Evolutionary games and language

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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 (Jäger and Rosenbach 2005; Croft and Nettle would perhaps not agree)

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Variation

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

Evolution

Replication

(at least) two modes of lingueme replication:

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

Variation

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

Selection

- social selection
- selection for learnability
- selection for primability

Fitness

learnability/primability

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

EGT and pragmatics

Horn strategies: prototypical meanings tend to go with simple expressions and less prototypical meanings with complex expressions.

(1)

- **a.** John went to church/jail. (prototypical interpretation)
- **b.** John went to the church/jail. (literal interpretation)

(2)

- **a.** I am going to marry you. (no indirect speech act)
- **b.** I will marry you. (indirect speech act)

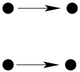
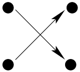
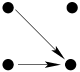
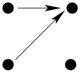
(3)

- **a.** I need a new driller/cooker.
- **b.** I need a new drill/cook.

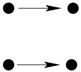
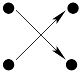
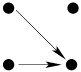
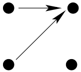
Horn strategies

- simple game:
  - players: speaker and hearer
  - two forms: f_0 (short) and f_1 (long)
  - two meanings: m_0 (frequent) and m_1 (rare)
  - speaker strategies: mappings from meanings to forms
  - hearer strategies: mappings from forms to meanings

Speaker strategies

- $S_1 : m_0 \mapsto f_0,\ m_1 \mapsto f_1$:  "Horn strategy"
- $S_2 : m_0 \mapsto f_1,\ m_1 \mapsto f_0$:  "anti-Horn strategy"
- $S_3 : m_0 \mapsto f_0,\ m_1 \mapsto f_0$:  "Smolensky strategy"
- $S_4 : m_0 \mapsto f_1,\ m_1 \mapsto f_1$:  "anti-Smolensky strategy"

Hearer strategies

- $H_1 : f_0 \mapsto m_0,\ f_1 \mapsto m_1$:  "Horn strategy'
- $H_2 : f_0 \mapsto m_1,\ f_1 \mapsto m_0$:  "anti-Horn strategy"
- $H_3 : f_0 \mapsto m_0,\ f_1 \mapsto m_0$:  "Smolensky strategy"
- $H_4 : f_0 \mapsto m_1,\ f_1 \mapsto m_1$:  "anti-Smolensky strategy"

Utility of Horn games

- whether communication works depends both on speaker strategy S and hearer strategy H
- two factors for functionality of communication
  - communicative success ("hearer economy")

$$\delta_m(S, H) = \begin{cases} 1 & \text{iff} \quad H(S(m)) = m \\ 0 & \text{else} \end{cases}$$

  - least effort ("speaker economy")

$$cost(f) \ldots \text{measure of complexity of expression}$$

Utility of Horn games

$$u_s(S,H) = \sum_m p_m \times (\delta_m(S,H) - cost(S(m)))$$

$$u_h(S,H) = \sum_m p_m \times \delta_m(S,H)$$

$p \ldots$ probability distribution over meanings

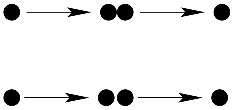
Utility of Horn game

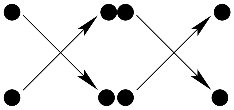
Let's make up some numbers:

- $p(m_0) = .75$
- $p(m_1) = .25$
- $cost(f_0) = .1$
- $cost(f_1) = .2$

Utility of Horn game

	H_1		H_2		H_3		H_4	
S_1	.875	1.0	-.125	0.0	.625	.75	.125	.25
S_2	-.175	0.0	.825	1.0	.575	.75	.25	.075
S_3	.65	.75	.15	.25	.65	.75	.15	.25
S_4	.05	.25	.55	.75	.55	.75	.05	.25





Utility of Horn game

	H_1		H_2		H_3		H_4	
S_1	.875	1.0	-.125	0.0	.625	.75	.125	.25
S_2	-.175	0.0	.825	1.0	.575	.75	.25	.075
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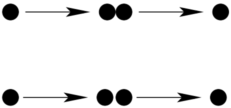
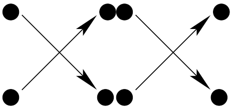
S_4	.05	.25	.55	.75	.55	.75	.05	.25





