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Language Emergence: a Computational Model of Coevolution of Lexicon and Syntax

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 - 1) Coevolution of lexicon and syntax
 - 2) Social structure's influence on language emergence

Limitations of Existing Computational Models

- 1) **Direct meaning transference;**
- 2) Syntax not as an emergent property;
- 3) Random interactions, disregarding the influence of social structure;
- 4) Homogeneous population;

Direct Meaning Transference (Kirby 1998, 2003; Batali 1998)

- **Direct meaning transference:** the intended meanings, encoded in the linguistic utterances produced by speakers, are always accurately available to listeners.

However,

- 1) There is usually no direct connection between speakers' production and listeners' comprehension (*Kirby 2002*).
- 2) Other channels, such as pointing while talking (*Quine 1960*) or certain feedback, can only provide a certain degree of confirmation.

Therefore,

Language is the result of many complex interacting dynamical systems and acquired in communications (*Kirby 2002; Oliphant 1997*).

- 1) Always assuming direct meaning transference between speakers and listeners in communication is unrealistic.
- 2) Comprehension is based on linguistic and nonlinguistic information

Limitations of Existing Computational Models

- 1) Direct meaning transference;
- 2) **Syntax not as an emergent property;**
- 3) Random interactions, disregarding the influence of social structure;
- 4) Homogeneous population;

Syntax should be an emergent property (Ke et al. 2002; Cangelosi and Parisi 2002; Smith et al. 2003)

Mainstream Scenarios on Syntax Emergence

- 1) Bickerton's "bootstrapping, innate" scenario (*Calvin and Bickerton 2000*);
- 2) Wray's "formulaic, emergent" scenario (*Wray 1998; 2000*);

From an evolutionary point of view, we adopt the "emergent" scenario and show a coevolution of lexicon and syntax during the transition from holistic signaling system to compositional language.

Limitations of Existing Computational Models

- 1) Direct meaning transference;
- 2) Syntax not as an emergent property;
- 3) Random interactions, disregarding the influence of social structure;
- 4) Homogeneous population;

Social structure, an intrinsic feature in human society, must influence language evolution (Nettle 1999)

- Many scholars (*Romaine 1994; Dunbar 1998; Knight et al. 2000*) assume that language emergence relies on or contributes to certain social factors.
 1. Social structures, formed by biological and/or socio-economic factors (e.g., kinship and social classes), place constraints on interactions among agents.
 2. Mutual understanding based on the evolving language can be a factor to trigger social connections.

Limitations of Existing Computational Models

- 1) Direct meaning transference;
- 2) Syntax not as an emergent property;
- 3) Random interactions, disregarding the influence of social structure;
- 4) **Homogeneous population;**

Homogeneous population

- **Homogeneous population:** each agent has same natural features (e.g., memory capacity) and identical linguistic behaviors (e.g., ability to use linguistic information).
- However,
 - Sociolinguists have observed dramatic variations in speech communities (*Romaine 1994*).
 - Studies on language acquisition have revealed various dichotomies in children's learning styles (*Shore 1995*).
- Therefore,
Simulation considering certain heterogeneity is more realistic.

Description of the model I

- 1) “Nonsituated, structured” model (*Wagner et al. 2003*) at macrohistory level (*Wang 1991*).
- 2) **Semantics**: agents express and comprehend 2 types of **integrated meanings**:
 - “predicate<agent>” (e.g., “run<wolf>”)
 - “predicate<agent, patient>” (e.g., “chase<wolf, cat>”).
- 3) **Utterances: strings of syllables**.
 1. Utterances can be mapped to either meaning constituent or integrated meanings.
 2. Utterances mapped to constituents can combine together under the regulation of “**syntax**” (**simple word order**) to map integrated meanings.

