Is natural language a good code from an information-theoretic perspective?

Vera Demberg and Matt Crocker

Information Theory Lecture, Universität des Saarlandes

April 14th, 2015
**Channel Capacity** is defined as

the **maximal amount of information** that can be conveyed through a channel in a given amount of time $t$, with **arbitrarily small error** (= “without error”).

\[
\text{Channel Capacity } C = \frac{1}{t} \max_{p_X(x)} I(X; Y)
\]

**Noisy Channel** means that

some of the **input might be corrupted during transmission**, so the output is different from the input. (E.g., for transmitting binary messages, some of the bits may be flipped during transmission.)
Channel Capacity is defined as
the maximal amount of information that can be conveyed through a channel in a given amount of time $t$, with arbitrarily small error (＝ “without error”).

What does this imply for optimal communication?
Optimal Communication through a Noisy Channel

**Channel Capacity** is defined as the maximal amount of information that can be conveyed through a channel in a given amount of time $t$, with arbitrarily small error (= “without error”).

What does this imply for optimal communication?

- How can we achieve optimal efficiency? (assuming no error)
- How can one avoid errors in a “noisy channel”?

**Example:**

we have a butterfly station, and want to transmit a message every day to another butterfly station, saying how far they have developed. Initially we have 5 eggs. States: egg, caterpillar, cocoon, butterfly.
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>What is a good code?</td>
</tr>
<tr>
<td>2</td>
<td>Good Code and Ambiguity</td>
</tr>
<tr>
<td>3</td>
<td>Redundancy</td>
</tr>
</tbody>
</table>
How can we address questions about the optimality of language?
How can we address questions about the optimality of language?

1. quantify amount of information conveyed by linguistic events
2. then we can calculate what is the shortest code necessary
3. then we can compare this to how natural languages encode information
Entropy and Surprisal

Step 1: quantifying the amount of information conveyed.

entropy:

\[ H(X) = \sum_x p(x) \log_2 \frac{1}{p(x)} \]

surprisal: 

\[ \text{surprisal} \overset{\star}{=} \log_2 \frac{1}{p(x)} \]

I allows us to quantify the information content of linguistic events.

I How many bits are minimally needed to convey a message?
I What’s the optimal code for conveying a message?

*(normally, we will talk about conditional probabilities for surprisal, i.e., \( p(x|\text{context}) \))
Entropy and Surprisal

Step 1: quantifying the amount of information conveyed.

entropy:

\[ H(X) = \sum_x p(x) \log_2 \frac{1}{p(x)} = - \sum_x p(x) \log_2 p(x) \]

surprisal:

\[ S(x) = \log_2 \frac{1}{p(x)} \]

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Example: Simplified Polynesian

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<thead>
<tr>
<th>p</th>
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<th>k</th>
<th>a</th>
<th>i</th>
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</thead>
<tbody>
<tr>
<td>1/16</td>
<td>3/8</td>
<td>1/16</td>
<td>1/4</td>
<td>1/8</td>
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Calculating Entropy for Simplified Polynesian

\[
H(X) = \sum_x p(x) \log_2 \frac{1}{p(x)}
\]

\[
= 2 \cdot \frac{1}{16} \log_2 16 + 2 \cdot \frac{1}{8} \log_2 8 + \frac{1}{4} \log_2 4 + \frac{3}{8} \log_2 \frac{8}{3}
\]

\[
= 2.28 \text{ bits per character}
\]
Example: Simplified Polynesian

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optimal code: 2.28 bit/char

Possible Codes

<table>
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<tr>
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<tbody>
<tr>
<td>000</td>
<td>001</td>
<td>010</td>
<td>011</td>
<td>100</td>
<td>101</td>
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Code for “pato” = 000011001101

(3 bits per character)
Entropy

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<td>110</td>
<td>111</td>
<td>00</td>
<td>01</td>
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Code for “pato” = 10011110101
Entropy