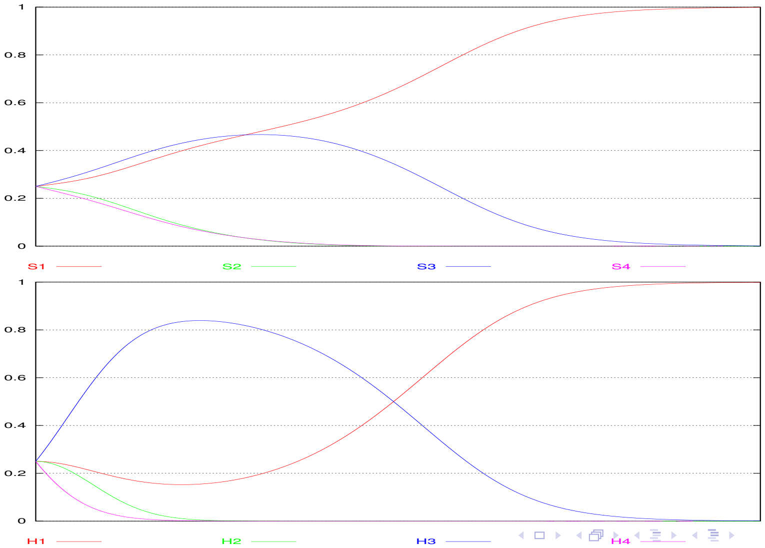
The problem of equilibrium selection

- both Horn and anti-Horn are evolutionarily stable
- EGT explains the aversion of natural against synonymy and ambiguity
- preference for Horn not directly explainable in standard EGT

The problem of equilibrium selection

- rationalistic considerations favor Horn over anti-Horn:
  - Horn strategy is **Pareto efficient** (nobody can do better in absolute terms)
  - Horn strategy **risk dominates** anti-Horn (if you know the population is in an equilibrium but you do not know in which one, going for Horn is less risky than anti-Horn)
- replicator dynamics favors Horn over anti-Horn:
  - complete random state evolves to Horn/Horn
  - basin of attraction of Horn is about 20 times as large as basin of attraction of anti-Horn (numerical approximation—does anybody know how to do this analytically?)

Dynamics starting from random state



The evolution of differential case marking

Ways of argument identification

- transitivity may lead to ambiguity

die Frau, die Maria kennt

the woman that Maria knows | the woman that knows Maria

- three ways out
  1. word order
  2. agreement
  3. **case**

die Frau, die er kennt	die Frau, die ihn kennt
the woman that he knows	the woman that knows him

- Suppose one argument is a pronoun and one is a noun (or a phrase)

$$\{\text{I, BOOK, KNOW}\}$$

- both conversants have an interest in successful communication
- case marking (accusative or ergative) is usually more costly than zero-marking (nominative)
- speaker wants to avoid costs

speaker strategies	*hearer strategies*
always case mark the object (accusative)	ergative is agent and accusative object
always case mark the agent (ergative)	pronoun is agent
case mark the object if it is a pronoun	pronoun is object
	pronoun is agent unless it is accusative
⋮	⋮

Statistical patterns of language use

four possible clause types

	O/p	O/n
A/p	he knows it	he knows the book
A/n	the man knows it	the man knows the book

statistical distribution (from a corpus of spoken English)

	O/p	O/n
A/p	$\text{pp} = 198$	$\text{pn} = 716$
A/n	$\text{np} = 16$	$\text{nn} = 75$

$$\text{pn} \gg \text{np}$$

- functionality of speaker strategies and hearer strategies depends on various factors:
  - How often will the hearer get the message right?
  - How many case markers does the speaker need per clause — on average?

speaker strategies that will be considered

agent is pronoun	*agent is noun*	*object is pronoun*	*object is noun*
e(rgative)	e(rgative)	a(ccusative)	a(ccusative)
e	e	a	z(ero)
e	e	z	a
e	e	z	z
e	z	a	a
...	...	...	...
z	e	z	z
z	z	a	a
z	z	a	z
z	z	z	a
z	z	z	z

- hearer strategies:
  - strict rule: ergative means "agent", and accusative means "object"
  - elsewhere rules:

1. *SO*: "The first phrase is always the agent."
2. *pA*: "Pronouns are agents, and nouns are objects."
3. *pO*: "Pronouns are objects, and nouns are agents."
4. *OS*: "The first phrase is always the object."

