Evolutionary Game Theory as a framework for modeling language evolution

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Overview

- lingueme-based evolution
- Evolutionary Game Theory
- evolutionary stability
- convex meanings
- color terms
- typology of case marking systems
- conclusion

Conceptualization of language evolution

prerequisites for evolutionary dynamics

- replication
- variation
- selection

Linguemes

- "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

- Linguemes are **replicators**
- comparable to genes
- structured configuration of replicators
    - Biology: genotype
    - Linguistics: utterance

Croft:

The utterance is the genome!

Evolution

Replication

(at least) two modes of lingueme replication:

- acquisition
- priming (see Jäger and Rosenbach 2005; Croft and Nettle would perhaps not agree)

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Selection

- social selection
- selection for learnability
- selection for primability

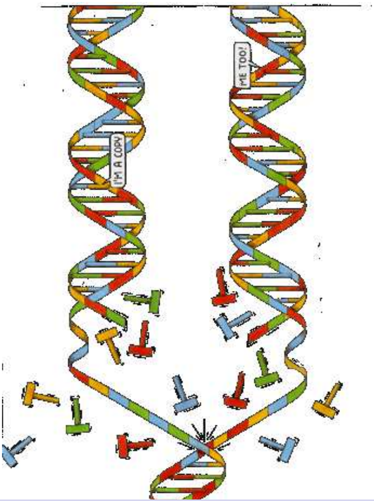
Fitness

learnability/primability

- selection **against complexity**
- selection **against ambiguity**
- selection **for frequency**

Evolutionary Game Theory

- populations of players
- individuals are (genetically) programmed for certain strategy
- individuals replicate and thereby pass on their strategy



Utility and fitness

- number of offspring is monotonically related to average utility of a player
- high utility in a competition means the outcome improves reproductive chances (and vice versa)
- number of expected offspring (Darwin's "fitness") corresponds to **expected utility** against a population of other players
- genes of individuals with high utility will spread

Replicator dynamics

- simplest dynamics that implements these ideas
- fitness is simply identified with utility

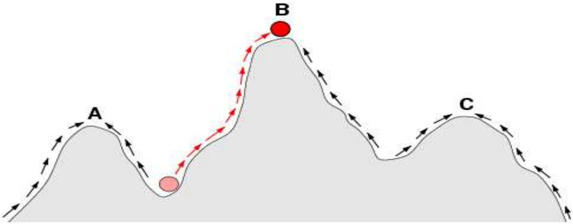
$$\frac{dx_i}{dt} = x_i(\sum_{j=1}^{n} y_j u_A(i,j) - \sum_{k=1}^{n} x_k \sum_{j=1}^{n} y_j u_A(k,j))$$

$$\frac{dy_i}{dt} = y_i(\sum_{j=1}^{m} x_j u_B(i,j) - \sum_{k=1}^{n} y_k \sum_{j=1}^{m} x_j u_B(k,j))$$

x_i ... proportion of s_i^A within the A-population
y_i ... proportion of s_i^B within the B-population

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?



Evolutionary stability (cont.)

- replication sometimes unfaithful (mutation)
- population is **evolutionarily stable** $\leadsto$ resistant against small amounts of mutation
- Maynard Smith (1982): static characterization of

  Evolutionarily Stable Strategies

  (ESS) in terms of utilities only

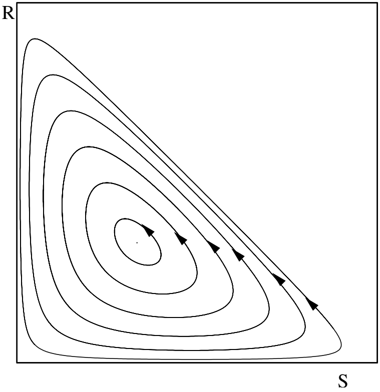
Evolutionary stability (cont.)

