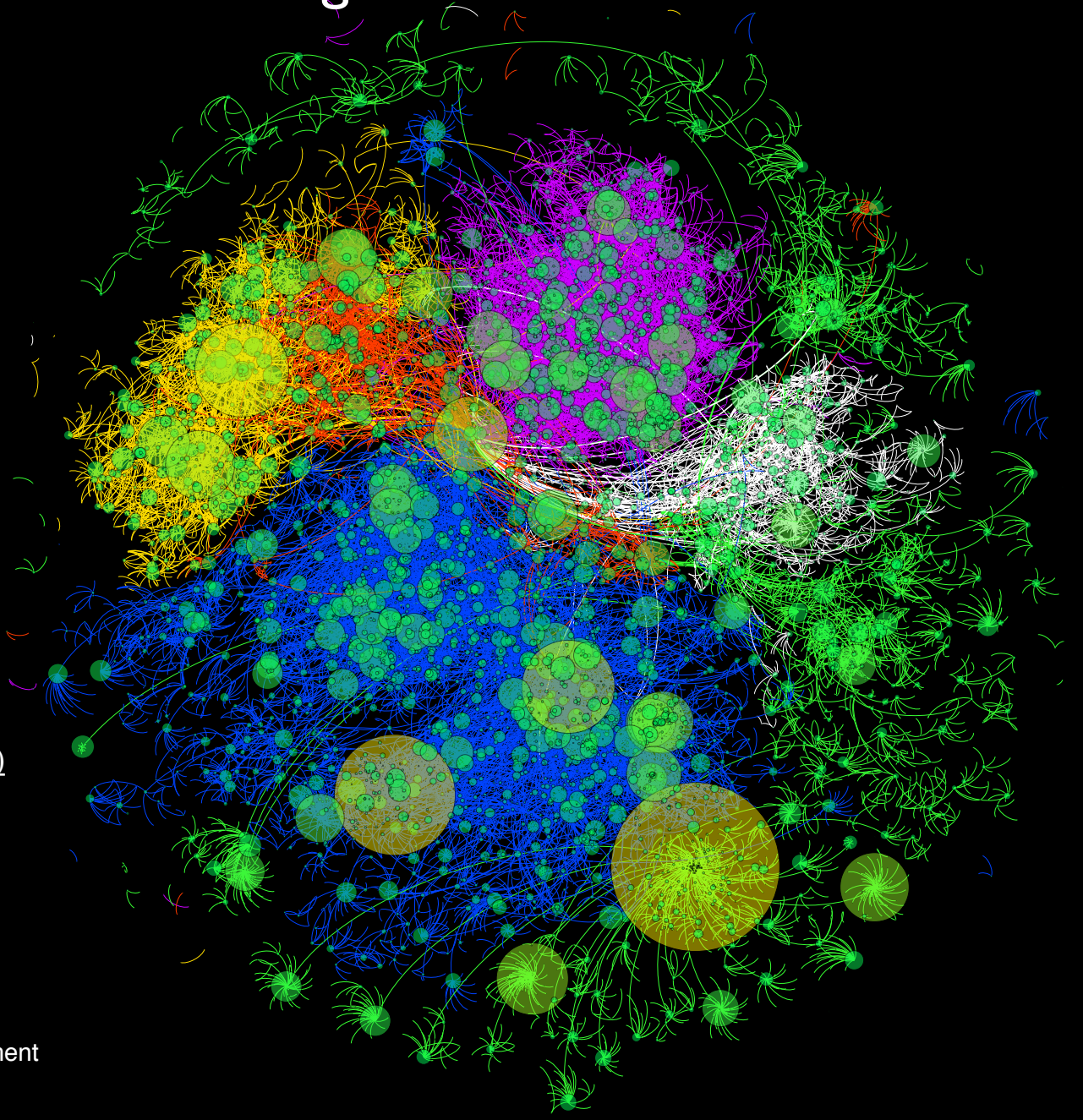
Language is a structured system

Association network of ~ 4000 anatomical words



Words interact forming a relational network



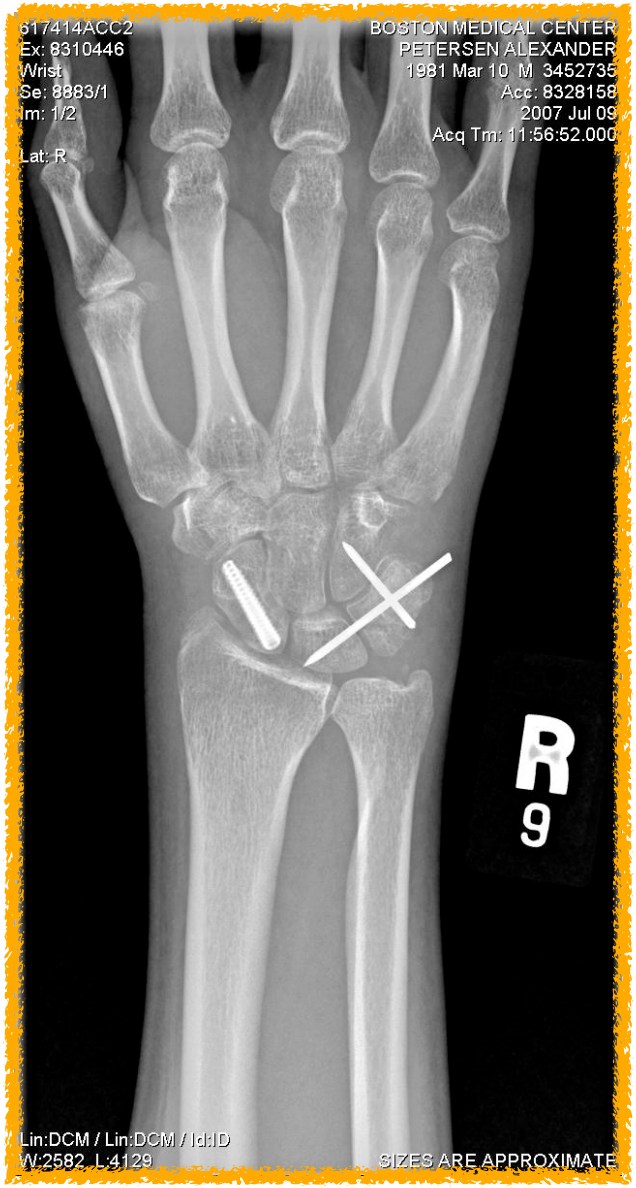
A word network constructed
from ~20,000 biomedical terms
(MeSH: medical subject headings)
developed by the
US National Library of Medicine

[A] Anatomy
[B] Organisms
[C] Diseases
[D] Chemicals and Drugs
[E] Analytical, Diagnostic
and Therapeutic Techniques and Equipment
[G] Biological Sciences

Language is a competitive system

A. M. Petersen, J. Tenenbaum, S. Havlin, H. E. Stanley.
Statistical Laws Governing Fluctuations in Word Use from Word Birth to Word Death
Scientific Reports 2, 313 (2012).

Evidence for competition in a limited marketplace



Is this a:

a) Xray

b) Radiogram

c) Roentgenogram

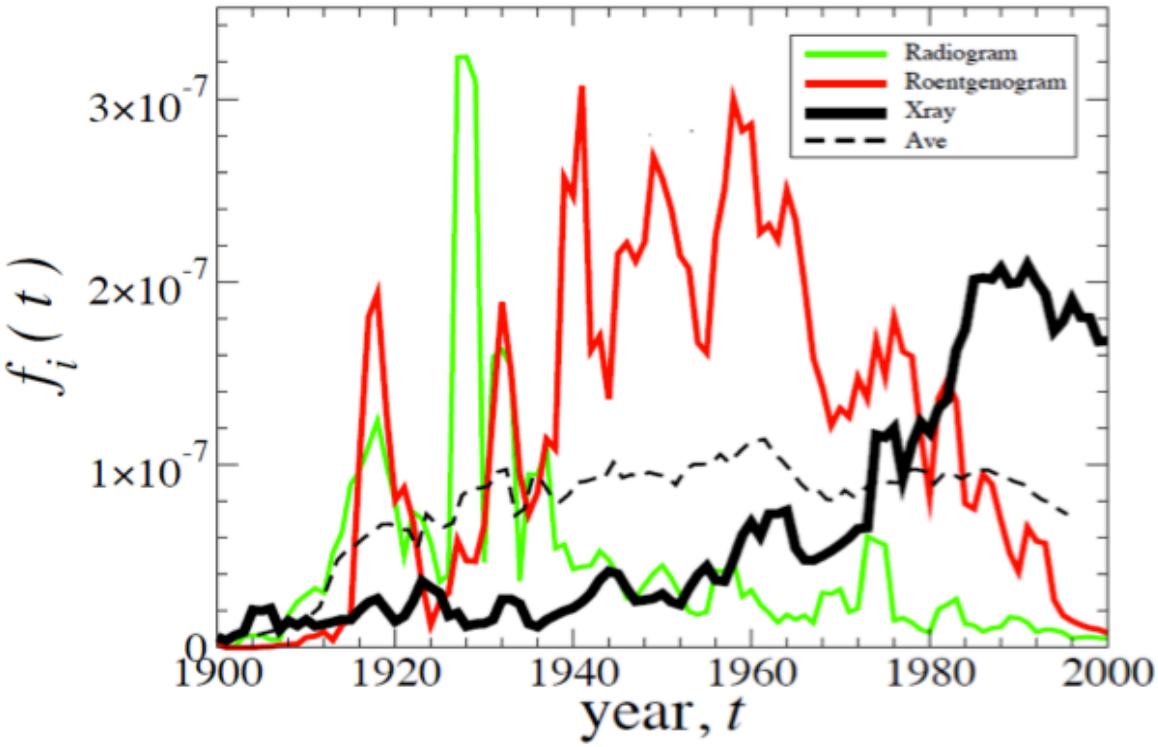
??

