Language Change & Cultural Evolution – Game-Theoretic Approaches

Current Trends in Linguistics

Roland Mühlenbernd
Overview

1. Language change & cultural evolution
2. Evolutionary game theory in linguistics
3. A case study: the progressive cycle
The Tree of Life
Natural Selection

- **Replication:** entities can produce copies
- **Mutation:** copies are not faithful
- **Variation:** plenty of variants exists (due to replication & mutation)
- **Differential Fitness:** number of offspring depends on contextual factors → selection

![Evolutionary diagram](image_url)

- Mutation creates variation
- Unfavorable mutations selected against
- Reproduction and mutation occur
- Favorable mutations more likely to survive
- ... and reproduce
Evolution Theory & Language

The formation of different languages and of distinct species, and the proofs that both have been developed through a gradual process, are curiously parallel. ...Max Müller has well remarked: ‘A struggle for life is constantly going on amongst the words and grammatical forms in each language. The better, the shorter, the easier forms are constantly gaining the upper hand, and they owe their success to their inherent virtue.’ ...The survival or preservation of certain favoured words in the struggle for existence is natural selection.

Charles Darwin, 1871

1The Descent of Man, and Selection in Relation to Sex, C2: Mental Powers
Evolution Theory & Language

Cultural transmission is analogous to genetic transmission in that, although basically conservative, it can give rise to a form of evolution. [...] Language seems to evolve by non-genetic means, and at a rate which is orders of magnitude faster than genetic evolution.

Richard Dawkins, 1976

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2 The Selfish Gene, Chapter 11: Memes: the new replicators
Mechanisms of Universal Darwinisms

1. *Variation*: continuing (abundance) of different elements

2. *Replication*: elements have the capacity to create copies or replicas of themselves

3. *Differential “Fitness”*: the number of copies of an element that are created in a given time varied, depending on interactions between
   - features of that element
   - features of the environment in which it persists

$\Rightarrow$ *Selection*

Daniel Dennett, 1995\(^3\)

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\(^3\)Darwin’s Dangerous Ideas, Chapter 12: *The Cranes of Culture*
Rosenbach’s Differentiation

- We have to distinguish i) the evolution of language faculty of Homo Sapiens from ii) the change of human language
- language change is part of cultural evolution

Quelle: *Language change as cultural evolution* (Rosenbach 2008)
Linguistic Replication

1. What are linguistic replicators in the first place?

Thus, the paradigm replicator in language is the lingueme, parallel to the gene as the basic replicator in biology; an utterance is made up of linguemes and linguemes possess structure.

William Croft (2000): Explaining Language Change
Linguistic Replication

2. What are the units of linguistic replication?

Well-known building blocks of linguistic structure:

- phonemes, morphemes, phrases, constructions, corresponding meaning (Croft 2000, Ritt 2004, Rosenbach 2008)
Linguistic Replication

3. **What is the replication mechanism?**

- first language acquisition (vertical transfer)
- repeated communication (horizontal transfer)
  - imitation (Ritt 2004)
  - accommodation (Croft 2000: important selection mechanism)
Language change as cultural evolution

1. Replication: production/adoption through repeated communication, first language acquisition
2. Variation: number of variants to express something
3. Selection: learnability, speaker/hearer economy (communicative functionality), social factors (register, prestige, accommodation)
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Explanatory Potential of EGT in Linguistics

Results and methods from game theory are apt to formalize the intuitive notion of ‘linguistic universals’ as emergent properties of communication. [...] Evolutionary game theory [...] provides a formal framework that models questions of language evolution that allows us to integrate the two approaches, innateness and social function of language.