Description of the model II

4) Rule-based system to indicate language

5) Heterogeneous agents

- ❑ Different storage capacity;
- ❑ Different linguistic abilities for random creation and rule generalization;

6) Communication:

- ❑ Concurrent communication among agents;
- ❑ Iterative communication;
- ❑ Horizontal transmission
- ❑ Indirect meaning transference;

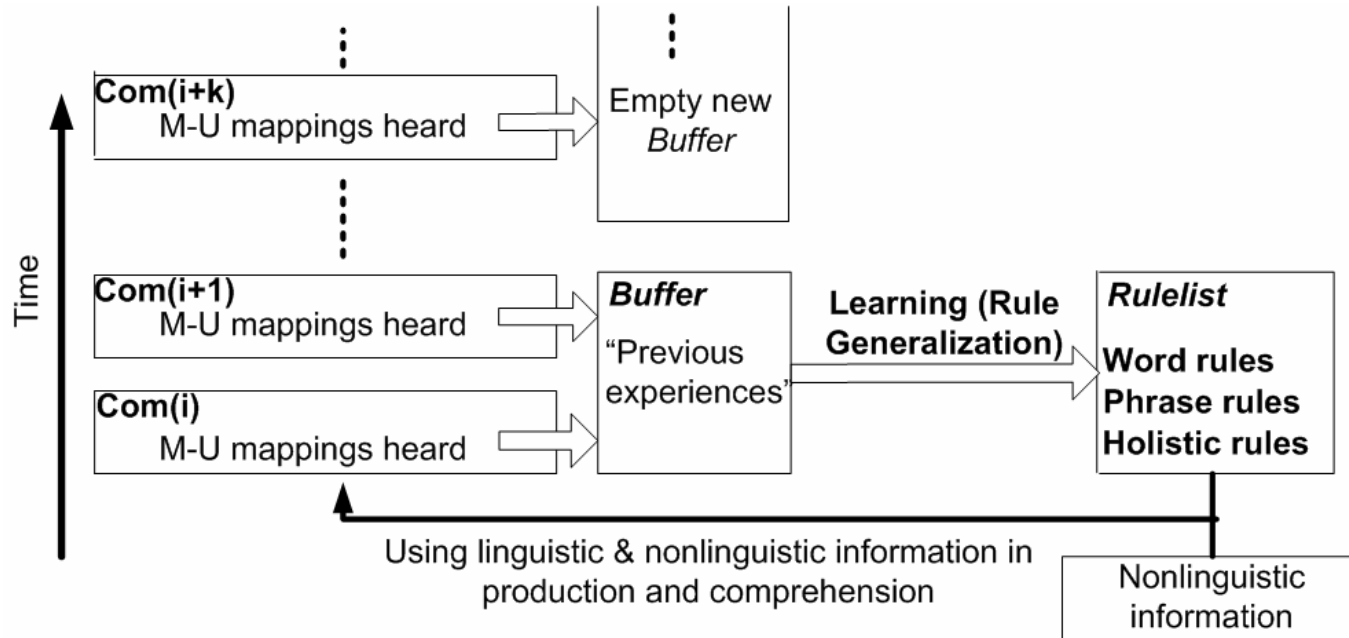
Rule-based system to indicate language

Two types of Linguistic rules (condition + strength):

- **Lexical rules** (mappings between meaning and utterance):
 - 1) **Holistic rule**: e.g., “run<wolf>” \leftrightarrow /a b c/ (0.4)
 - 2) **Compositional rule**:
 - a) **Word rule**: e.g., “eat<#, #>” \leftrightarrow /d e/ (0.3) or “meat” \leftrightarrow /c/ (0.5)
 - b) **Phrase rule**: e.g., “eat<wolf, #>” \leftrightarrow /c * f/ (0.4).
- **Word order rules** (simple sequences to regulate utterances):
 - 1) **Domain-general Sequencing Ability** (*Christiansen 2001*);
 - 2) **Language predisposition of Declarative Memory** (*Terrace 2002*);Agents can use general orders to regulate linguistic utterances to express integrated meanings with 2 or 3 constituents.
e.g., “utterance for Predicate precedes that for Agent”(VS)(0.6) or
“utterance for Agent first; for Predicate second; for Patient last” (SVO)(0.7);

Agents start from a holistic signaling system (share only some common holistic rule) and no dominant word order (all word order rules have same strength).