Words compete for limited market share

$u_i(t)$: # of uses of word i in year t

word frequency in year t

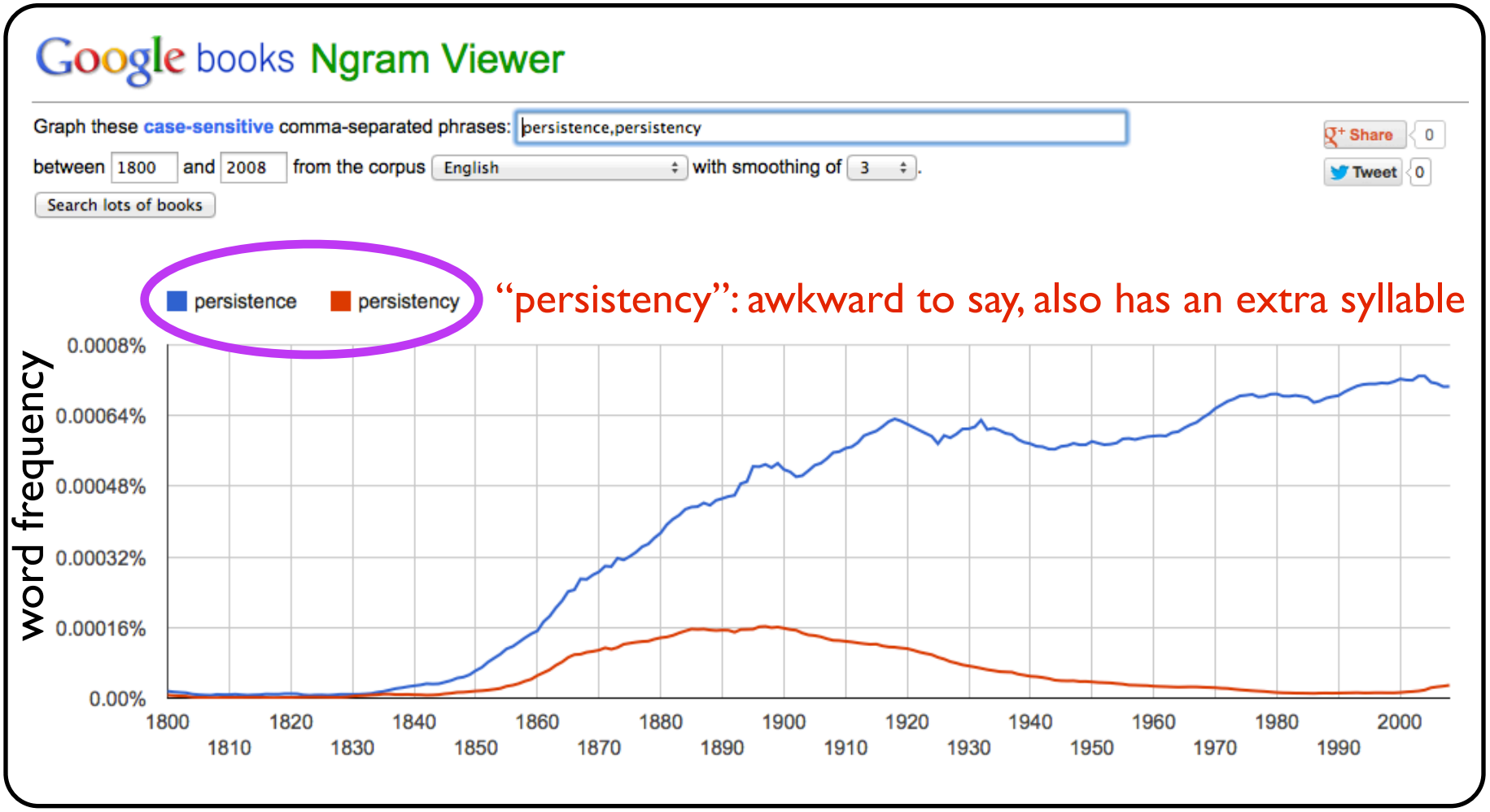
$$f_i(t) \equiv u_i(t)/N_u(t),$$



Competition between:

- Synonyms
- Spellings (e.g. color vs. colour)
- other ideas in an abstract "idea space". Consider the Euphemism treadmill:
  shell shock (WWI) ⇒
  battle fatigue (WWII) ⇒
  operational exhaustion (Korean War) ⇒
  PTSD (Vietnam War)

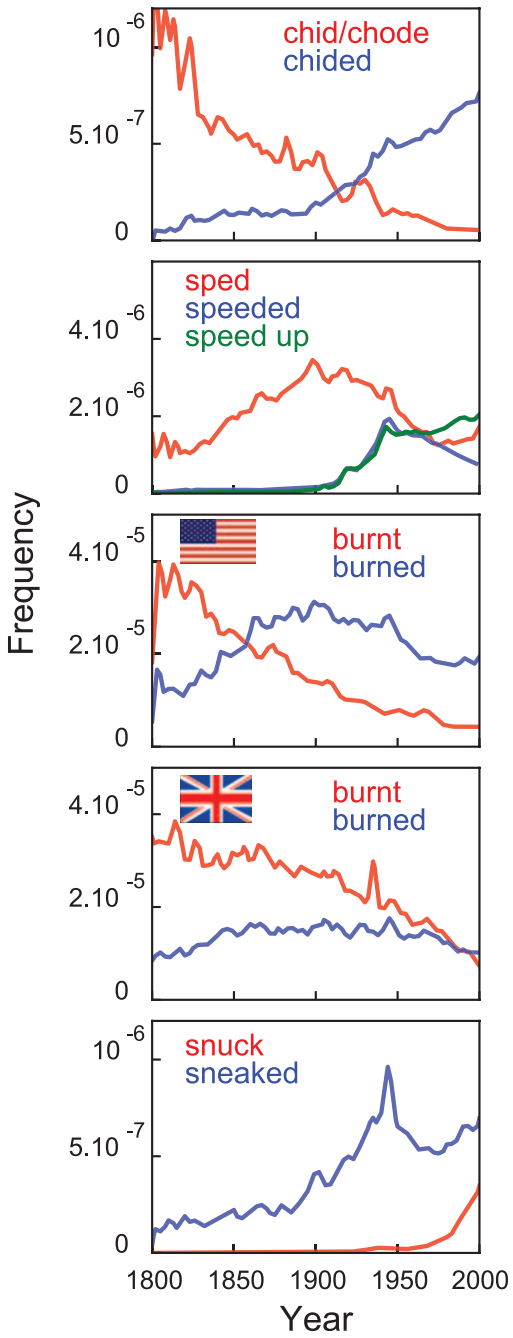
Competition in subtle spelling variations

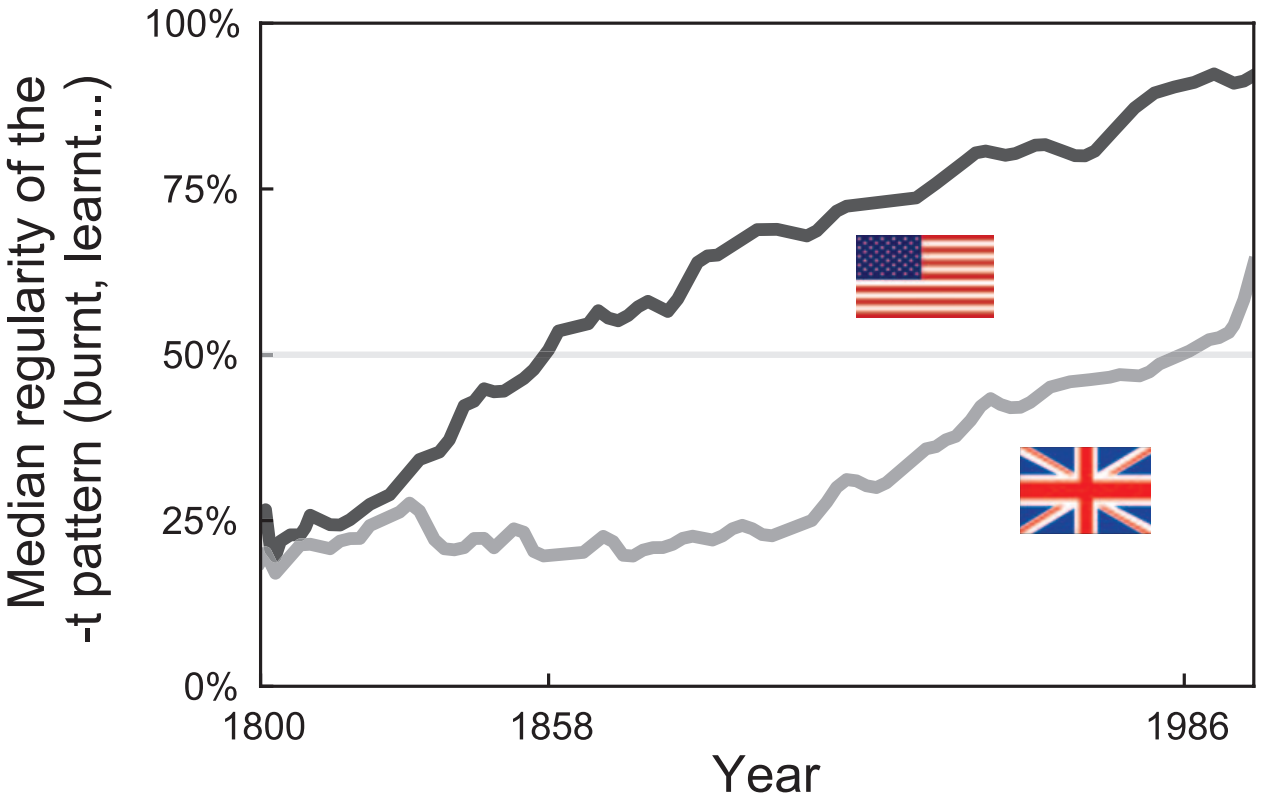


"Rich get richer" and the survival of the fittest....

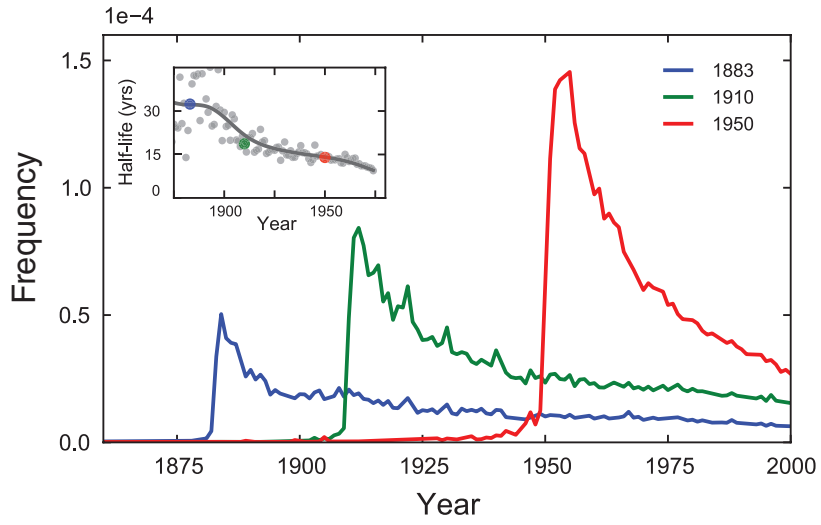
Geographic variation in the battle of the (ir)regular verb conjugations:

the past tense "-ed", "-t", ...





Quantitative Analysis of Culture Using Millions of Digitized Books. Michel, et al. (2011) Science.



