Evolutionary Game Theory as a framework for modeling language evolution

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Overview

- lingueme-based evolution
- Evolutionary Game Theory
- evolutionary stability
- typology of vowel systems
- exemplar dynamics
- evolutionarily stable vowel systems
Conceptualization of language evolution

prerequisites for evolutionary dynamics

- replication
- variation
- selection
“any piece of structure that can be independently learned and therefore transmitted from one speaker to another” (Nettle 1999:5)

Croft (2000) attributes the name *lingueme* to Haspelmath (Nettle calls them *items*)

Examples:
- phonemes
- morphemes
- words
- constructions
- idioms
- collocations
- ...
Linguemes are replicators
- comparable to genes
- structured configuration of replicators
  - Biology: genotype
  - Linguistics: utterance
Evolution

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Evolution

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- linguistic creativity
- reanalysis
- language contact
- ...

Selection

- social selection
- selection for learnability
- selection for primability
Evolution

### Replication

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### Variation

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### Selection

- social selection
- selection for learnability
- selection for primability
learnability/primability

- selection against complexity
- selection against ambiguity
- selection for frequency
Evolutionary stability

- Darwinian evolution predicts ascent towards local fitness maximum
- Once local maximum is reached: stability
- Only random events (genetic drift, external forces) can destroy stability
- Central question for evolutionary model: what are stable states?
Why Game Theory?

- evolutionary dynamics may be modeled via Evolutionary Game Theory (EGT)

### Advantages

- EGT is abstract enough to subsume both biological and cultural evolution, without conflating them
- Game Theory as unifying framework for linguistic description
  - rationalistic: pragmatics
  - evolutionary: typology, language structure
- factorization of
  - dynamics: replicator dynamics (inter alia)
  - stability: ESS
Applications

- Pragmatics: Horn strategies (van Rooij 2004, de Jaegher 2006)
- Semantics: convexity of semantic categories (Jäger 2006)
- Syntax: typology of case marking systems (Jäger in press)
- Phonology: rest of the talk
The evolution of vowel spaces

- micro-variation in the inventory of vowels between languages: every language is different
- however, very strong tendencies:
  - most languages have five vowels
  - (almost) every language has [a], [i] and [u] like vowels
  - most vowel inventories are peripheral and symmetric etc.
- proposal (see for instance de Boer 2001):

  **Vowel inventories must be evolutionarily stable!**
What is a vowel?

Articulation

- speech sound
- voiced
- no constriction of the vowel tract
- vowel quality depends on
  - position of tongue
  - gesture of the lips
  - ...
What is a vowel?

**Acoustics**

- periodic sonic wave

**Figure:** Amplitude of the vowel /u/
What is a vowel?

Acoustics

- spectral analysis:

Figure: Spectrogram of /a/-/e/-/i/-/o/-/u/
What is a vowel?

Acoustics

- vowel is superposition of discrete harmonic waves:
  - fundamental frequency
  - formants

Figure: first five formants of /a-e-i-o-u/
What is a vowel?

**Acoustics**

- first two formants are crucial for identification of vowels
What is a vowel?

Acoustics

- more realistic picture:
Universal tendencies of vowel inventories

- comparison of vowel inventories in hundreds of languages reveals
  - virtually all languages use the vowels [a], [i], [u]
  - almost all vowels in all languages are peripheral
  - vowel inventories tend to be symmetrical
  - ...