Example: Simplified Polynesian

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<td>100</td>
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<td>00</td>
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average message length for this code:

\[
\frac{1}{16} \times 3 + \frac{3}{8} \times 3 + \frac{1}{16} \times 3 + \frac{1}{4} \times 3 + \frac{1}{8} \times 2 + \frac{1}{8} \times 2 = 2.75 \text{ bits}
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Entropy

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optimal code: 2.28 bit/char

Possible Codes

- Code for “pato” = 000011001101 (3 bits per character)
- Code for “pato” = 10011110101 (2.75 bits per character)
- Code for “pato” = 1000100111 (2.375 bits per character)

(short codes for probable events to reach short average message length)
and we might find an even better code if the letters in simplified Polynesian are not independent of one another, and we use a code that reflects that.

The CV model is a better language model for Polynesian than the one that does not know about syllable structure.
Information theory and natural language

- How good a code is natural language?
- Are humans able to generate encodings of their messages that allow them to communicate optimally*?

* efficiently and effectively given their environment (= through a noisy channel)
Efficient code is one that allows us to, on average, encode short messages.

Observation: frequent events have shorter codes.

(Zipf, 1949) “Principle of least effort”

A language where frequent words are short is optimal if words occur independently of one another.
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A language where frequent words are short is optimal if words occur independently of one another.

But: in natural languages, word probabilities change depending on their context.
Entrophy and language models

Remember:

- better language model = lower entropy = shorter codes
  Example: simplified Polynesian modelling letter frequencies vs. letter frequencies in syllable contexts.
Entropic and language models

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- Word frequency = very simple (unigram) language model
Entropy and language models

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- Word frequency = very simple (unigram) language model

- If the human language system has good code design, we’d expect a strong (positive) correlation between word length and information content (=surprisal) of a word given its context.
Test whether surprisal of a word is correlated with word length.

How to test this (given a very large corpus)

- calculate the average surprisal of a word $w$ given its context $c$:

$$\sum_c P(C = c|W = w) \ast - \log P(W = w|C = c)$$
Piantadosi, Tily and Gibson 2011

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How to test this (given a very large corpus)

- calculate the average surprisal of a word $w$ given its context $c$:

\[
\sum_c P(C = c \mid W = w) \ast - \log P(W = w \mid C = c)
\]

\[
= - \frac{1}{N} \sum_{i=1}^{N} \log P(W = w \mid C = c_i)
\]

(note that Zipf at the time did not have the means to test this.)
Test whether surprisal of a word is correlated with word length.

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(weight information content)

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Test whether surprisal of a word is correlated with word length.

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- calculate the average surprisal of a word $w$ given its context $c$:

$$\sum_c P(C = c | W = w) \cdot - \log P(W = w | C = c)$$

- test whether word length negatively correlated with average word predictability
  (= word length positively correlated with average surprisal).

(note that Zipf at the time did not have the means to test this.)
Experiments: Piantadosi, Tily, Gibson (2011)

1. Google n-grams
   - 500 billion words for English
   - 11 languages tested (ca 130 billion words for other languages)
   - n-gram model, no smoothing
   - word length in characters
   - on 25k most common words; each data set has ca. 10m different words

2. British National Corpus
   - 100 million words
   - English only
   - n-gram model, with smoothing
   - word length in characters

3. Word length estimate in terms of phones / syllables
   - German, Dutch, English
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Google n-grams

Methods

- Spearman’s rank correlation
Google n-grams

Methods
- Spearman’s rank correlation

Results
- information content better predictor than frequency
- 2-grams: correct for all languages
- 3-grams: significant for all except Polish
- 4-grams: except Czech, Italian, Polish, Swedish
- Partial correlations provide a similar picture
Predictability vs. Frequency

Correlation of frequency vs. length and predictability vs. length (English)

(high frequency = small $-\log$ Unigram Probability)
Predictability vs. Frequency

Correlation of frequency vs. length and predictability vs. length (English)

Frequency doesn’t predict word length well for low-frequency words, but average information content does.
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BNC results

British National Corpus

- predictability of words better than frequency
- after partialing out: no effect of frequency beyond predictability

Spearman’s rank correlation on BNC

- frequency
- bigram
- trigram
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Does predictability work better than frequency?