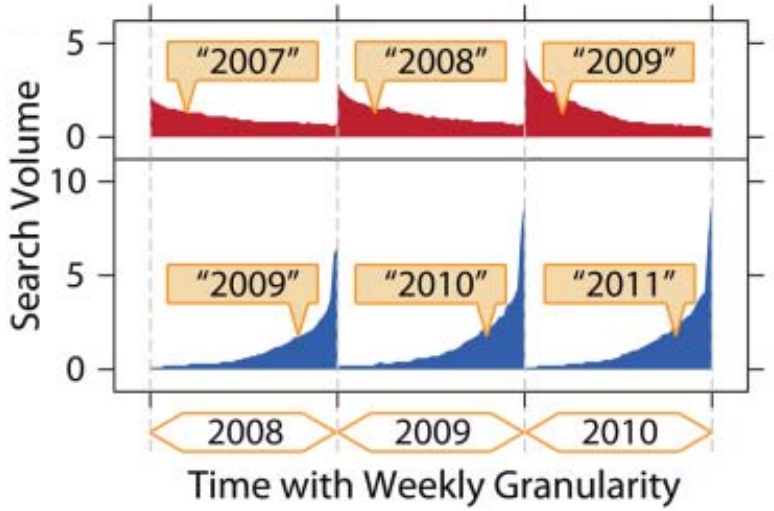
Quantitative Analysis of Culture Using Millions of Digitized Books. Michel, et al. (2011) Science.

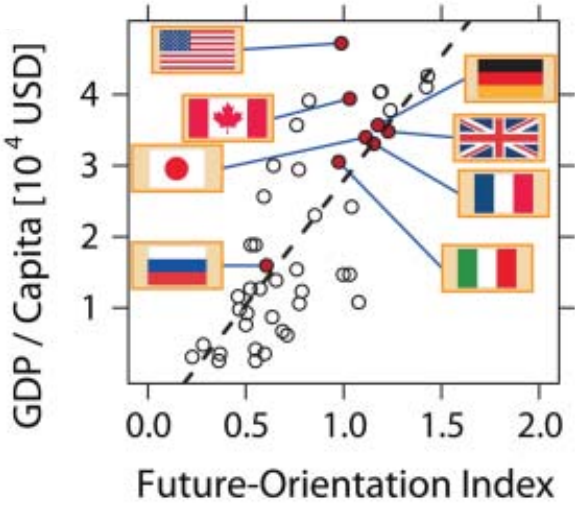
Digital traces of cultural Nostalgia & Optimism

How often do we dream about the *future*?

and

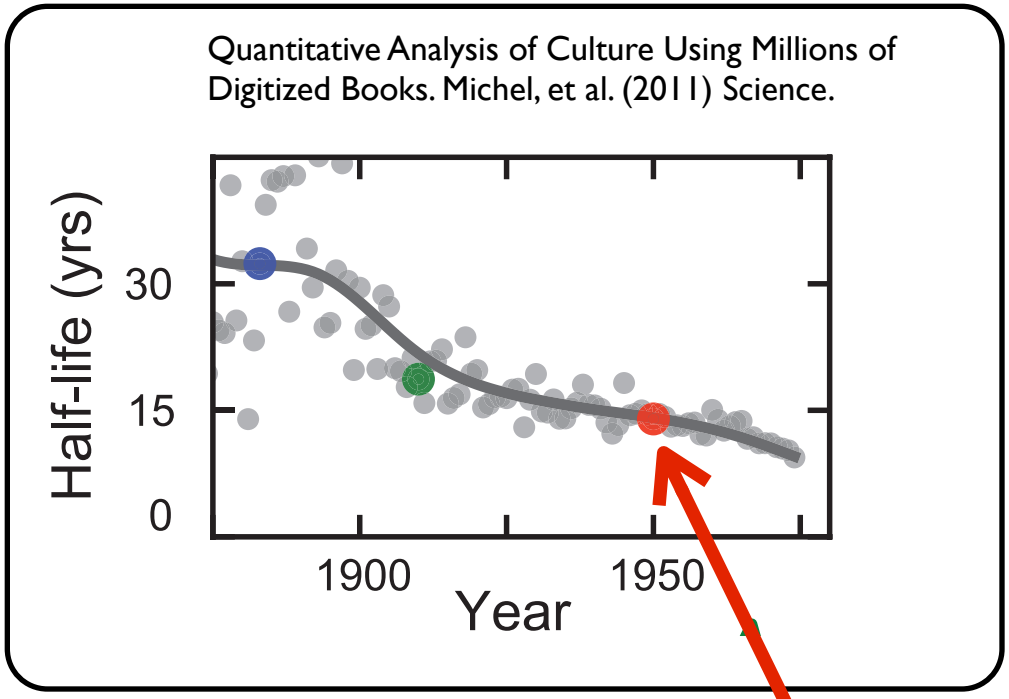
How often do we refer to the *past*?



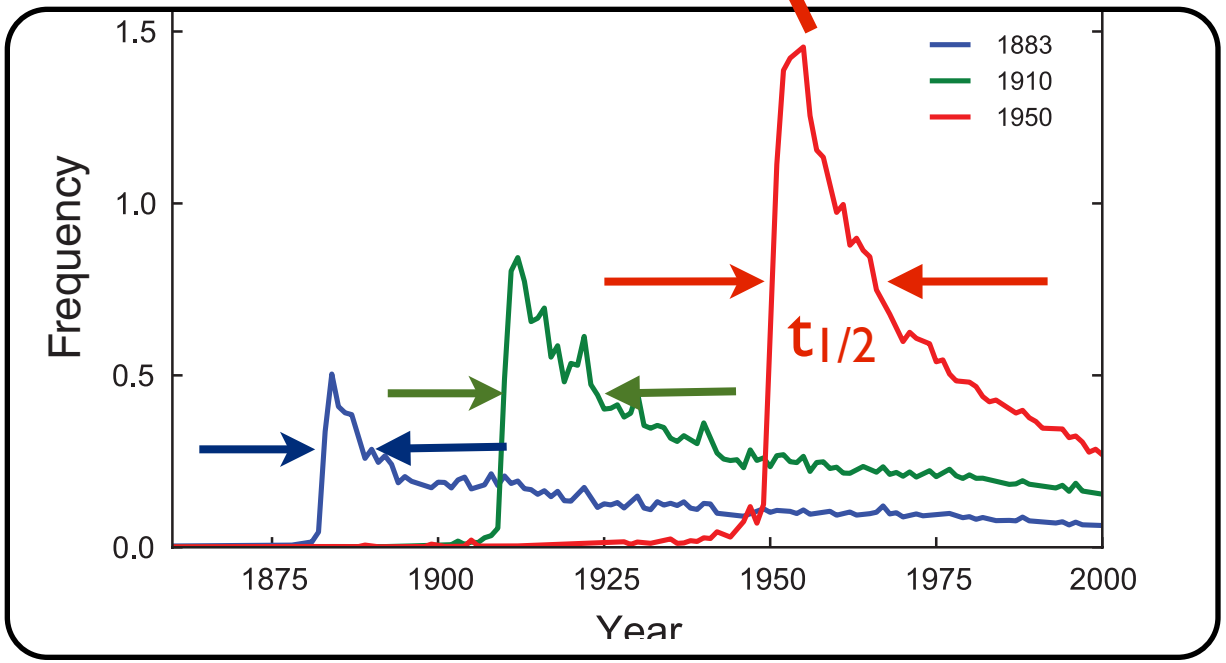


Quantifying the advantage of looking forward.
Preis et al. (2013) Scientific Reports.

Digital traces of cultural Nostalgia & Optimism

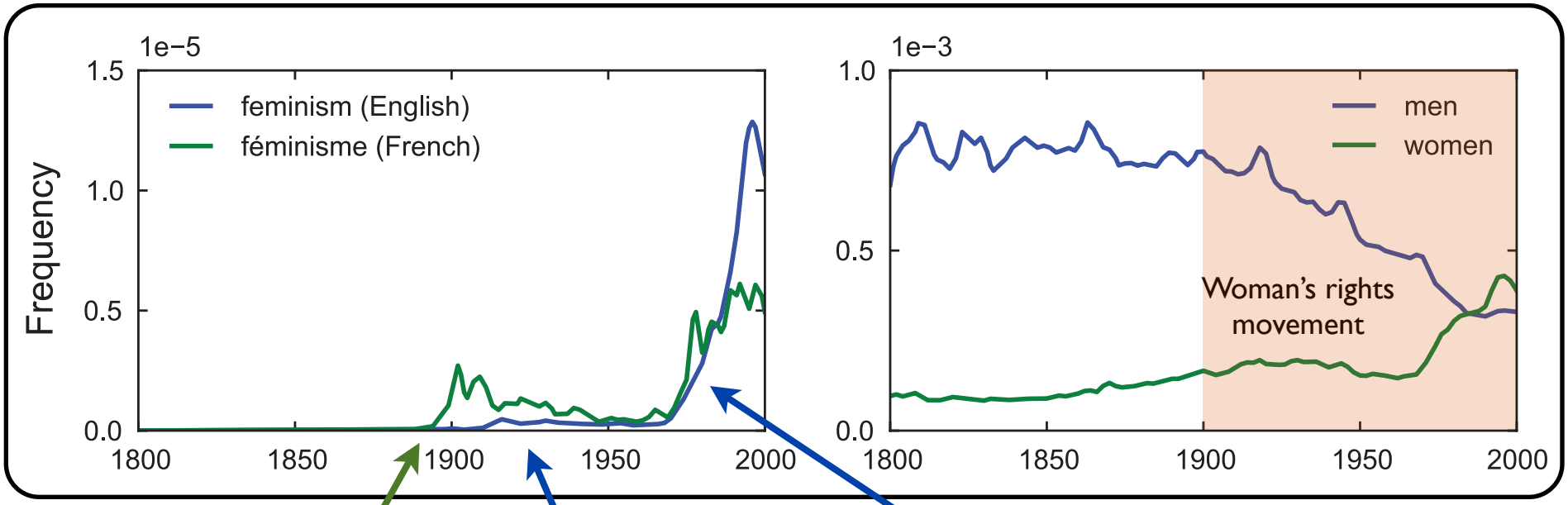


How quickly do we FORGET the *past*?



Quantitative Analysis of Culture Using Millions of Digitized Books. Michel, et al. (2011) Science.