The game of case

- strategy space and utility function are known
- probability of meaning types can be estimated from corpus study
- hard to estimate how the complexity of a case morpheme compares to its benefit for disambiguation from the speaker perspective
- parameterized utility function

$$u(S, H) = \sum_m p_m \times (\delta_m(S, H) - k \times cost(S(m)))$$

Utility of case marking

- let us assume $k = .1$

Speaker strategies	Hearer strategies			
	SO	*pA*	*pO*	*OS*
eezz	0.90	0.90	0.90	0.90
zzaa	0.90	0.90	0.90	0.90
ezaz	0.85	0.85	0.85	0.85
zeza	0.81	0.81	0.81	0.81
zeaz	0.61	0.97	0.26	0.61
ezzz	0.86	0.86	0.87	0.86
zezz	0.54	0.89	0.54	0.54
zzaz	0.59	0.94	0.59	0.59
zzza	0.81	0.81	0.82	0.81
zzzz	0.50	0.85	0.15	0.50

Utility of case marking

- let us assume $k = .1$

Speaker strategies	Hearer strategies			
	SO	*pA*	*pO*	*OS*
eezz	0.90	0.90	0.90	0.90
zzaa	0.90	0.90	0.90	0.90
ezaz	0.85	0.85	0.85	0.85
zeza	0.81	0.81	0.81	0.81
zeaz	0.61	0.97	0.26	0.61
ezzz	0.86	0.86	0.87	0.86
zezz	0.54	0.89	0.54	0.54
zzaz	0.59	0.94	0.59	0.59
zzza	0.81	0.81	0.82	0.81
zzzz	0.50	0.85	0.15	0.50

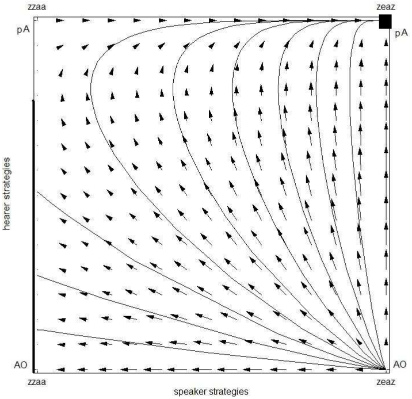
Utility of case marking

- only one evolutionarily stable state: *zeaz*/*pA* (*split ergative*)
- very common among Australian aborigines languages

Non-strict Nash equilibria

Why are non-strict Nash Equilibria unstable?

- Dynamics without mutation



Non-strict Nash equilibria

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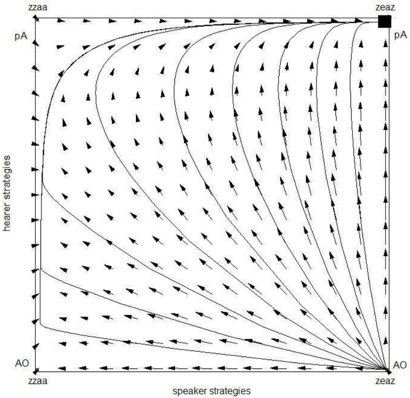

Utility of case marking

If speakers get lazier...

- $k = 0.45$

Speaker strategies	Hearer strategies			
	SO	*pA*	*pO*	*OS*
eezz	0.550	0.550	0.550	0.550
zzaa	0.550	0.550	0.550	0.550
ezaz	0.458	0.458	0.458	0.458
zeza	0.507	0.507	0.507	0.507
zeaz	0.507	0.863	0.151	0.507
ezzz	0.545	0.538	0.553	0.545
zezz	0.505	0.861	0.148	0.505
zzaz	0.510	0.867	0.154	0.510
zzza	0.539	0.531	0.547	0.539
zzzz	0.500	0.849	0.152	0.500

Utility of case marking

If speakers get lazier...