Gerhard Jäger, 2014

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What is a universal? On the explanatory potential of evolutionary game theory in linguistics
Coordination & Signaling Games

signaling game: \( \langle \{S, H\}, M, F, P, U \rangle \)

\[
U(m_i, m_j) = \begin{cases} 
1 & \text{if } i = j \\
0 & \text{else}
\end{cases}
\]

- speaker \( S \), hearer \( H \)
- meanings \( M = \{m_c, m_t\} \)
- forms \( F = \{f_h, f_b\} \)
- \( P \in \Delta(M) \), \( P(m_c) = P(m_t) = .5 \)
Signaling Strategies

- **Speaker strategy** $s$: speaker behavior formalized as a function $s: M \rightarrow F$:

  $s_1: \begin{align*} m_c &\rightarrow f_b \\ m_t &\rightarrow f_h \end{align*} \\
  s_2: \begin{align*} m_c &\rightarrow f_b \\ m_t &\rightarrow f_h \\ m_t &\rightarrow f_h \end{align*} \\
  s_3: \begin{align*} m_c &\rightarrow f_b \\ m_t &\rightarrow f_h \end{align*} \\
  s_4: \begin{align*} m_c &\rightarrow f_b \\ m_t &\rightarrow f_h \end{align*}$

- **Hearer strategy** $h$: hearer behavior formalized as a function $h: F \rightarrow M$:

  $h_1: \begin{align*} f_b &\rightarrow m_c \\ f_h &\rightarrow m_t \end{align*} \\
  h_2: \begin{align*} f_b &\rightarrow m_c \\ f_h &\rightarrow m_t \\ f_h &\rightarrow m_t \end{align*} \\
  h_3: \begin{align*} f_b &\rightarrow m_c \\ f_h &\rightarrow m_t \end{align*} \\
  h_4: \begin{align*} f_b &\rightarrow m_c \\ f_h &\rightarrow m_t \end{align*}$
Signaling Systems...

- are combinations of pure strategies.
  The coffeehouse game has two: \( L_1 = \langle s_1, h_1 \rangle \) and \( L_2 = \langle s_2, h_2 \rangle \)

\[
\begin{align*}
  m_c &\rightarrow f_b &\rightarrow m_c &\quad m_c &\rightarrow f_b &\rightarrow m_c \\
  L_1: &\quad m_t &\rightarrow f_h &\rightarrow m_t &\quad L_2: &\quad m_t &\rightarrow f_h &\rightarrow m_t
\end{align*}
\]

- are one-to-one mappings between form and meaning
- are strict Nash equilibria of the EU-table:

<table>
<thead>
<tr>
<th></th>
<th>( h_1 )</th>
<th>( h_2 )</th>
<th>( h_3 )</th>
<th>( h_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( s_1 )</td>
<td>1</td>
<td>0</td>
<td>.5</td>
<td>.5</td>
</tr>
<tr>
<td>( s_2 )</td>
<td>0</td>
<td>1</td>
<td>.5</td>
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<tr>
<td>( s_3 )</td>
<td>.5</td>
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<td>.5</td>
</tr>
<tr>
<td>( s_4 )</td>
<td>.5</td>
<td>.5</td>
<td>.5</td>
<td>.5</td>
</tr>
</tbody>
</table>

- whereby \( EU(s, h) = \sum_{m \in M} P(m) \times U(m, h(s(m))) \)

- and are therefore evolutionary stable under evolutionary dynamics
Signaling Games and Cultural Evolution

- **Replicators**: form-meaning mappings in terms of strategy pairs
- **Variation**: is given for any signaling game with $|M| > 1$ and/or $|F| > 1$
- **Replication and Selection**: defined as ‘update mechanism/rule’ for ‘repeated plays’
Overview: Update Mechanisms

<table>
<thead>
<tr>
<th>perspective</th>
<th>replicator dynamics</th>
<th>imitation</th>
<th>learning</th>
</tr>
</thead>
<tbody>
<tr>
<td>memory size</td>
<td>population-based</td>
<td>agent-based</td>
<td>agent-based</td>
</tr>
<tr>
<td>0</td>
<td>static</td>
<td>1</td>
<td>(whole) history</td>
</tr>
<tr>
<td>game type</td>
<td>pure</td>
<td>static</td>
<td>static/dynamic</td>
</tr>
<tr>
<td>strategy</td>
<td></td>
<td>pure</td>
<td>pure/probabilistic</td>
</tr>
</tbody>
</table>