Let's talk about SEX



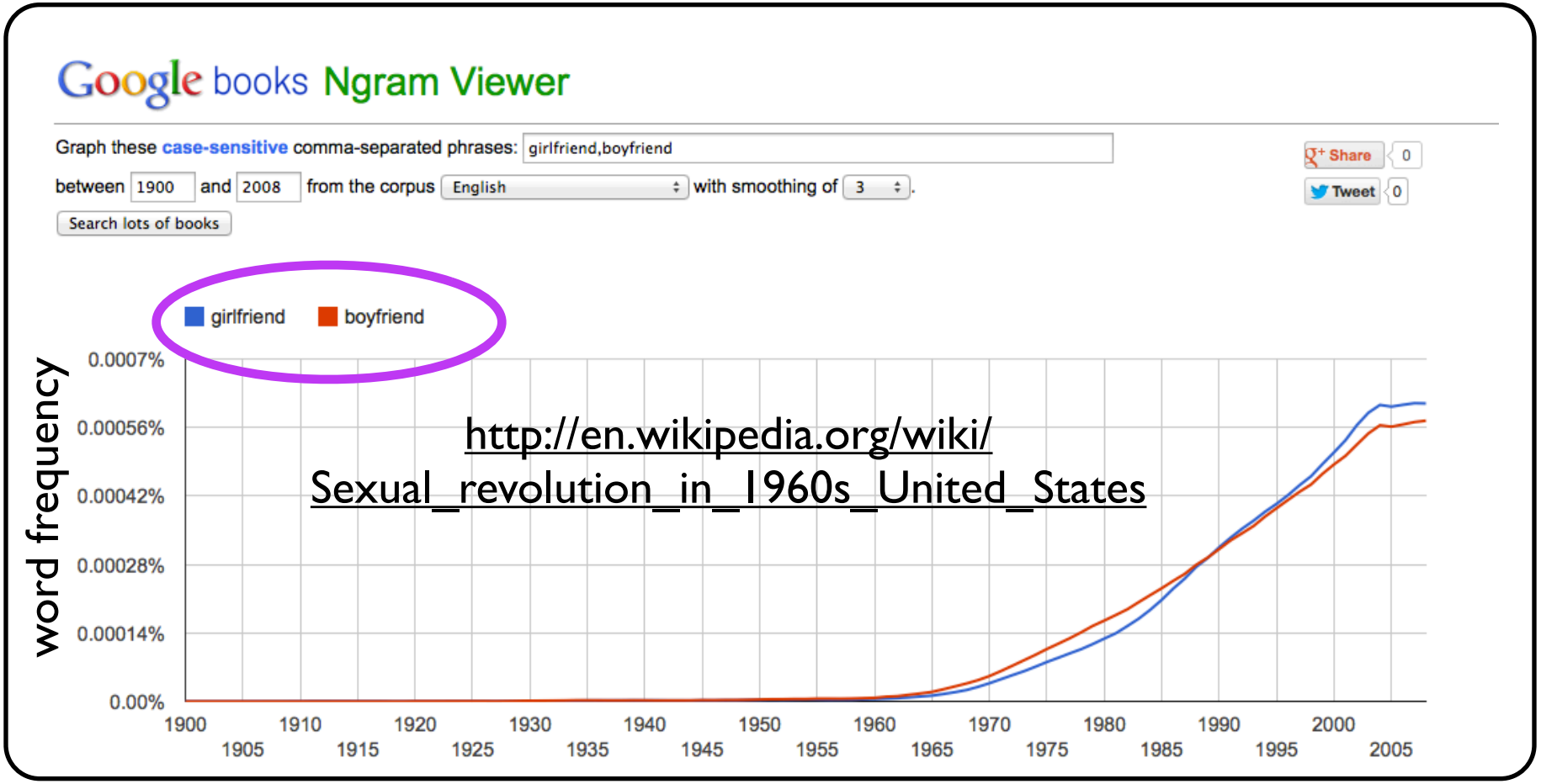
Initiated in France

Incubated in the 1920s and championed in the 1960s in the USA

Changing norms of sexual equality in our society

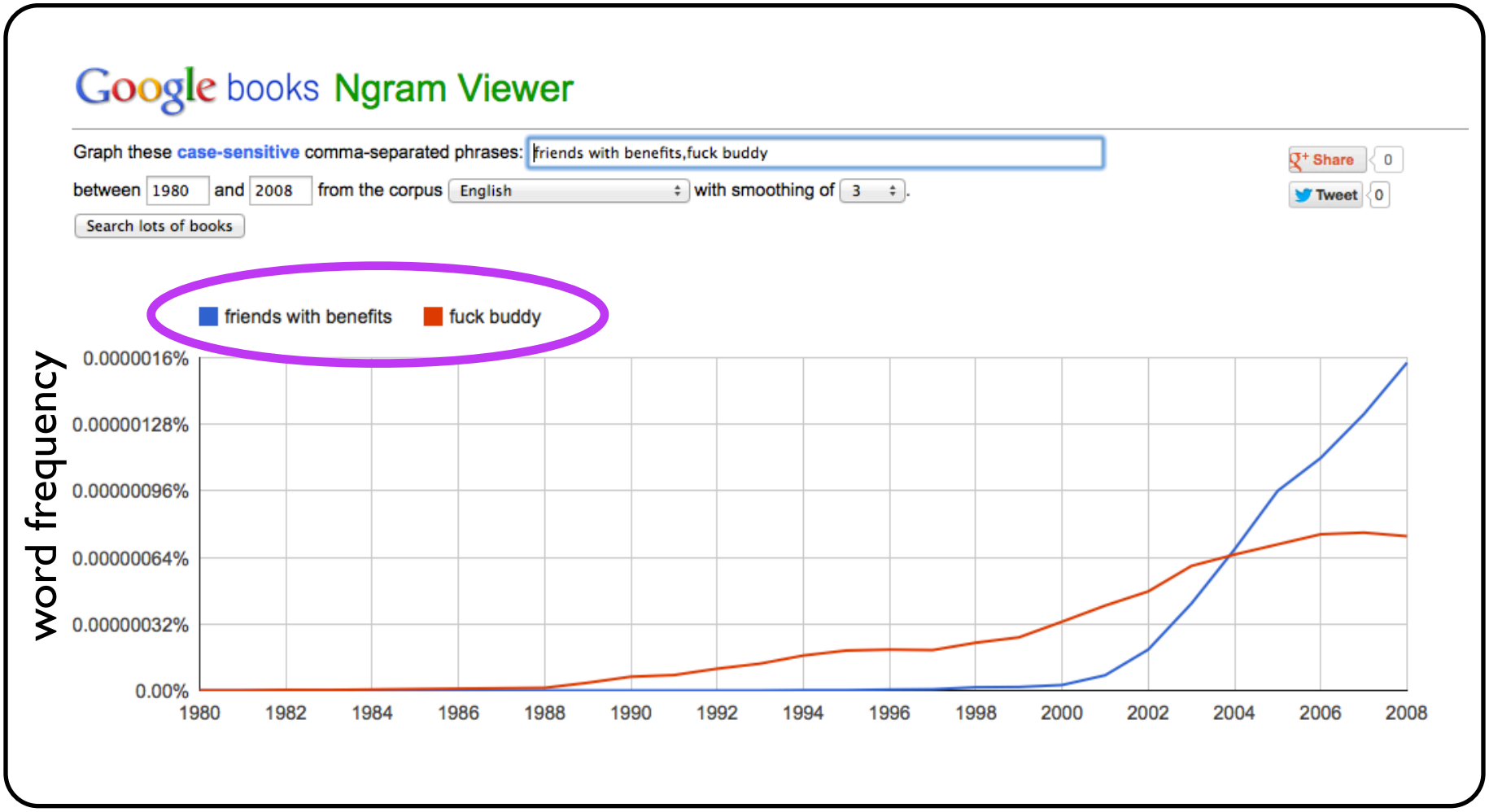
Quantitative Analysis of Culture Using Millions of Digitized Books. Michel, et al. (2011) Science.

.... sexual revolution of the 1960s: courting norms changing



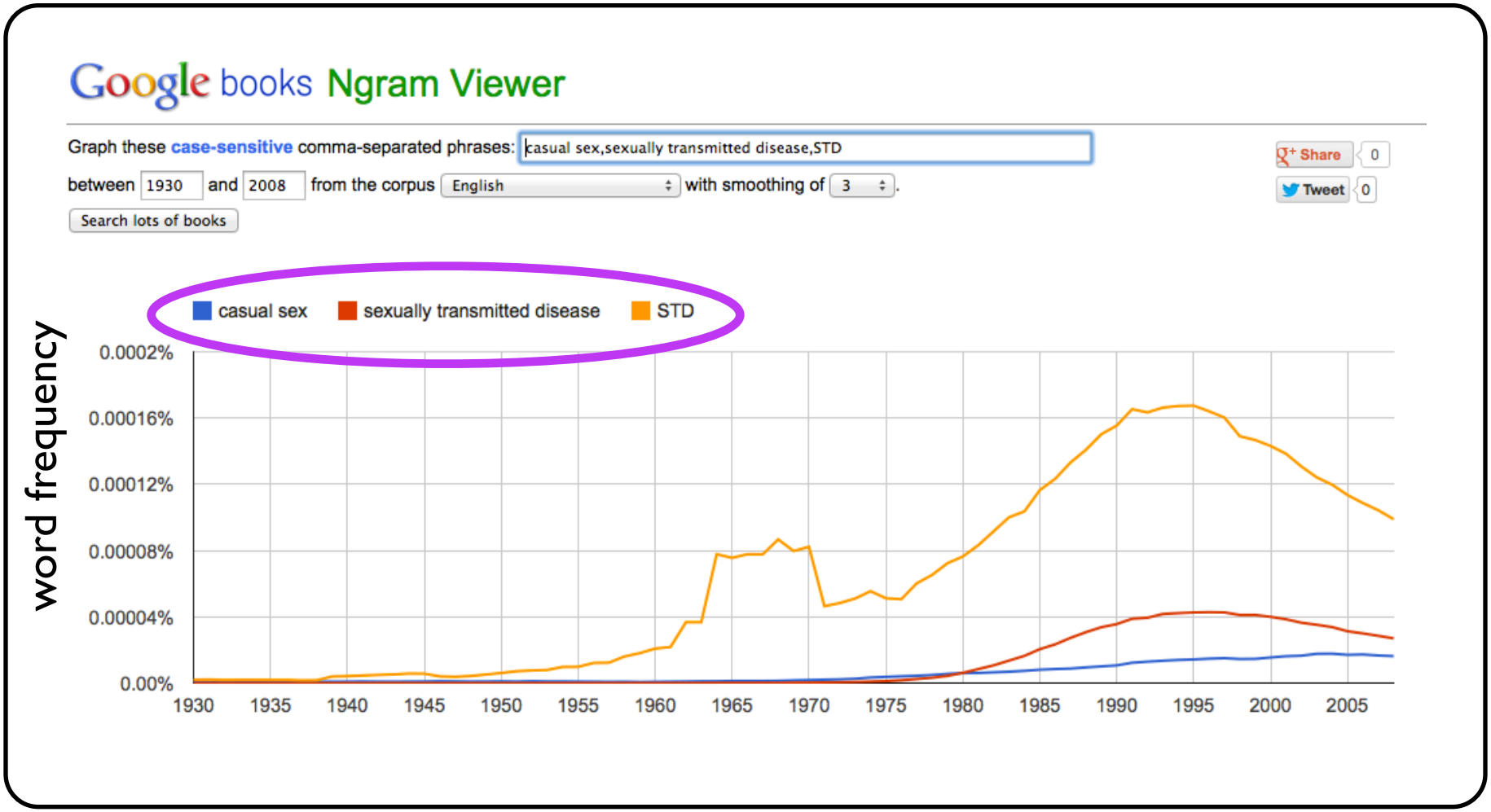
"With its roots in the first perceived sexual revolution in the 1920s, this 'revolution' in 1960s America encompassed many groups who are now synonymous with the era. Feminists, gay rights campaigners, hippies and many other political movements were all important components and facilitators of change."