- $k = 0.45$

Speaker strategies	Hearer strategies *SO*	*pA*	*pO*	*OS*
eezz	0.550	0.550	0.550	0.550
zzaa	0.550	0.550	0.550	0.550
ezaz	0.458	0.458	0.458	0.458
zeza	0.507	0.507	0.507	0.507
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zzzz	0.500	0.849	0.152	0.500

Utility of case marking

… and lazier …

- $k = 0.53$

Speaker strategies	Hearer strategies			
	SO	*pA*	*pO*	*OS*
eezz	0.470	0.470	0.470	0.470
zzaa	0.470	0.470	0.470	0.470
ezaz	0.368	0.368	0.368	0.368
zeza	0.436	0.436	0.436	0.436
zeaz	0.483	0.839	0.127	0.483
ezzz	0.473	0.465	0.480	0.473
zezz	0.497	0.854	0.141	0.497
zzaz	0.494	0.850	0.137	0.494
zzza	0.476	0.468	0.484	0.476
zzzz	0.500	0.848	0.152	0.500

Utility of case marking

... and lazier ...

- $k = 0.53$

Speaker strategies	Hearer strategies			
	SO	*pA*	*pO*	*OS*
eezz	0.470	0.470	0.470	0.470
zzaa	0.470	0.470	0.470	0.470
ezaz	0.368	0.368	0.368	0.368
zeza	0.436	0.436	0.436	0.436
zeaz	0.483	0.839	0.127	0.483
ezzz	0.473	0.465	0.480	0.473
zezz	0.497	0.854	0.141	0.497
zzaz	0.494	0.850	0.137	0.494
zzza	0.476	0.468	0.484	0.476
zzzz	0.500	0.848	0.152	0.500

Utility of case marking

... and lazier...

- $k = 0.7$

Speaker strategies	Hearer strategies			
	SO	*pA*	*pO*	*OS*
eezz	0.300	0.300	0.300	0.300
zzaa	0.300	0.300	0.300	0.300
ezaz	0.177	0.177	0.177	0.177
zeza	0.287	0.287	0.287	0.287
zeaz	0.431	0.788	0.075	0.431
ezzz	0.318	0.310	0.326	0.318
zezz	0.482	0.838	0.126	0.482
zzaz	0.457	0.814	0.101	0.457
zzza	0.343	0.335	0.350	0.343
zzzz	0.500	0.848	0.152	0.500

Utility of case marking

… and lazier…

- $k = 0.7$

Speaker strategies	Hearer strategies			
	SO	*pA*	*pO*	*OS*
eezz	0.300	0.300	0.300	0.300
zzaa	0.300	0.300	0.300	0.300
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Utility of case marking

...

- $k = 1$

Speaker strategies	Hearer strategies: *SO*	*pA*	*pO*	*OS*
eezz	0.000	0.000	0.000	0.000
zzaa	0.000	0.000	0.000	0.000
ezaz	−0.160	−0.160	−0.160	−0.160
zeza	0.024	0.024	0.024	0.024
zeaz	0.340	0.697	−0.016	0.340
ezzz	0.045	0.037	0.053	0.045
zezz	0.455	0.811	0.099	0.455
zzaz	0.394	0.750	0.037	0.394
zzza	0.106	0.098	0.144	0.106
zzzz	0.500	0.848	0.152	0.500

Utility of case marking

...