Two-level storage to handle lexical rules

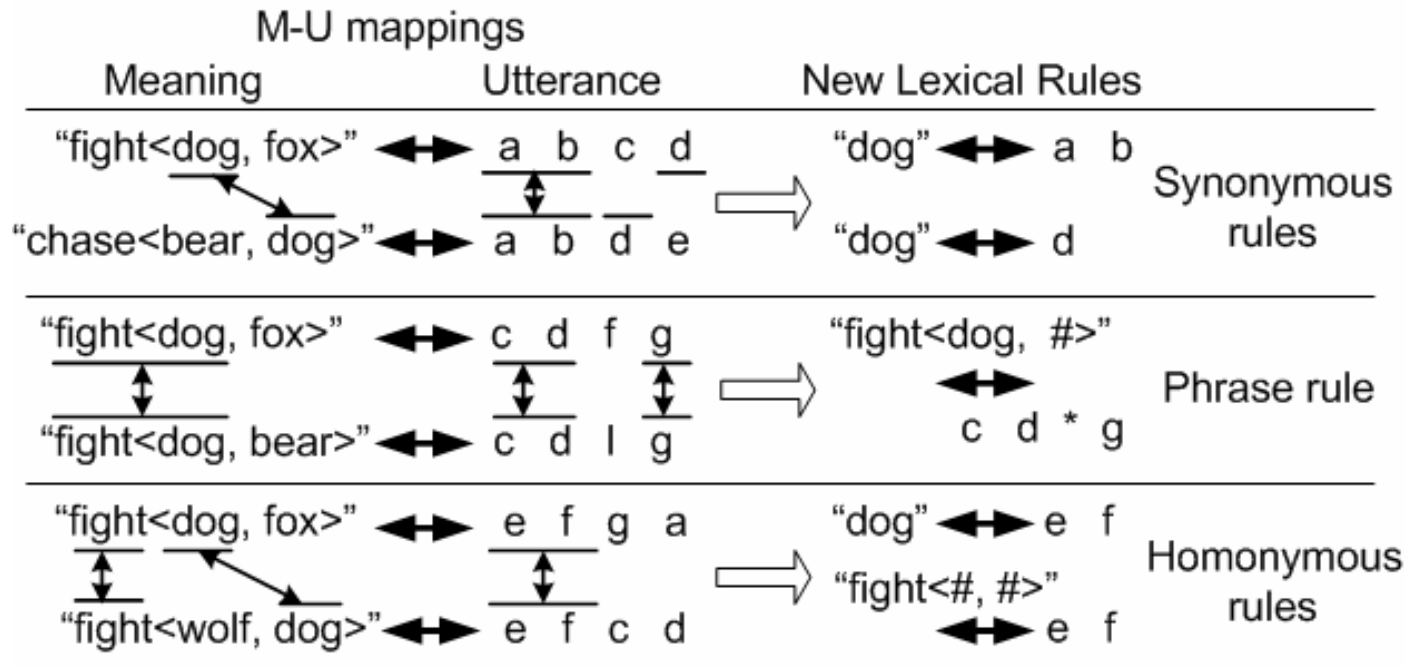


Linguistic ability (Rule Acquisition Mechanisms)

- **Random creation** (similar to Kirby 1998)

Under certain possibility, speakers can create lexical rules (holistic or compositional) to help their production of integrated meanings.

- **Rule generalization through detecting recurrent patterns**



Considering: 1) Limited size of storage; 2) Independent M-U mappings
Homonym and Synonym avoidances are built in (discussed later!).