Ok Let's Really talk about SEX



evolution of not only terminology representing social norms....

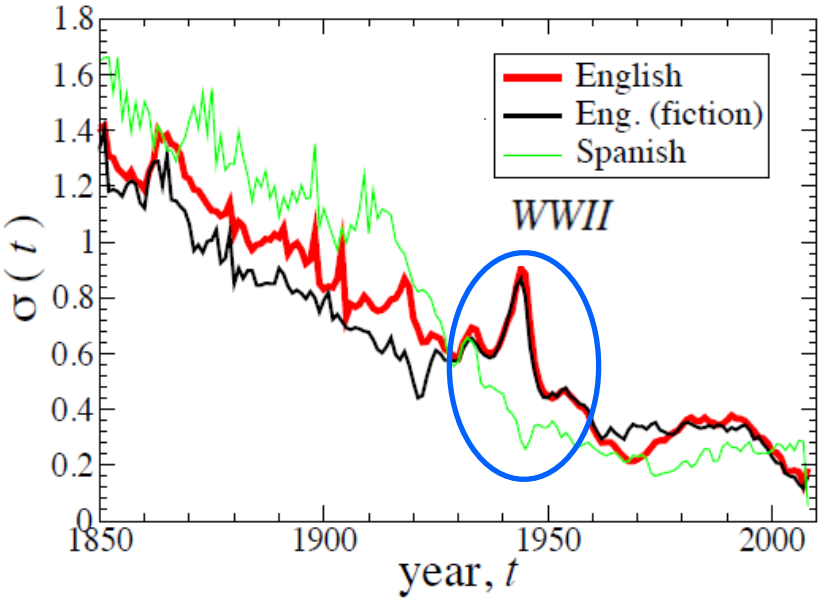
Ok Let's Really talk about SEX



but cultural evolution of sexual norms also has significant implications for disease control and human reproduction...

Do historical events change the dynamics?

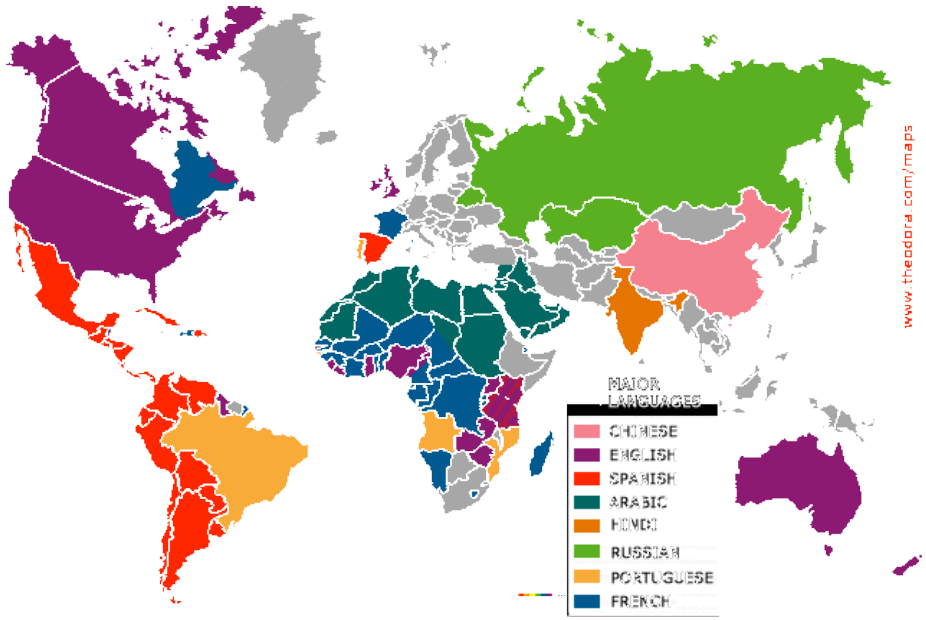
Spanish speaking countries less involved in WWII



annual growth rates

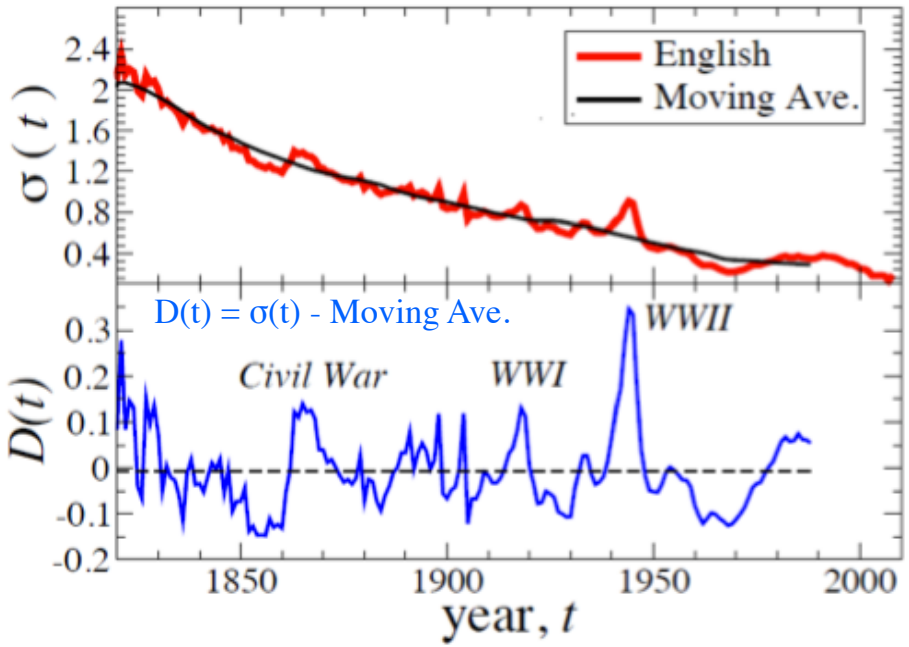
$$r_i(t) \equiv \ln f_i(t+\Delta t) - \ln f_i(t) = \ln\left(\frac{f_i(t+\Delta t)}{f_i(t)}\right)$$

σ(t) = std. deviation of $r_i(t)$



External socio-political "shocks" bring separated languages into contact

Role of political conflict on language

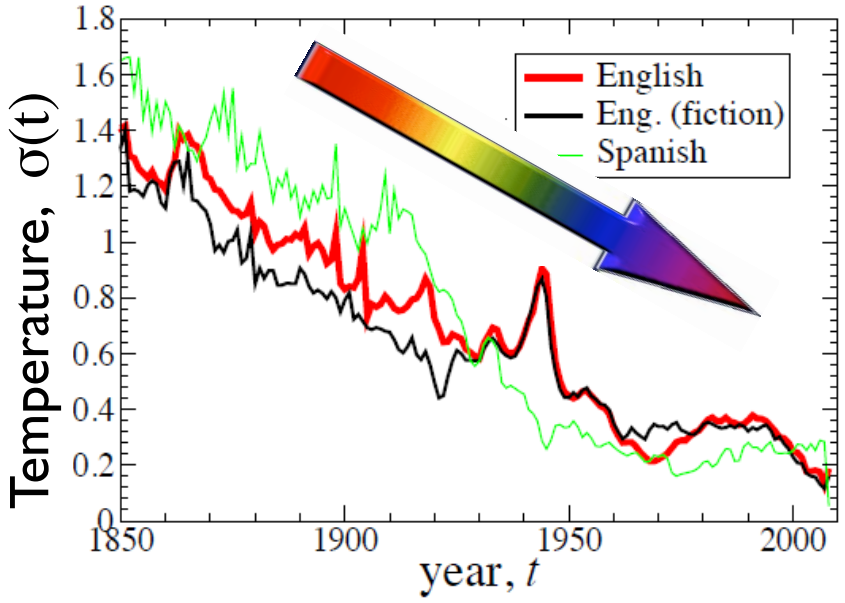


New war words (peak year)

Vichyites (1941)
Coprosperity (1942)
UDSR (1947)
fascismo (1926)
breechloader (1940, a type of gun loaded via a magazine instead of through the tip)
divebomber (1943)
Heinkels (1939) (a type of German bomber)
sonsabitches (1944)
shellshocked (1944)
profascist (1943)
antifascists (1945)
foxtrots (1946)

Political conflict causes periods of increased fluctuations in language and an increased rate of cross-fertilization between languages

Languages "cool as they expand"



annual growth rates

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σ(t) = std. deviation of $r_i(t)$

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measures the characteristic fluctuations in word growth

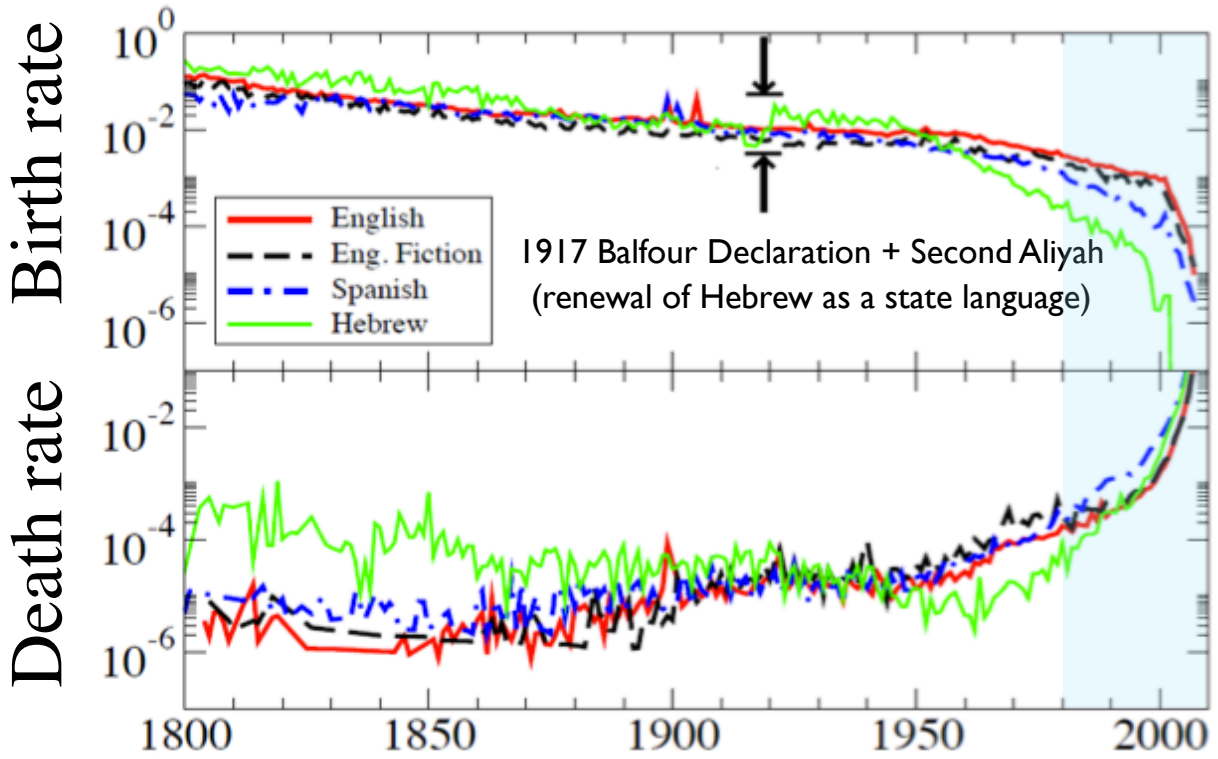
~ "system temperature"

Q: Is language evolution slowing down?