- $k = 1$

Speaker strategies	Hearer strategies			
	SO	*pA*	*pO*	*OS*
eezz	0.000	0.000	0.000	0.000
zzaa	0.000	0.000	0.000	0.000
ezaz	−0.160	−0.160	−0.160	−0.160
zeza	0.024	0.024	0.024	0.024
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zzaz	0.394	0.750	0.037	0.394
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zzzz	0.500	0.848	0.152	0.500

Taking stock

zeaz/pA split ergative	
zzaz/pA differential object marking	*ezzz/pO* inverse DOM —
zezz/pA differential subject marking	*zzza/pO* inverse DSM
zzzz/pA no case marking	*zzza/pO*
zzzz/pA	

Taking stock

zeaz/*pA* split ergative Australian languages	
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zezz/*pA* differential subject marking	*zzza*/*pO* inverse DSM
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zzzz/*pA*	

Taking stock

zeaz/*pA* split ergative Australian languages	
zzaz/*pA* differential object marking English, Dutch, ...	*ezzz*/*pO* inverse DOM —
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zzzz/*pA*	

Taking stock

zeaz/pA split ergative Australian languages	
zzaz/pA differential object marking English, Dutch, ...	*ezzz/pO* inverse DOM —
zezz/pA differential subject marking several caucasian languages	*zzza/pO* inverse DSM
zzzz/pA no case marking	*zzza/pO*

zzzz/pA

Taking stock

zeaz/pA
split ergative
Australian languages

zzaz/pA	*ezzz/pO*
differential object marking	inverse DOM
English, Dutch, ...	—
zezz/pA	*zzza/pO*
differential subject marking	inverse DSM
several caucasian languages	
zzzz/pA	*zzza/pO*
no case marking	
Chinese, Thai	

zzzz/pA

Taking stock

zeaz/pA split ergative Australian languages	
zzaz/pA differential object marking English, Dutch, ...	*ezzz/pO* inverse DOM —
zezz/pA differential subject marking several caucasian languages	*zzza/pO* inverse DSM Nganasan
zzzz/pA no case marking Chinese, Thai	*zzza/pO*
zzzz/pA	

Taking stock

- only very few languages are not evolutionary stable in this sense
  zzaa: Hungarian, ezza: Parachi, Yazguljami (Iranian languages), eeaa: Wangkumara
- curious asymmetry: if there are two competing stable states, one is common and the other one rare
- similar pattern as with Horn vs. anti-Horn

Alle equilibria are stable, but some equilibria are more stable than others.

Stochastic EGT

Random mutation and stability

- idealizations of standard Evolutionary Game Theory
  - populations are (practically) infinite
  - mutations rate is constant and low
- better model (Young 1993; Kandori, Mailath and Rob 1993)
  - finite population
  - mutation is noisy

Consequences of finite population model

- every mutation barrier will occasionally be taken
- no absolute stability
- if multiple Strict Nash Equilibria coexist, system will oscillate between them
- some equilibria are more stable than others
- system will spend most of the time in most robustly stable state
- stochastically stable states

A particular model

- discrete time/finite population version of replicator dynamics
- mutations occur rarely (most generations have no mutants at all)
- if mutation occurs, each individual in this generation has same probability to be a mutant
- mutation frequency and mutation rate equal for both populations
- each strategy is equally likely for a mutant (within its population)

The formulas

$$\frac{\Delta x_i}{\Delta t} = x_i(\tilde{u}_i - \tilde{u}^A) + \sum_j \frac{Z_{ji} - Z_{ij}}{n}$$

$$\frac{\Delta y_i}{\Delta t} = y_i(\tilde{u}_i - \tilde{u}^B) + \sum_j \frac{Z_{ji} - Z_{ij}}{n}$$

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- x_i: frequency of speaker strategy i

The formulas

$$\frac{\Delta x_i}{\Delta t} = x_i(\tilde{u}_i - \tilde{u}^A) + \sum_j \frac{Z_{ji} - Z_{ij}}{n}$$

$$\frac{\Delta y_i}{\Delta t} = y_i(\tilde{u}_i - \tilde{u}^B) + \sum_j \frac{Z_{ji} - Z_{ij}}{n}$$

- x_i: frequency of speaker strategy i
- y_i: frequency of hearer strategy i

The formulas

$$\frac{\Delta x_i}{\Delta t} = x_i(\tilde{u}_i - \tilde{u}^A) + \sum_j \frac{Z_{ji} - Z_{ij}}{n}$$

$$\frac{\Delta y_i}{\Delta t} = y_i(\tilde{u}_i - \tilde{u}^B) + \sum_j \frac{Z_{ji} - Z_{ij}}{n}$$