Description of the model II

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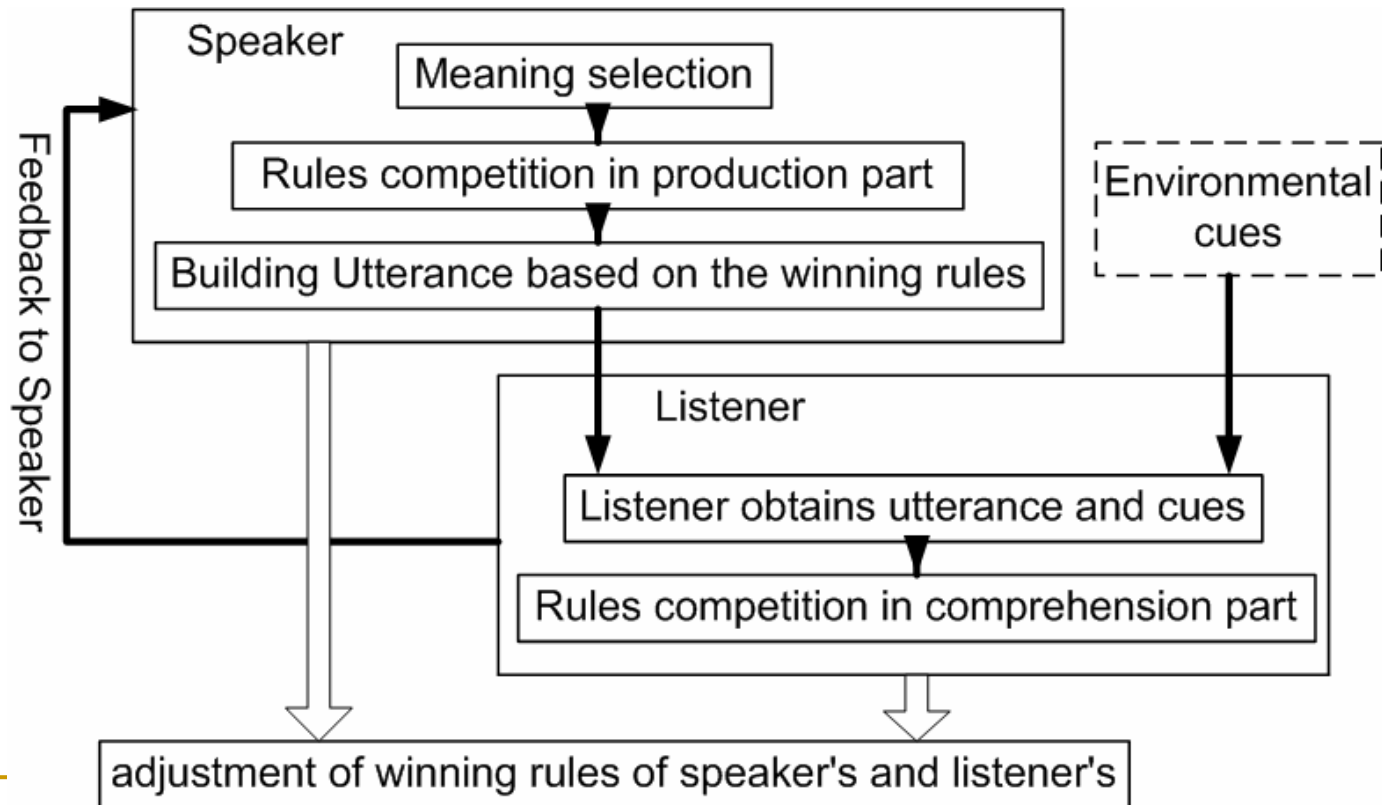
- ❑ Concurrent communication among agents;
- ❑ Iterative communication;
- ❑ Horizontal transmission
- ❑ Indirect meaning transference;

Indirect meaning transference

Unreliable cues (nonlinguistic information, events happening in the environment):

- Integrated meanings having some strength. e.g., “chase<fox, dog>” (0.5).
- Reliability of cues (**RC**, whether the speaker’s intended meaning is contained in one of the cues) is manipulated.

Communication with Indirect Meaning Transference



Results

■ *Indices to test language emergence*

1. **Rule expressivity (RE)** — the average number of meanings that all agents can express:

$$RE = \frac{\sum_i \text{number of meanings that agent } i \text{ can express}}{\text{number of agents}}$$

2. **Understanding rate (UR)** — the average proportion of the number of meanings understandable to every pair of agents based on linguistic information only:

$$UR = \frac{\sum_{i,j} \text{number of understandable meanings between agent } i, j}{\text{number of all possible pairs of } i, j}$$

UR evaluates the real representation ability (**Displacement (Hockett 1960)**) of the emergent language, not only the RE, but also whether such expressions are understandable using linguistic information only.