Q: What is the counteractive role of new language platforms? e.g. text messaging, Twitter

A. M. Petersen, J. Tenenbaum, S. Havlin, H. E. Stanley, M. Perc
Languages cool as they expand: Allometric scaling and the decreasing need for new words
Scientific Reports 2, 943 (2012)

Birth and Death of Words



Era of automatic spell-check editing

The modern era of publishing, which is characterized by more strict editing procedures at publishing houses and computerized word processing (automatic spell-checking) technology, has led to a *drastic increase in the death rate of words*.

The birth rate has also decreased, indicating the *decreasing marginal need for new words*. However, the new words that do survive have relatively high word use frequency (intrinsic fitness, e.g. e-mail, Google).

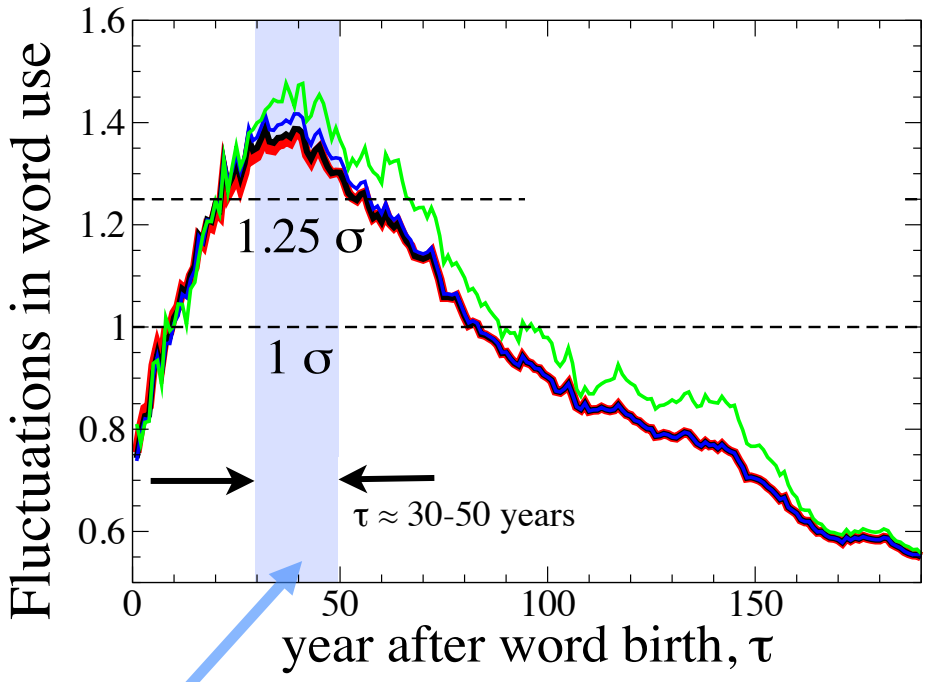
The life-cycle of a new word

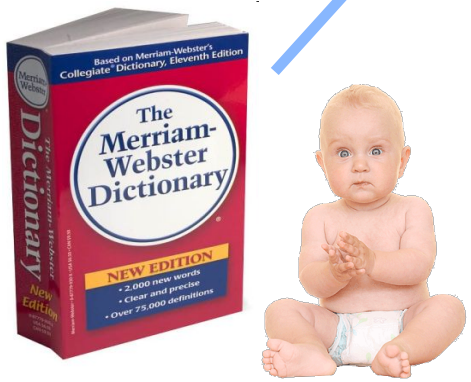
Is there a tipping point in the life-cycle of a new word?

New words demonstrate peak "instability" when they are ≈ 30 – 50 years old, corresponding to:

a) the typical time it takes to be accepted into a dictionary

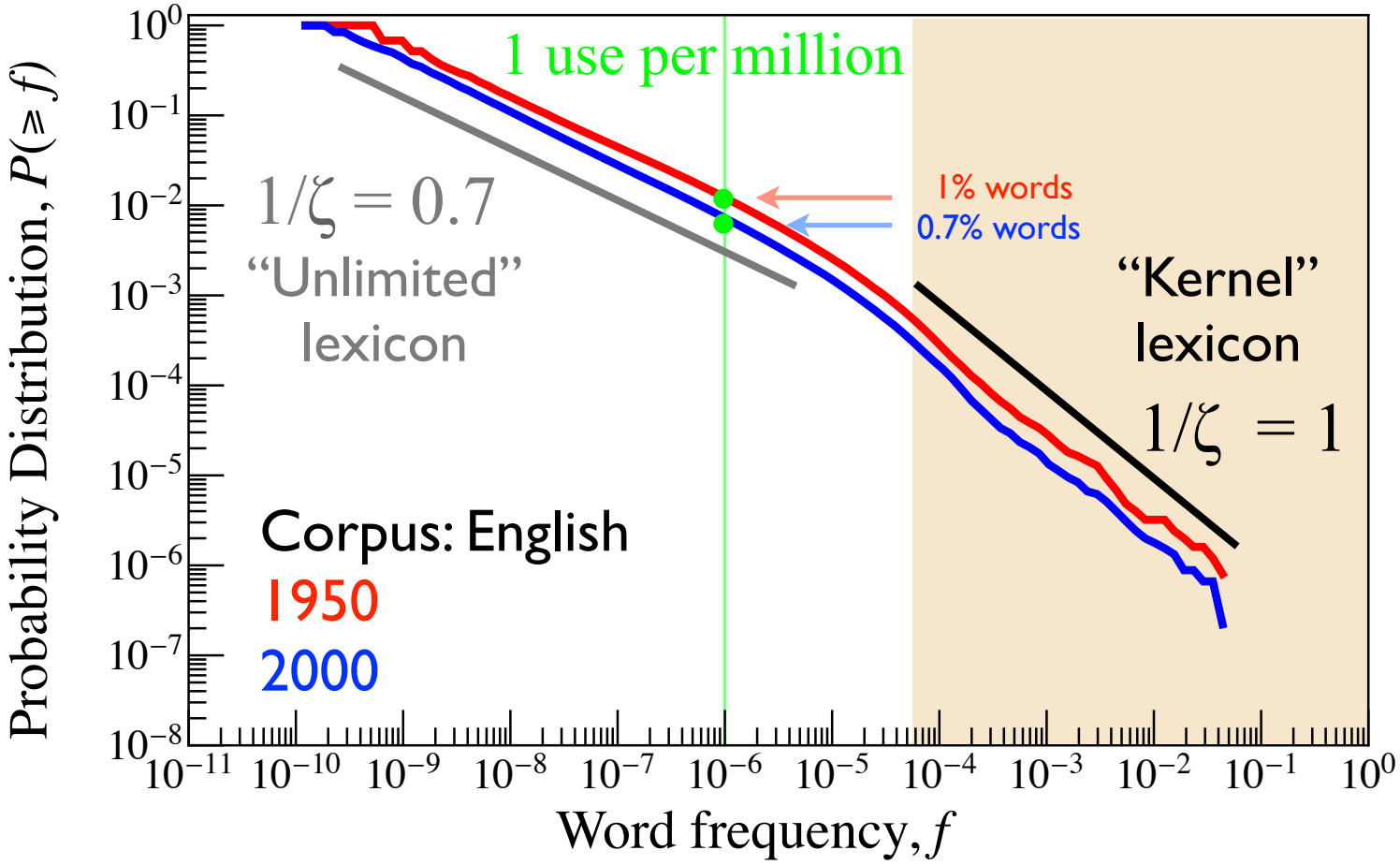
b) the generational timescale of humans (and language evolution)





"Dark Language": a hidden Zipf's law

$P(\geq f)$ is the percentage of 1-grams ("words") with observed frequency larger than f



Only ~1% of words in each corpora belong to the "Kernel" lexicon (words that a typical person could recognize)

A vast hidden "Dark language" (Unlimited Lexicon) accounts for approximately 99% of the 1-grams recorded in each corpora,

Hidden content: an analogy with “Dark Matter”

95.5%

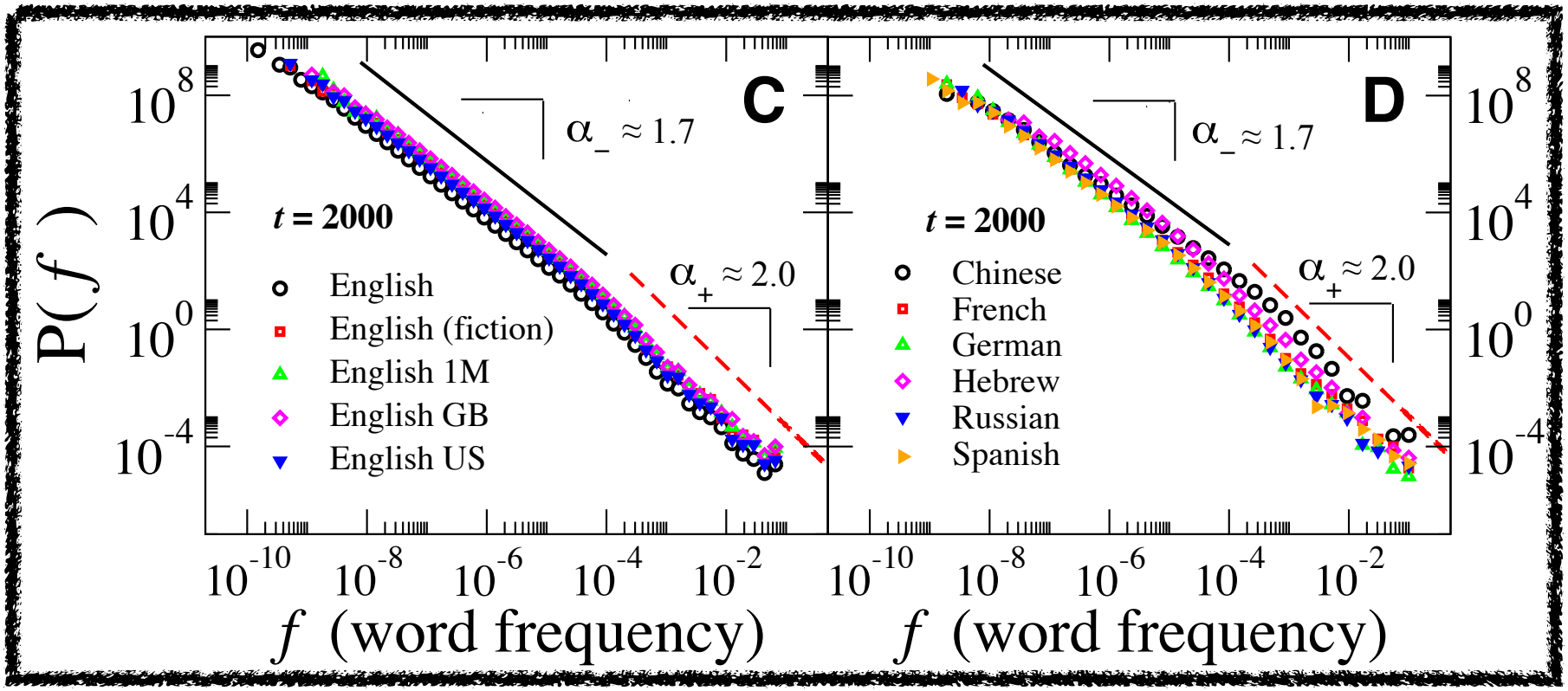
?