- replicator dynamics is standard model in EGT
- imitation is the basic mechanism for cultural evolution
- “it can be shown that exactly the same strategies are evolutionary stable under the replicator dynamics and under the imitation dynamics” (Jäger 2007)
- learning rules i) can be combined with actual ‘communicative acts’ and ii) add the aspect of language acquisition/ontogeny
Applications of Signaling Games I

Functional explanations for typological universals:

- **morphology**: evolutionary stability of case marking systems for semantic core roles via (i) replicator dynamics, and (ii) stability analysis (Jäger 2007)
- **phonology**: stability of vowel systems (separating acoustic space) via (i) exemplar learning, and (ii) simulation experiments (Jäger 2008)
- **pragmatics**: evolutionary stability of the ‘Horn strategy’ via (i) reinforcement learning, fictitious play, and (ii) simulation experiments (Mühlenbernd 2011)
Applications of Signaling Games II

Functional explanations for ‘diachronic’ universals:

- **negation**: evolutionary trajectories of the ‘Jespersen cycle’ via (i) replicator dynamics, and (ii) stability/trajectory analysis (Ahern & Clark 2014, Ahern 2016)
- **morphosemantics**: evolutionary trajectories of the ‘progressive cycle’ via (i) replicator dynamics, and (ii) stability/trajectory analysis (Deo 2015, Yanovich 2016)
- **morphosemantics**: evolutionary trajectories of the ‘progressive cycle’ via (i) reinforcement learning, and (ii) simulation experiments (Enke, Mühlenbernd, Yanovich 2016)
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The Imperfective Domain

- the imperfective form makes explicit reference to the internal temporal structure of a situation
- the imperfective range (Comrie, 1976):

  Imperfective

  Habitual
  - Kim used to smoke

  Continuous
  - Steve is smoking

  Progressive
  - Meg lives in York

  Non-Progressive

- fundamental classification of the types of knowledge we possess (Goldsmith & Woisetschlaeger, 1982):
  - **structural:** stable facts, generalizations that characterize the world
  - **phenomenal:** facts that pertain to specific times and the events that occupy such times
Marking Strategies of the Imperfective Domain

<table>
<thead>
<tr>
<th>system</th>
<th>strategy</th>
<th>sample language</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZP</td>
<td>zero progressive</td>
<td>$X_{imp}$</td>
</tr>
</tbody>
</table>

(1) Olga **pisa-la** pis’ma kogda pojavilsja Vadim ‘Olga was writing letters when Vadim appeared.’

(2) Olga **pisa-la** pis’mo materi po voskresenjam on Sunday ‘Olga used to write a letter to her mother on Sundays.’
Marking Strategies of the Imperfective Domain

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<tr>
<td>OP</td>
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<td>Italian, Early Modern English</td>
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</table>

(3) Che fai? Ridi? what do.PRS.1SG laugh.PRS.1SG ‘What are you doing? Are you laughing?’

(4) Che stai facendo? Stai ridendo? what stay.PRS.1SG doing stay.PRS.1SG laughing ‘What are you doing? Are you laughing?’
# Marking Strategies of the Imperfective Domain

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<td><em>Italian</em>, <em>Early Modern English</em></td>
</tr>
<tr>
<td>CP</td>
<td>$X_{imp}, Y_{prog}$</td>
<td><em>PM Turkish</em>, <em>English</em>, <em>Irish</em></td>
</tr>
</tbody>
</table>

(5) Genekkikle iki saat çaliş-*ir*-di-m
    Usually for two hours work-IMPF-PST.COP-1.SG
    ‘I *usually work* for two hours.’

(6) Saat ikide çaliş-*iyor*-du-m
    At two o’clock work-PROG-PST.COP-1.S
    ‘A two o’clock I *was working*.’
Marking Strategies of the Imperfective Domain

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</tr>
<tr>
<td>CP</td>
<td>$X_{imp}, Y_{prog}$</td>
<td>PM Turkish, English, Irish</td>
</tr>
<tr>
<td>ZP*</td>
<td>$Y_{imp}$</td>
<td>Turkish, Welsh</td>
</tr>
</tbody>
</table>

(7) Sen Ömer’i benden daha iyi tan-iyor-du-n
you Ömer me better than know-PROG-PST.COP.2.SG
‘You knew (were knowing) Ömer better than me.’