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<tr>
<th>language</th>
<th>2-gram</th>
<th>3-gram</th>
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</tr>
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<tbody>
<tr>
<td>English phonemes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>English syllables</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Dutch phonemes</td>
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<td>yes</td>
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Discussion

1. How does the Piantadosi et al’s account differ from Zipf’s account?

2. How does the lexicon end up having this property?

3. Ways of measuring information content given the context?
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5 min time for you to discuss this with neighbors
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Differences Zipf’s account vs. information content

- Lexicon
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- Lexicon
  - Zipf (principle of least effort): best lexicon is the most concise one
  - Information content: highly informative word should not necessarily be shortened even if shorter codes are still available.
Differences Zipf’s account vs. information content

- **Lexicon**
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- **Message**
Differences Zipf’s account vs. information content

- **Lexicon**
  - Zipf (principle of least effort): best lexicon is the most concise one
  - Information content: highly informative word should not necessarily be shortened even if shorter codes are still available.

- **Message**
  - Information content: Easily predictable information has a short code, lots of information has a long code.
  - Using such a code, information is conveyed at an almost constant rate.
  - Good usage of channel capacity.
  - Zipf’s account does not smooth out information content over time.
Zipf vs. Piantadosi

Relationship of the two accounts

- predictability account as a refinement of Zipf’s account.
- assigning word length by information content is
  - least effort if one assumes a superlinear relationship between effort and information content.
  - optimal given a constraint on channel capacity.
Discussion

1. How does the Piantadosi et al’s account differ from Zipf’s account?

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3. Ways of measuring information content given the context?
How come that natural language has developed this property?

Everyday language usage
- information content influences pronunciation (duration, clarity)
- abbreviations are used for long words which are predictable / familiar to the listener

Language evolution
- through lexicalization, predictable words end up being shorter.
- over time, abbreviations can become the new lexical item.
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Estimating Predictability

The role of context:

- discourse context
- local linguistic context
- syntactic context
- world knowledge

→ n-gram model estimation clearly a rough simplification (might not work so well for languages with freer word order)

Questions:

- Could the effect of frequency be explained away completely if we had better models of predictability in context?
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Questions:

- Could the effect of frequency be explained away completely if we had better models of predictability in context?
- What about effects of a word’s meaning on length and difficulty beyond its predictability? (denotation, connotation, significance)
- N-gram estimation impoverished but mathematically precise meaning of quantifying the number of bits needed to encode the message
Jamie Reilly and Jacob Kean wrote a letter which was published in PNAS (2011) in response to Piantadosi et al.’s article.
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Main objections:

- information content is just one aspect of a word
- analysis is confounded by syntactic dimensions such as grammatical class (e.g., nouns vs. verbs) and other dimensions of word meaning (e.g., word concreteness):
  - verbs are longer than nouns in many languages
  - abstract words tend to be longer than concrete ones. (due to inflection, e.g.: friend vs. friendliness)
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- Do verbs and abstract nouns convey more information content than concrete nouns?
Do verbs and abstract nouns convey more information content than concrete nouns?

- Yes.

**Corpus study**

verbs / abstract nouns are longer than concrete nouns (verbs and abstract nouns: 7.24 chars; concrete nouns: 5.99 chars)

verbs and abstract nouns convey more information than concrete nouns: (verbs and abstract nouns: 8.23 bits; concrete nouns: 7.52 bits)

- concreteness ratings from MRC psycholinguistic database
- selected only unambiguous nouns/verbs
Reply by Piantadosi, Tily and Gibson (2011)

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Information content correlates negatively with concreteness ($R = -0.24$). Why?

- predictable words, which tend to be concrete, will over time get shortened, while the abstract ones will then be longer in comparison.
Only offline or also online?