4.5%

*Recent estimates indicate that 95% of the universe is composed of dark matter/energy (72.8% dark energy, 22.7% dark matter), and only the remaining 4.6% ordinary matter.

("Seven-Year Wilson Microwave Anisotropy Probe (WMAP) Observations: Sky Maps, Systematic Errors, and Basic Results". nasa.gov)

Consistent patterns of “dark language” across 7 languages



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Food for thought

- Digitization of historical archives is vastly extending our quantitative perspective on history
- A vast amount o language belongs to an "unlimited" lexicon, consisting of highly specific contextual terminology. Consider that the common everyday words, roughly the top 30,000 most used words which are used with a frequent of more than 1 per million, account for only 1% of the English language vocabulary
- Words compete with irregular forms and synonyms in a competitive environment: "persistence" is gradually suffocating the use of "persistency"
- The growth of language is very sensitive to socio-political shocks, such as war. New words enter largely as a result of technological innovation, but also due to shifts in social behavior: consider that the words "girlfriend" and "boyfriend" emerged only in the early 1960s, likely reflecting a sexual revolution which has major biological implications (e.g. disease spreading, birth rate, etc.). Also, the words "treehuggers" and "ecowarriors" emerged in the early 1990s in conjunction with the "save the earth" movement.
- The sustainability of new and old words likely reflects the word's marginal utility as derived from the implicit dependency structure of language (grammar)

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Thank You!

A special thanks to my collaborators:
Joel Tenenbaum, Matjaz Perc,
Shlomo Havlin, Gene Stanley

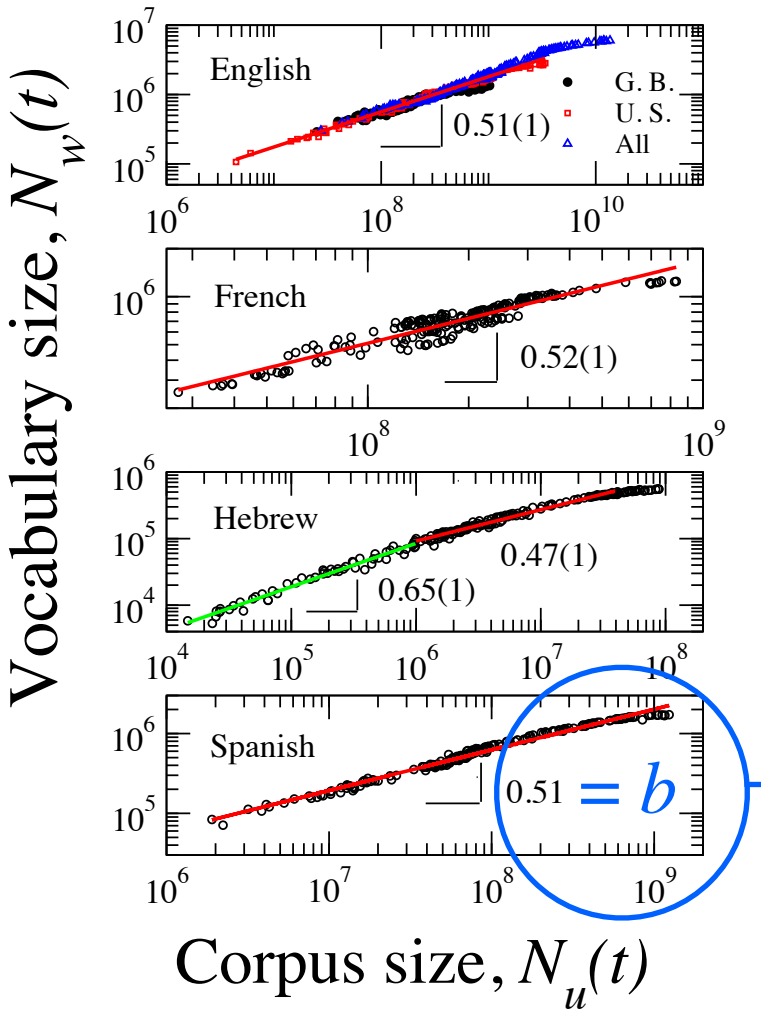
http://physics.bu.edu/~amp17/

Title: Using big data to quantify the evolution of written corpora at the micro and macro scale

Abstract:

What if you could analyze every word every book in every library, bookcase, and attic around the world? What kind of trends and changes in culture could you discover? All of the world's books constitute an immense "crowd-sourced" historical record that traces the evolution of culture beyond the limits of oral history. But to analyze individual words over time has been incredibly painstaking-- until now. Google has digitzed a huge collection of written language in the form of the Google Books Ngram Viewer web application (https://books.google.com/ngrams). 4% of all books ever published have been digitally scanned, making 10 million histories for individual words, a vast archive of cultural dynamics over more than two centuries. With statistical methods borrowed from physics, we show what the frequencies of words can tell us about every aspect of society, from the recent emergence of the environmentalism to the impact of feminism on human sexual behavior over the last 200+ years, from the the impact of globalization on vocabularies in 7 languages, to the role of spell-checkers on the survival rate of "mutant" words.

Using Heaps' law to reveal the marginal utility of new words



Allometric scaling analysis is used to quantify the role of system size on general phenomena characterizing a system, and has been applied to understand the metabolic (activity) rate of systems with sizes ranging from mitochondria to cities.

Here each data point corresponds to one year: $N_u(t)$ is the total number of "tokens" printed in year t and $N_w(t)$ is the number of distinct tokens in the same year

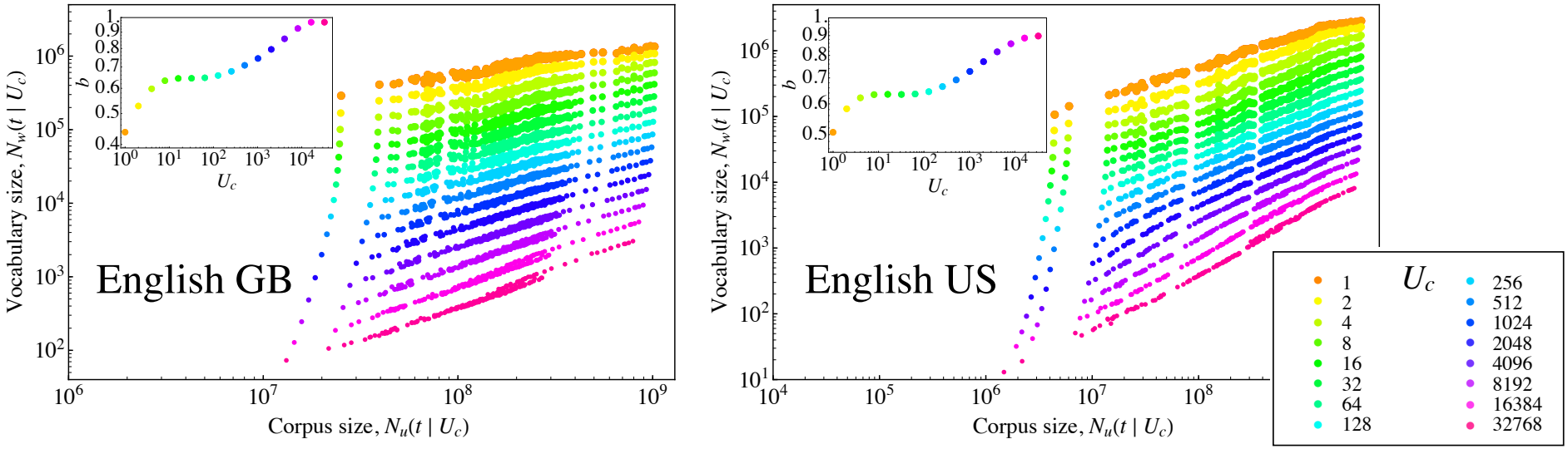
Heaps' law: $N_w(t) \sim (N_u(t))^b$

Marginal need for new words (decreasing for $b<1$)

$$\partial N_w / \partial N_u \sim (N_u)^{b-1}$$

$b < 1$ corresponds to an "economies of scale" and implies a decreasing marginal need for additional words as a corpora grows. Because we get more and more "mileage" out of new words in an already large language, additional words are needed less and less. Interestingly, many economic systems have $b > 1$, whereas biological systems have $b < 1$.

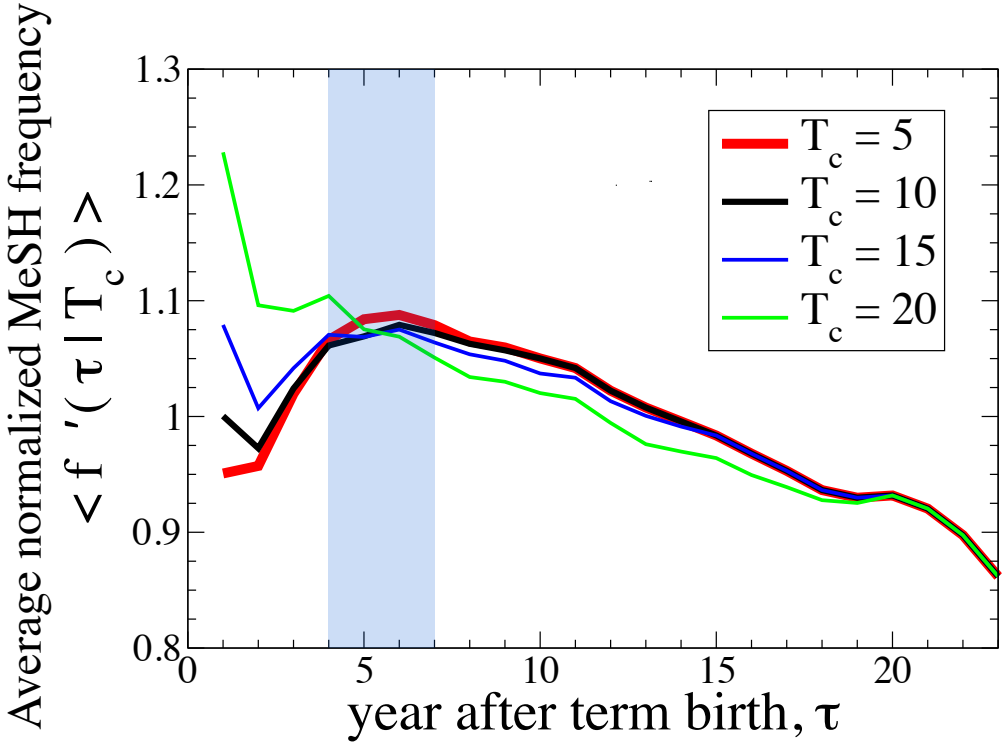
Using Heaps' law to provide insight into the dependency structure between words



Q: How does *b* change if we only include words with $u_i \geq U_C$ in our allometric scaling analysis??