(8) O zamanlarda Mehmet çok sigara
At the time Mehmet lot cigarette
iç-iyor-du
smoke-IMPF-PST.COP.3.SG
‘At that time, Mehmet used to smoke a lot.’
The Functional Progressive Cycle

Old English, Russian
Turkish, Welsh

English?

English, Irish, Old Turkish

Keys:
P: phenomenal
S: structural

CP
OP
The Formal Progressive Path

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<tr>
<td>ZP</td>
<td>zero progressive</td>
<td>Russian, Old English</td>
</tr>
<tr>
<td>OP</td>
<td>optional progressive</td>
<td><em>Italian</em>, Early Modern English</td>
</tr>
<tr>
<td>CP</td>
<td>categorical progressive</td>
<td>PM <em>Turkish</em>, English, Irish</td>
</tr>
<tr>
<td>ZP*</td>
<td>zero progressive</td>
<td><em>Turkish</em>, Welsh</td>
</tr>
</tbody>
</table>

**OP**: \(X_Y \times\)  
**CP**: \(Y \times\)  
**ZH**: \(X \times\)

**progressive path**

**ZP**  
**ZH**: \(X \times\)

**hypothetical habitual path**

**OH**: \(X \times Y\)  
**CH**: \(X \times Y\)

**Innovation**  
**Categorization**  
**Generalization**
Research Questions

▶ What kind of conjectures can explain the existence of the following crosslinguistically attested ‘universal’ patterns inside the imperfective domain?
  ▶ the cyclic pattern of the progressive’s functional evolution
  ▶ the non-cyclic (dead-end) trajectory of the habitual’s functional evolution

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**Progressive path**

- **OP:** $XY\ X$
- **CP:** $Y\ X$

**Hypothetical habitual path**

- **ZP:** $X\ X$
- **ZH:** $X\ XY$
- **ZH*: $Y\ Y$
- **OH:** $X\ XY$
- **CH:** $X\ Y$
- **ZP*:** $Y\ Y$

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**Innovation Categorization Generalization**
Research Project

**Given**: typologically supported theory of HOW a diachronic process (of morphosemantic change) happens

**Wanted**: potential conjectures responsible for WHY there is no alternative development (diachronic universal)

**Approach**: game theoretic model $\rightarrow$ evolutionary population model $\rightarrow$ synthetic analysis: simulation experiments for different conjectures
Signaling game

- game theoretic model that represents a communicative situation between a speaker $S$ and a hearer $H$

- Imperfective game: $IG = \langle (S, H, C, M, F, P, U) \rangle$

- forms: $F = \{ f_{old}, f_{new} \}$

- meanings: $M = \{ m_s, m_p \}$

- contexts: $C = \{ c_s, c_p \}$

- probabilities: $P(m_s|c_s) = P(m_p|c_p) = .9$

- utility function: $U(m, s, h) = \begin{cases} 1 & \text{if } h(s(m)) = m \\ 0 & \text{else} \end{cases}$
Extensive Form of the Imperfective Game
### Speaker strategies

\( s \in S : M \times C \rightarrow F \)