3. **Convergence time (CT)** — number of iterations required on average to achieve a language where $UR \geq 80\%$.

Coevolution of Lexicon and Syntax

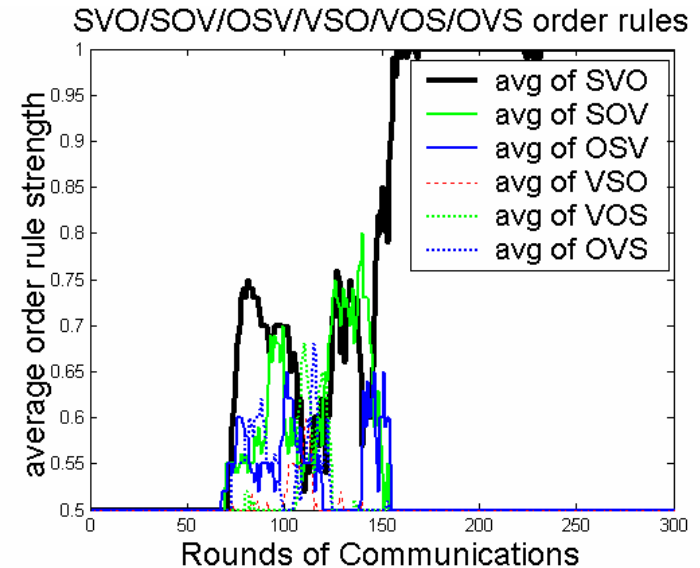
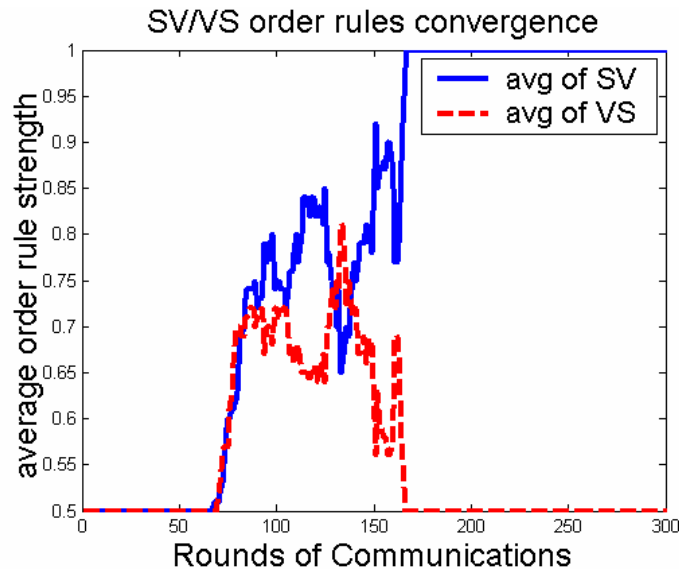
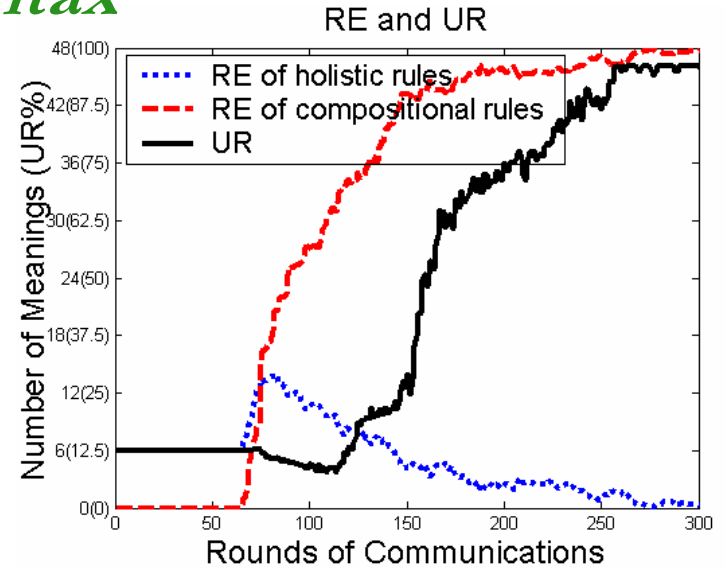
(Simulation condition: 10 agents, 500*5 communications, RC=0.7)

