The cultural evolution of linguistic structure
Kenny Smith
The University of Edinburgh
Acknowledgements

Thanks to:

- Henry Brighton
- Simon Kirby
The uniqueness of language

Language exhibits a unique bundle of features:

- Cultural transmission
- Compositionality
- Recursion
- Duality of patterning
- ...

Echoes of these in animal communication.
Cultural transmission

Learned from the behaviour of other individuals, as opposed to being genetically transmitted.
Compositionality

The meaning of an expression is a function of the meaning of its parts and the way in which they are combined.

In language

John kick -ed Mary

In animals?
Explaining design features

**In general:** Design features are a consequence of cultural transmission.

**Today:** Compositionality is a consequence of cultural transmission through a bottleneck.
Outline of the talk

1. The role of cultural evolution in explaining language.
3. Cultural evolution of compositionality: other factors.
Language evolution as biological evolution

Language as a consequence of biological evolution of the language faculty:

- Adaptationist explanation: language faculty evolved because language is useful (e.g., Pinker & Bloom 1990)
- Non-adaptationist explanation: language faculty evolved as a side-effect (e.g., Chomsky 1975)
The role of culture?

Language acquisition is the “growth of cognitive structures along an internally-directed course under the triggering and partially shaping effect of the environment” (Chomsky 1980:34).

What is the environment? Presumably the Primary Linguistic Data.

\[ \ldots \rightarrow \text{PLD} \rightarrow \text{Competence} \rightarrow \text{PLD} \rightarrow \text{Competence} \rightarrow \ldots \]

This is cultural transmission. But does it actually do anything?
Cultural transmission leads to cultural evolution

Pressures acting on genetic transmission $\Rightarrow$ biological evolution

Pressures acting on cultural transmission $\Rightarrow$ cultural evolution

What pressures?

- functionality and natural selection?
- learner biases
- poverty of the stimulus
Cultural evolution of language: POS

Poverty of the stimulus: shortcomings in the data available to children e.g.

- contains many errors
- solely positive
- finite data, but acquire an infinite system

This last point has been called the transmission or learning bottleneck.
Cultural evolution of language: transmission bottleneck

Transmission through a bottleneck:

“The sample of observations will be finite, yet the range of meanings that individuals may wish to communicate about is likely to be very large or infinite. This learning bottleneck leads inevitably to the emergence of a language in which structure is preserved in the mapping between semantics and strings” (Kirby 2002:199)
The computational model

LEC trademark: applying techniques from machine learning, multi-agent systems and evolutionary computation to investigation of language evolution.

Two goals for this model:

1. To show (again) how the poverty of the stimulus leads to the cultural evolution of compositionality.

2. To allow manipulation of other factors (e.g. environment structure, learner bias).
The Iterated Learning Model

An idealised model of the cultural transmission of language.

M₀

H₀

produce observe produce observe produce

A₀ Generation 0

H₁

M₁

H₂

A₁ Generation 1

M₂

A₂ Generation 2
Compositionality: a structural hallmark of language

In a compositional system the meaning of a signal is a function of the meaning of its parts, and the way they are combined.

e.g. John kick -ed Mary

Can be contrasted with holistic mappings, where the signal stands for the meaning as a whole.

e.g. bought the farm
Measuring compositionality

Compositionality is a property of the system of meaning-signal mappings.

In a compositional system, similar meanings map to similar signals. In a holistic system, they don’t.
Measuring compositionality

Measure of compositionality ($c$): Pearson’s Product-Moment correlation coefficient of the pairwise distances between all the meanings and the pairwise distances between their corresponding signals.

- $c = 1$ for a perfectly compositional language.
- $c \approx 0$ for a holistic system.
Simplified semantics and signals

Meanings are drawn from an $F$-dimensional space, where each dimension has $V$ possible values.

e.g. (4 1 2)

Signals are strings of characters of length 1 to $L$. The characters are drawn from some alphabet $\Sigma$.

e.g. $b a c$

I will present results for $F = 3$, $V = 5$,
$L = 3$, $\Sigma = \{a, b, c, d, e, f, g, h, i, j\}$. 
A model of a linguistic agent

A neural network model.

meaning nodes

meanings and bits of meanings

modifiable connections

signals and bits of signals

signal nodes
A model of learning

Learners are exposed to *meaning-signal* pairs.
Production

Learners are prompted to produce with a *meaning* ...
...and produce a *signal*.
Modelling the poverty of the stimulus

Transmission bottleneck: finite data, but acquire an infinite system

In the ILM we can model this by exposing learners to the whole language of the previous generation (no bottleneck), or some subset of the language (bottleneck).
Results: no bottleneck

![Graph showing frequency of compositionality, c, for initial and final states. The graph indicates a significant peak at c=0 for the final state, suggesting a bottleneck effect.]
Results: bottleneck

Compositionality, \( c \)

Frequency

- Initial
- Final
Example time-courses

Compositionality, $c$

Generations

Compositionality, $c$

Generations

no bottleneck

bottleneck
**Explanation**

Why does a transmission bottleneck lead to the emergence of compositional language?

- When there is no bottleneck on transmission, the whole set of meaning-signal pairs can simply be memorised.

- When there is a bottleneck on transmission, there is pressure for the language to be *generalisable* from a subset.

Language adapts to this pressure. Holistic mappings can’t be generalised. Compositional languages can be learned from a subset, and will be favoured.
Other factors

- Frequency of meanings (Kirby 2001)
- Meaning space structure (Brighton 2002)
- Environment structure
- Learner bias
Other factors: environment structure

The advantage of compositionality is at a maximum when meanings are clustered together in the meaning space.

Other factors: learner bias

Different weight-update procedures result in different *learning biases* — some systems will be easier or harder to learn than others.

In order for a compositional language to evolve culturally, learners must:

1. be biased in favour of learning mappings between bits of meanings and bits of signals.
2. be biased in favour of acquiring one-to-one mappings between meanings and signals.

SMITH, K. Forthcoming. Learning biases for the evolution of linguistic structure: an associative network model. To appear in *Advances in Artificial Life (Proceedings of the 7th European Conference on Artificial Life)*
Conclusions

- Cultural transmission can lead to cultural evolution. We can model this.
- The transmission bottleneck leads to the cultural evolution of compositionality.
- This is influenced by factors such as:
  - Environment structure.
  - Learner bias.