<table>
<thead>
<tr>
<th>ZH</th>
<th>S_0</th>
<th>f_{old}</th>
<th>f_{old}</th>
<th>f_{old}</th>
<th>f_{old}</th>
</tr>
</thead>
<tbody>
<tr>
<td>S_1</td>
<td>f_{old}</td>
<td>f_{old}</td>
<td>f_{old}</td>
<td>f_{new}</td>
<td></td>
</tr>
<tr>
<td>S_2</td>
<td>f_{old}</td>
<td>f_{old}</td>
<td>f_{new}</td>
<td>f_{old}</td>
<td></td>
</tr>
<tr>
<td>S_3</td>
<td>f_{old}</td>
<td>f_{old}</td>
<td>f_{new}</td>
<td>f_{new}</td>
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<tr>
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<td>f_{old}</td>
<td>f_{new}</td>
<td>f_{old}</td>
<td>f_{old}</td>
<td></td>
</tr>
<tr>
<td>S_5</td>
<td>f_{old}</td>
<td>f_{new}</td>
<td>f_{old}</td>
<td>f_{new}</td>
<td></td>
</tr>
<tr>
<td>S_6</td>
<td>f_{old}</td>
<td>f_{new}</td>
<td>f_{new}</td>
<td>f_{old}</td>
<td></td>
</tr>
<tr>
<td>S_7</td>
<td>f_{old}</td>
<td>f_{new}</td>
<td>f_{new}</td>
<td>f_{new}</td>
<td></td>
</tr>
<tr>
<td>S_8</td>
<td>f_{new}</td>
<td>f_{old}</td>
<td>f_{old}</td>
<td>f_{old}</td>
<td></td>
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<tr>
<td>S_9</td>
<td>f_{new}</td>
<td>f_{old}</td>
<td>f_{old}</td>
<td>f_{new}</td>
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<tr>
<td>S_{10}</td>
<td>f_{new}</td>
<td>f_{old}</td>
<td>f_{new}</td>
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<tr>
<td>S_{11}</td>
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<tr>
<td>S_{12}</td>
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<td>f_{old}</td>
<td>f_{old}</td>
<td></td>
</tr>
<tr>
<td>S_{13}</td>
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<td>f_{old}</td>
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<tr>
<td>S_{14}</td>
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<tr>
<td>S_{15}</td>
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</table>

### Hearer strategies

\( h \in H : F \times C \rightarrow M \)

<table>
<thead>
<tr>
<th>ZP</th>
<th>CP</th>
</tr>
</thead>
<tbody>
<tr>
<td>h_0</td>
<td>m_p</td>
</tr>
<tr>
<td>h_1</td>
<td>m_p</td>
</tr>
<tr>
<td>h_2</td>
<td>m_p</td>
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<tr>
<td>h_3</td>
<td>m_p</td>
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<td>h_{14}</td>
<td>m_s</td>
</tr>
<tr>
<td>h_{15}</td>
<td>m_s</td>
</tr>
</tbody>
</table>

#### ZP(*)

#### OP

#### CP
Evolutionary Population Model

- *population size*: of 200 agents
- *simulation*: agents play the imperfective game pairwise and repeatedly (→ horizontal transfer)
- *replacement*: agents get older and old agents (here: 5000 interactions) get replaced by ‘newbies’ (→ vertical transfer)
- *initial setting*: at the beginning agents can only use form $f_{old}$, after a while (here: 1000 simulation steps) new form $f_{new}$ will be introduced
Experiments & Results

Exp. 1: basic model
Result: ‘odd’ context strategy \( \langle s_6, h_9 \rangle \) \((f_{new} \text{ marks ‘context-unusual’})\)

Exp. 2: reduced context cues \((-10\%)
Result: both categorical systems emerge with same probability; optional systems are short intermezzos

Exp. 3: increasing costs factor \(\alpha\)
Result: both zero systems emerge with same probability via both paths

Exp. 4: asymmetry for input of newbies
Result: reconstruction of expected paths

\[
IR(m_s|n) = \begin{cases} 
0.5n_{\text{child}} & \text{if } n \leq n_{\text{child}} \\
0.5 & \text{else}
\end{cases}
\]

\[
IR(m_p|n) = 1.0 - IR(m_s|n)
\]
Summary

- Given typological data, the progressive cycle can be seen as a diachronic language universal.
- The cycle can be divided in 3 different stages.
- The presented model can reproduce these stages in their assumed diachronic order, under the following assumptions:
  - Reduced access to context information.
  - Increasing costs for complex systems (in favor of speaker economy).
  - Asymmetry for young agents’ input in favor of phenomenal situations.
Language Change is Cultural Evolution

Vielen Dank!
Referenzen