Rock-Paper-Scissor

	R	P	S
R	0	-1	1
P	1	0	-1
S	-1	1	0

- one stationary state ("Nash equilibrium"): $(\frac{1}{3}, \frac{1}{3}, \frac{1}{3})$
- not evolutionarily stable though

Trajectories



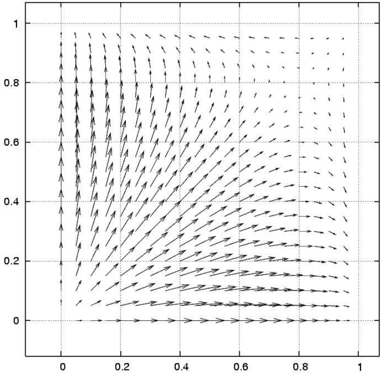
Hawks and Doves

Hawks and Doves

	H	D
H	1,1	7,2
D	2,7	3,3

- two-population setting:
  - both A and B come in hawkish and dovish variant
  - everybody only interacts with individuals from opposite "species"
  - excess of A-hawks helps B-doves and vice versa
  - population push each other into opposite directions

Vector field



Evolutionary stability

Definition (Strict Nash Equilibrium)

A pair of strategies (S, H) *is a Strict Nash Equilibrium iff*

$$\forall S'(S' \neq S \rightarrow u(S, H) > u(S', H))$$

and

$$\forall H'(H' \neq H \rightarrow u(S, H) > u(S, H'))$$

- in a SNE, S is unique best response to H and vice versa

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Theorem (Selten 1980)

(S, H) *is evolutionarily stable if and only if it is a Strict Nash Equilibrium.*

Cognitive semantics

Gärdenfors (2000):

- meanings are arranged in **conceptual spaces**
- conceptual space has geometrical structure
- dimensions are founded in perception/cognition

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Criterion P

A *natural property* is a convex region of a domain in a conceptual space.

Examples

- spatial dimensions: *above, below, in front of, behind, left, right, over, under, between ...*
- temporal dimension: *early, late, now, in 2005, after, ...*
- sensual dimenstions: *loud, faint, salty, light, dark, ...*
- abstract dimensions: *cheap, expensive, important, ...*

The naming game

- two players:
  - **S**peaker
  - **H**earer
- infinite set of **M**eanings, arranged in a finite metrical space *distance is measured by function* $d : M^2 \mapsto R$
- finite set of **F**orms
- sequential game:
  1. nature picks out $m \in M$ according to some probability distribution p and reveals m to S
  2. S maps m to a form f and reveals f to H
  3. H maps f to a meaning m'

The naming game

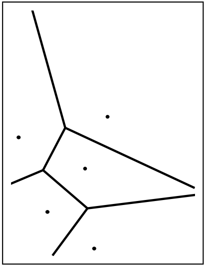
- **Goal:**
  - optimal communication
  - both want to minimize the distance between m and m'
- **Strategies:**
  - speaker: mapping S from M to F
  - hearer: mapping H from F to M
- **Average utility:** (identical for both players)

$$u(S,H) = \int_M p_m \times \exp(-d(m, H(S(m)))^2)dm$$

vulgo: average similarity between speaker's meaning and hearer's meaning

Voronoi tesselations

- suppose H is given and known to the speaker: which speaker strategy would be the best response to it?
  - every form f has a "prototypical" interpretation: $H(f)$
  - for every meaning m: S's best choice is to choose the f that minimizes the distance between m and $H(f)$
  - optimal S thus induces a **partition** of the meaning space
  - Voronoi tesselation, induced by the range of H



Voronoi tesselation

Okabe et al. (1992) prove the following lemma (quoted from Gärdenfors 2000):

Lemma

The Voronoi tessellation based on a Euclidean metric always results in a partioning of the space into convex regions.