The results from Piantadosi et al. indicate that language developed such that information is conveyed at a uniform rate.
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But is this just a long-term effect, or do people try to convey information uniformly during online production?
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15 min BREAK
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*Speakers make use of the variability present in language during online production to achieve a uniform rate of conveying information.*
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(Tomorrow, we will look at work showing / discussing this more generally.)
Controlling information rate online

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Controlling information rate online

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→ Is there any evidence that people do this?
Wasn’t this already shown in Piantadosi (2011)?

Do people manipulate word length during production to achieve a uniform rate of information transmission?
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Do people manipulate word length during production to achieve a uniform rate of information transmission?

Not really:

- no control for meaning
- relationship could arise from differences between classes of words
  - e.g.: function words shorter and less informative than content words
  - e.g.: difference between nouns and verbs, or other regularities
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Not really:

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- relationship could arise from differences between classes of words
  - e.g.: function words shorter and less informative than content words
  - e.g.: difference between nouns and verbs, or other regularities

Mahowald et al. study

Test for correlation between length and information content while keeping the meaning constant.

chimp / chimpanzee
math / mathematics
chemo / chemotherapy
Expected Pattern

Predictions:

- predictive context $\rightarrow$ exam
- non-constraining context $\rightarrow$ examination

If this holds: People actively choose forms during production.

Otherwise: Effect in Piantadosi et al. likely to simply arise from differences in word classes or long-term pressure for linguistic efficiency, but not active speaker choice.
Corpus Study

Compare unambiguous forms that are near-synonyms.

\[-\frac{1}{N} \sum_{i=1}^{N} \log P(W = w | C = c_i)\]

avg. information content of shorter forms (exam): 6.90
avg. information content of longer forms (examination): 9.21

- possible confounding factor: short word forms are also more frequent
- but effect of information content also hold after accounting for frequency effect
Completion Experiment (Mechanical Turk)

Forced choice completion test with neutral vs. predictive context:

Example item: math / mathematics

Supportive: Susan was very bad at algebra, so she hated ...

Neutral: Susan introduced herself to me as someone who loved ...

Experimental control

- no common phrases like “final exam”
- cloze completion task to test supportive / neutral context (supportive: 52.4% cloze prob, 1.6% cloze prob)
Completion Experiment (Mechanical Turk)

Forced choice completion test with neutral vs. predictive context:

Example item: math / mathematics

Supportive: Susan was very bad at algebra, so she hated ...

Neutral: Susan introduced herself to me as someone who loved ...

Results
- short form chosen more often in predictive context (67%) than neutral context (56%).
- short form chosen more often overall.
Forced choice completion test with neutral vs. predictive context:

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**Results**

- short form chosen more often in predictive context (67%) than neutral context (56%).
- short form chosen more often overall.

Speakers actively select shorter word forms in more predictive contexts.
Discussion

Information content given context

- corpus study: predictability given n-gram model
- forced choice completion study: many linguistic factors determine predictability
- results hold across both ways of estimating information content

At what level of abstraction does this knowledge exist?

- association between word length and informativity?
- learned preferences for different types of context?

Relation between online choice and long-term lexicon evolution

- a word’s information content decreases → abbreviation
Some questions for discussion

- For the corpus study on chimp/chimpanzee, why not calculate predictability of \{chimp, chimpanzee\}?

- Lexical items can be shortened as they get more predictable on average, can words that get less common also become longer?