As U_C increases the Heaps scaling exponent increases from $b \approx 0.5$, approaching $b \approx 1$, indicating that core "Kernel" words are structurally integrated into language as a proportional background, $N_u(t) \sim N_w(t)$, quantifying how the kernel lexicon is the structural "glue" with larger marginal utility per word

Life-cycle analysis of Mesh terms



The growth trajectory of individual mesh terms.

Most new MeSH concepts reach their peak popularity around roughly 4-7 years.

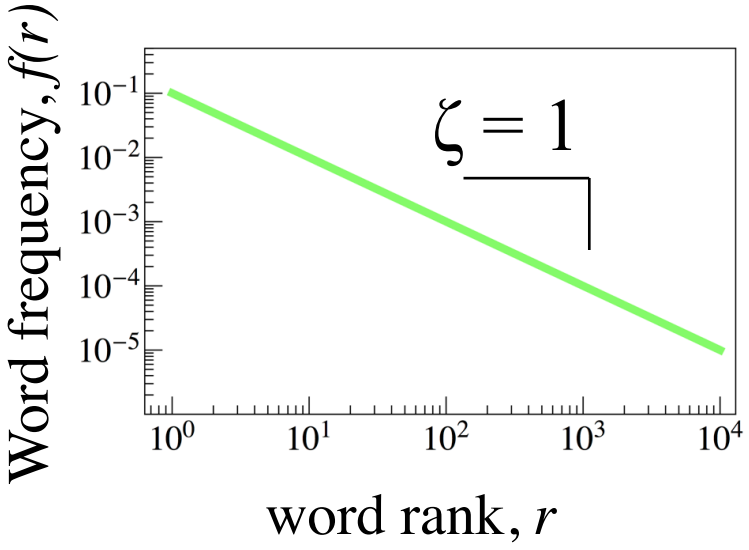
The 4 trajectories are calculated using only MeSH terms with lifetime $L_i > T_c = \{5,10,15, 20\}$ years and birth year $y_i(0) \geq 1987$.

Is there a characteristic life-cycle for scientific trends? 4-7 years is also consistent with the peak in the citation trajectory of highly cited papers

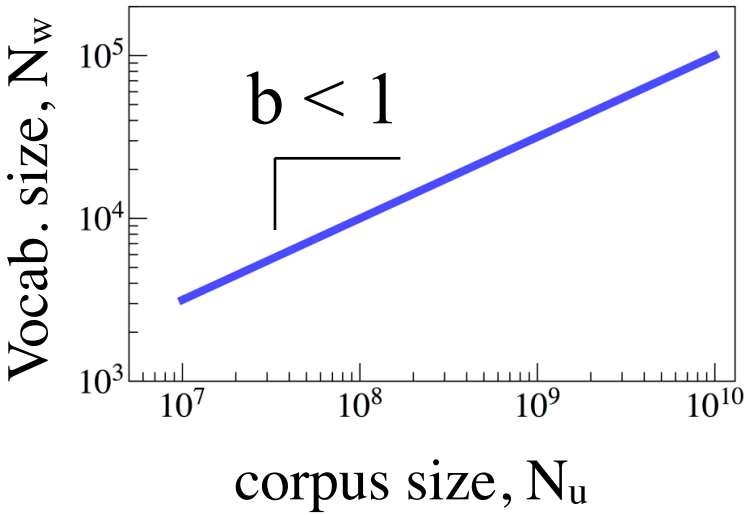
Structural evolution of languages across time

Famous Zipf + Heaps' laws are based on *static* snapshots of (relatively) small texts/corpora

Zipf's law: $f(r) \sim 1/r^{\zeta}$

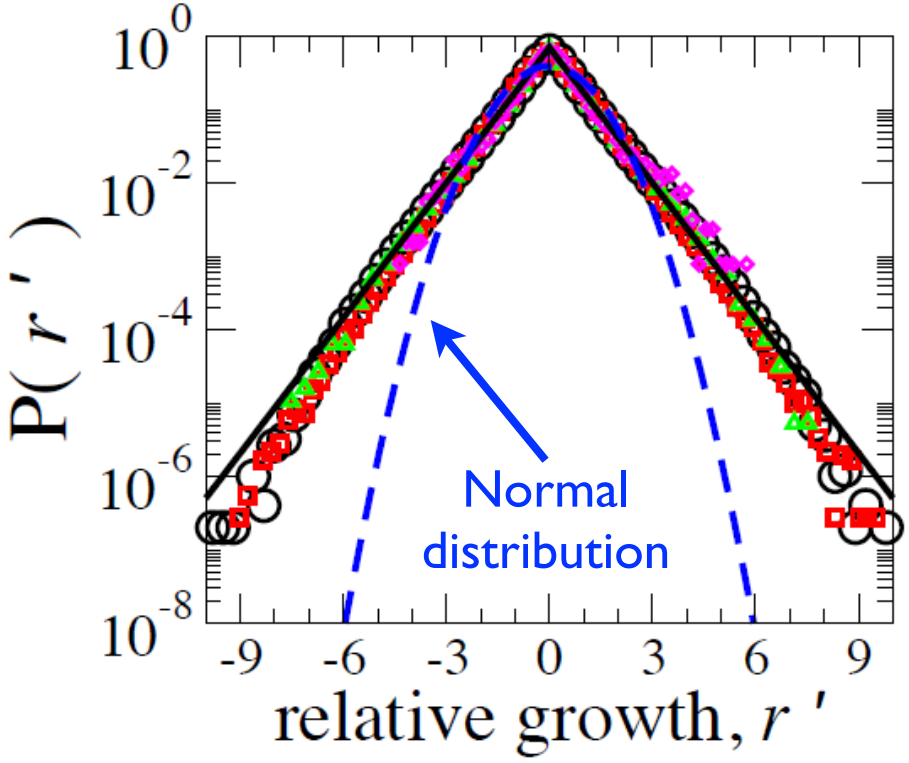


Heaps' law: $N_w \sim (N_u)^b$



Q: can we learn anything from analyzing the properties of these statistical laws over time?

"zero sum" competitive system



Common words
using $f_i \geq f_c$

○	English:	$f_c = 5 \times 10^{-8}$
□	Eng. (fict.):	$f_c = 10^{-7}$
△	Spanish:	$f_c = 10^{-6}$
◇	Hebrew:	$f_c = 10^{-5}$

r = annual growth rates in the word usage frequency

$$r_i(t) \equiv \ln f_i(t+\Delta t) - \ln f_i(t) = \ln\left(\frac{f_i(t+\Delta t)}{f_i(t)}\right)$$

P(r) is centered around $r \cong 0$, a "zero sum" competitive system

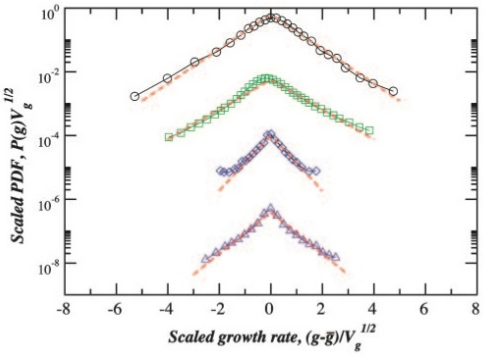
"tent-shaped" growth patterns are common in complex systems

Q: How do complex systems grow ?

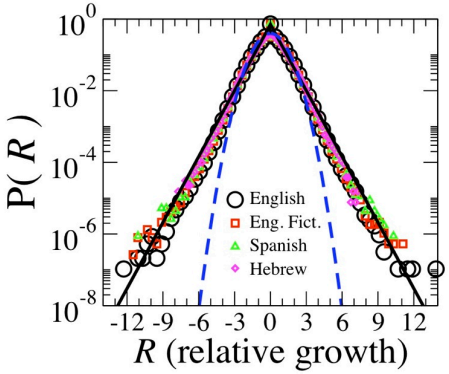
Q: How big are the rare events (often neglected by simple models) ?

Excess number of large growth (+/-) events as compared to the Gibrat multiplicative growth model which predicts a Gaussian distribution for P(R)

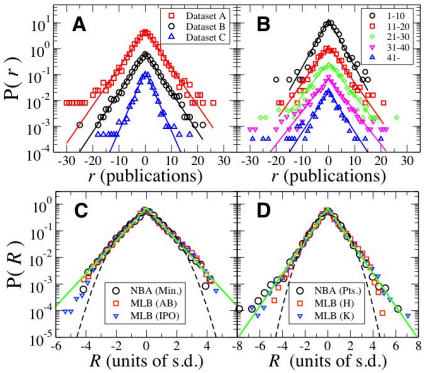
Firm size / Country GDP [1]



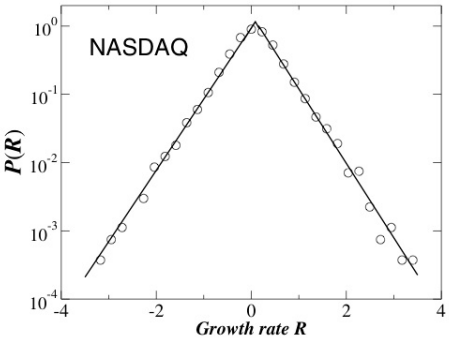
Word Use [2]



Individual Productivity [3]



Stock Price [4]



[1] D. Fu, et al., The Growth of Business Firms: Theoretical Framework and Empirical Evidence. Proc. Natl. Acad. Sci. USA 102, 18801 (2005).

[2] A M. Petersen, et al., Statistical Laws Governing Fluctuations in Word Use from Word Birth to Word Death, submitted.

[3] A M. Petersen, et al., Quantitative Relations between Group Collaboration and the Productivity Growth Dynamics of Individuals, in preparation.

[4] B. Podobnik, et al., Common scaling behavior in finance and macroeconomics. Eur. Phys. J. B 76, 487 (2010).