- x_i: frequency of speaker strategy i
- y_i: frequency of hearer strategy i
- $\tilde{u}_i$: expected utility of strategy i

The formulas

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- Z_{ij}: random variable; distributed according to the binomial distribution $b(p_{ij}, \lfloor x_i n \rfloor)$
- p_{ij}: probability that an i-individual mutates to strategy j

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- p_{ij}: probability that an i-individual mutates to strategy j
- n: population size

A simulation

Stochastic stability

- punctuated equilibria
- long periods of dynamic stability alternate with short transition periods
- in the long run, more time in Horn state (67% vs. 26% in anti-Horn)
- simulation suggests that Horn is stable while anti-Horn is not
- can this be proved?

Analytic considerations

- Simple recipes for finding stochastically stable state in 2×2 games
- not easily extrapolated to larger games
- basic idea:
    - calculate the height of the invasion barrier of each ESS
    - the ESSs with maximal invasion barrier is stochastically stable

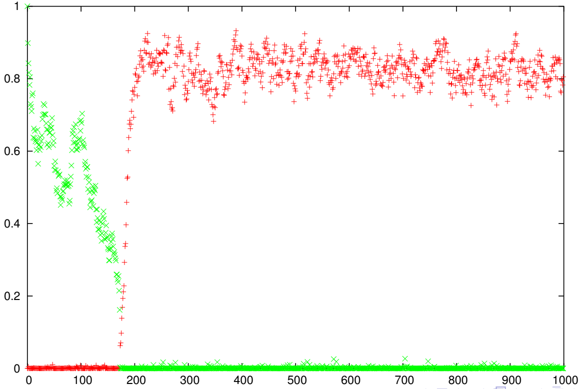
Analytic considerations

- invasion barrier = amount of mutations necessary to push the system into the basin of attraction of another ESS
- Horn $\Rightarrow$ anti-Horn: 50%
- anti-Horn $\Rightarrow$ Horn: 47.5%
- Hence:

Horn strategy is the only stochastically stable state

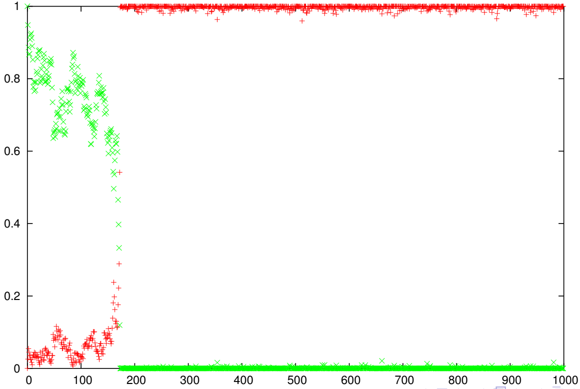
Stochastic evolution of case marking

- $k = 0.45$
- competition between *zzaz*/*pA* and *ezzz*/*pO*
- evolution of speaker population:



Stochastic evolution of case marking

- $k = 0.45$
- competition between *zzaz*/*pA* and *ezzz*/*pO*
- evolution of hearer population:



Analysis

- invasion barriers:
  - differential object marking: 45.2%
  - inverse differential subject marking: 2.06%

Differential object marking is stochastically stable; inverse differential subject marking is not.

- likewise, differential subject marking is stochastically stable while inverse differential object marking is not.

Stochastically stable states

zeaz/*pA*
split ergative
Australian languages

zzaz/*pA*
differential object marking
English, Dutch, ...

zezz/*pA*
differential subject marking
several caucasian languages

zzzz/*pA*
no case marking
Chinese, Thai

Conclusion

- out of $4 \times 16 = 64$ possible case marking patterns only four are stochastically stable
- vast majority of all languages that fit into this categorization are stochastically stable
- precise numbers are hard to come by though
- linguistic universals can be result of evolutionary pressure in the sense of cultural evolution