- We’ve been talking about word lengths — does this mean that Finnish/Turkish etc. are badly-designed languages?
Table of Contents

1. What is a good code?
2. Good Code and Ambiguity
3. Redundancy
Ambiguity exists at all levels of linguistic analysis.

- words (homonymy, polysemy)
- morphemes (-s in works, balls)
- syntactic ambiguity (e.g., attachment)
- semantic ambiguity (e.g., scopus)

Wouldn’t it be much better for communication, if language was unambiguous???
The natural approach has always been: Is it well designed for use, understood typically as use for communication? I think that’s the wrong question. The use of language for communication might turn out to be a kind of epiphenomenon... If you want to make sure that we never misunderstand one another, for that purpose language is not well designed, because you have such properties as ambiguity. If we want to have the property that the things that we usually would like to say come out short and simple, well, it probably doesn’t have that property. (Chomsky, 2002 p.107).
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Good code and ambiguity

Remember that we already saw a very good ambiguous code earlier today:

Syllable structure: CV

\[
\begin{array}{cccccc}
\text{p} & \text{t} & \text{k} & \text{a} & \text{i} & \text{o} \\
00 & 1 & 01 & 1 & 00 & 01
\end{array}
\]

Code for “pato” = 001101

1 → ambiguous between t and a \textit{when out of context}

00 → ambiguous between p and i \textit{when out of context}

01 → ambiguous between k and o \textit{when out of context}
Why ambiguity?

Hypothesis:
Ambiguity makes it possible to reuse short and simple codes.

- context (situation, world knowledge, linguistic context) very often disambiguates meaning
- an unambiguous signal would then be redundant.
- ambiguity allows for multiple use of speech signals that are easy to
  - produce
  - comprehend
  - remember

The extremes
- no ambiguity: different word for every meaning, marking of every attachment ambiguity etc.
- full ambiguity: just one totally ambiguous word, e.g. “ba”.
Is ambiguity optimal?

An optimally efficient communication system will not convey unnecessary (redundant) information.

Therefore, ambiguity is beneficial IF:

- speakers can effectively use the context for disambiguation
- AND ambiguous words usually occur in disambiguating contexts
- AND ambiguous words are the ones that are easy to produce
Question: How is ambiguity distributed?

- **If ambiguity is a random bug**
  short and common words, syllables and phonemes should not be more likely
to be ambiguous than long and rare ones.

- **If ambiguity is a means for optimal code**
  we should be able to observe that short words / syllables / phonemes are more
  ambiguous, so these easy and short units can be reused.
Homophones: (short and frequent words should be more ambiguous)

(a) (b) (c)

(low negative log probability = high frequency)
Syllables (short and frequent syllables should be more ambiguous)

(low negative log probability = high frequency)
Conclusion on Ambiguity

For word homophones and syllables, the predictions for *ambiguity as a way to optimize code* were borne out:
Short and frequent words and syllables were more ambiguous than long / rare ones.

Relation to UID

- Good codes achieve more uniform information density on average
- but there are many short codes available in our languages which are not used
- information density / code length focusses on information per unit of language / unit of time, and does not take into account “production ease”.
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15 min BREAK
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Getting back to the **noisy channel**:

- What if transmission isn’t error-free?
- If we have a maximally efficient code, how does a noisy channel affect message transfer?
- How can we avoid this?
Noisy Channel

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Simple idea: **Redundancy**
Getting back to the **noisy channel**:

- What if transmission isn’t error-free?
- If we have a maximally efficient code, how does a noisy channel affect message transfer?
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simple idea: **Redundancy** (e.g., repeat each word three times)
Dealing with a noisy channel: the NATO phonetic alphabet.

System of naming letters which is used by the military and pilots:
A is Alpha
B is Bravo
C is Charlie
etc.
We said at the beginning:  
**Channel capacity** is defined as the maximal amount of information that can be conveyed through a channel in a given amount of time, with arbitrarily small error.

Channel capacity depends on speed of transmission and level of noise.  
or  
Speed of transmission depends on channel capacity and level of noise.

We can use these notions to derive predictions about language processing, in a noisy environment and/or with a smaller channel.
Discussion topics

- What's the channel in language comprehension? Input? Output? What's the information flow?

- What does the general knowledge about the fact that the channel may be noisy entail for rational communication?

- What happens if we try to transmit information at a rate higher than channel capacity? Does this imply anything about the uniformity of transmission rate?
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