ESSs of the naming game

- best response of H to a given speaker strategy S not as easy to characterize
- general formula

$$H(f) = \arg\max_{m} \int_{S^{-1}(f)} p_{m'} \times \exp(-d(m, m')^2) dm'$$

- such a hearer strategy always exists
- linguistic interpretation: H maps every form f to the **prototype** of the property $S^{-1}(f)$

ESSs of the naming game

Lemma

In every ESS $\langle S, H \rangle$ of the naming game, the partition that is induced by S^{-1} on M is the Voronoi tesselation induced by $H[F]$.

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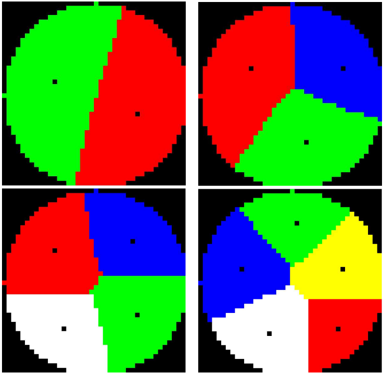
In every ESS $\langle S, H\rangle$ of the naming game, the partition that is induced by S^{-1} on M is the Voronoi tesselation induced by $H[F]$.

Theorem

For every form f, $S^{-1}(f)$ is a convex region of M.

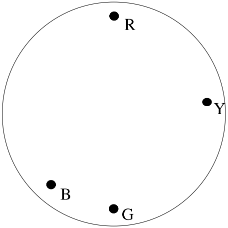
Simulations

- two-dimensional circular meaning space
- discrete approximation
- uniform distribution over meanings
- initial stratgies are randomized
- update rule according to (discrete time version of) replicator dynamics



A toy example

- suppose
  - circular two-dimensional meaning space
  - four meanings are highly frequent
  - all other meanings are negligibly rare
- let's call the frequent meanings Red, Green, Blue and Yellow



$$p_i(\text{Red}) > p_i(\text{Green}) > p_i(\text{Blue}) > p_i(\text{Yellow})$$

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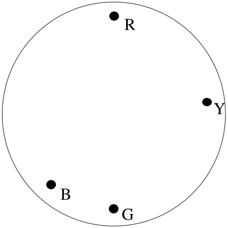
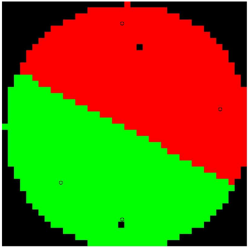


$$p_i(\text{Red}) > p_i(\text{Green}) > p_i(\text{Blue}) > p_i(\text{Yellow})$$

Yes, I made this up without empirical justification.

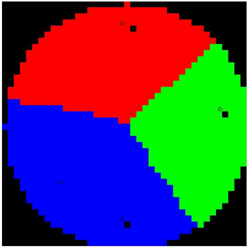
Two forms

- suppose there are just two forms
- only one Strict Nash equilibrium (up to permuation of the forms)
- induces the partition {**Red, Blue**}/{**Yellow, Green**}



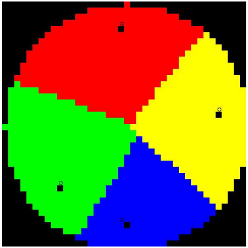
Three forms

- if there are three forms
- two Strict Nash equilibria (up to permuation of the forms)
- partitions {Red}/{Yellow}/{Green, Blue} and {Green}/{Blue}/{Red, Yellow}
- only the former is **stochastically stable** (resistent against random noise)



Four forms

- if there are four forms
- one Strict Nash equilibrium (up to permuation of the forms)
- partitions {Red}/{Yellow}/{Green}/{Blue}



Conclusion

Meaning spaces

- assumption: utility is correlated with similarity between speaker's meaning and hearer's meaning
- consequences:
  - convexity of meanings
  - prototype effects
  - uneven probability distribution over meanings leads to the kind of implicational universals that are known from typology of color terms

Conclusion

EGT and language evolution

- EGT is well-suited to model utterance based, horizontal cultural language evolution
- allows to characterize attractor states in a static way, regardless of the micro-structure of language change
- possible refinements
  - stochastic evolution
  - spatial/network structure between agents

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