Liljencrans and Lindblom (1972)

- vowel systems tend to maximize perceptual distance between vowels
- can be modeled as minimizing potential energy of a vowel system
- energy is proportional to sum of inverse squared distances
- fairly good typological predictions
Survey of 500+ vowel inventories

<table>
<thead>
<tr>
<th>number of vowels</th>
<th>vowel systems and their frequency of occurrence</th>
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<tr>
<td>3</td>
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Communication via the vowel space

Game theoretic model

- Signaling game
- types: between 3 and 9 vowel categories
- signals: each point within the two-dimensional (F1/F2) vowel space
Communication via the vowel space

One round of an evolutionary signaling game

- Nature picks a vowel category $v_S$ and shows it to $S$.
- $S$ picks a point $p_{\text{intend}}$ in the vowel space.
- A normally distributed random variable is added to $p_{\text{intend}}$, yielding $p_{\text{prod}}$.
- Another normally distributed random variable is added to $p_{\text{prod}}$, yielding $p_{\text{perc}}$.
- $R$ observes $p_{\text{perc}}$ and picks a vowel category $v_R$.
- If $v_S = v_R$, both players score a point.
Exemplar dynamics

- empiricist view on language processing/language structure
- popular in functional linguistics (esp. phonology and morphology) and in computational linguistics (aka. “memory-based”)

Basic idea

- large amounts of previously encountered instances ("exemplars") of linguemes are stored in memory
- very detailed representation of exemplars
- little abstract categorization
- similarity metric between exemplars
- new linguemes are processed in a similarity-based way
Exemplar dynamics: implementation

Sender

- chooses \( p_{\text{intend}} \) at random from multiset \( \{p | \langle v_S, p \rangle \in \text{memory} \} \)
- if communication succeeds (\( v_S = v_R \)), oldest item in memory is replaced with \( \langle v_S, p_{\text{prod}} \rangle \)
- otherwise memory remains unchanged

Receiver

- \( v_H \) is picked such that \( \min \{d(p_{\text{perc}}, p) | \langle v_H, p \rangle \in \text{memory} \} \) is minimized
- if communication succeeds (\( v_S = v_R \)), oldest item in memory is replaced by \( \langle v_R, p_{\text{perc}} \rangle \)
- otherwise memory remains unchanged
### Simulations

#### Setup

- population of 20 agents
- each agent has a memory of 4000 previous observations per vowel category (initialized with random values)
- 300k iterations of the signaling game
- sender and receiver are picked at random

Inspired by much more sophisticated simulations by Bart de Boer.
Simulation results

- black dots display average sender strategy for each agent and vowel category
- colored dots display receiver strategies (colors represent vowel categories)
In detail
In detail

4 14 5 4 2

Diagram with grid and points.
In detail

5

97 3

28/37
In detail

<table>
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<tr>
<th>6</th>
<th>26</th>
<th>12</th>
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[Diagram showing a grid with numbers 6, 26, 12, and 12.]
In detail
## In detail

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In detail
more than half of the typologically dominant patterns correspond to (experimentally determined) ESSs (150 out of 264 in the database)

five out of seven ESSs correspond to empirically attested vowel systems

even the two outliers look natural (symmetric systems with peripheral prototypes)
Theoretical considerations

ESS under replicator dynamics: strict Nash equilibria

- sender strategy: mapping from vowel categories to points in the vowel space
- receiver strategy: categorization of points
Voronoi tessellations

- Suppose receiver strategy $R$ is given and known to the sender: which sender strategy would be the best response to it?

  - Every signal $p$ has a "prototypical" interpretation: $R(p)$
  - For every vowel category $v$: S’s best choice is to choose the $p$ that minimizes the distance between $p$ and $R(p)$
  - Optimal $S$ thus induces a **partition** of the meaning space
  - Voronoi tessellation, induced by the range of $R$
Open question

- numeric calculation of the ESSs for the human vowel space
- Exemplar Dynamics is similar but not identical to replicator dynamics
- conjecture: as the variance of the random variables goes to 0, the attractor states of the exemplar dynamics converges towards SNEs
EGT and language evolution

- EGT is well-suited to model utterance-based, horizontal cultural language evolution
- Expectation: most languages spend most of the time in ESSs
- Possible refinements
  - Variants of exemplar dynamics (like \(k\)-nearest neighbor classification as receiver strategy)
  - Different similarity metrics (beyond Euclidean distance)
  - Spatial/network structure between agents