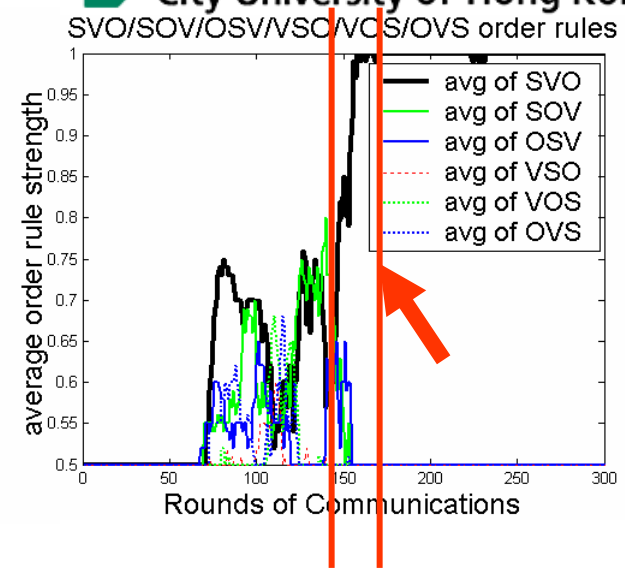
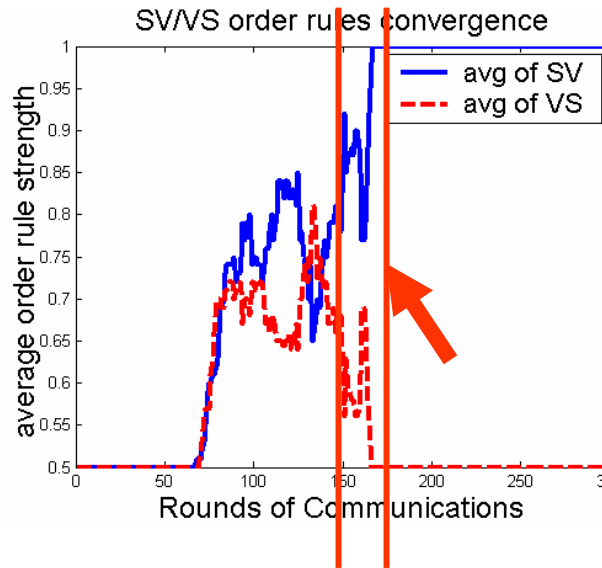
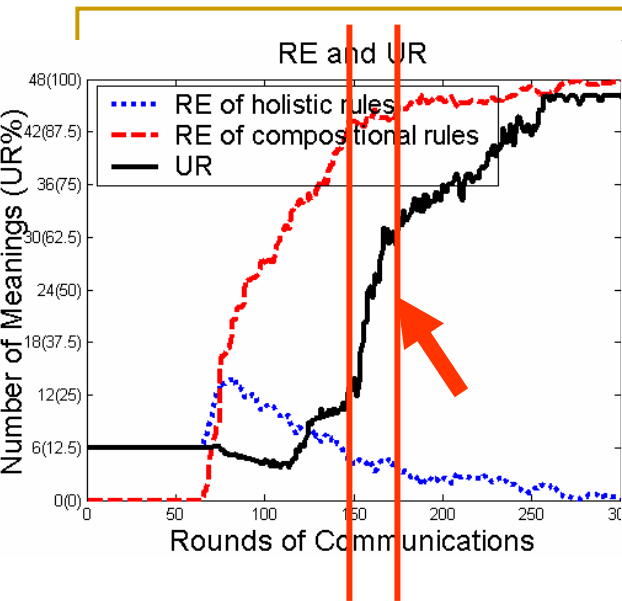
Emergence of Lexicons: →

UR curve follows a “S-shape” curve.
(Ke et al. 2000)

Convergence of syntax: ↓

Randomly converge to 2 dominant orders without any prerequisite





■ *Coevolution of lexicon and syntax:*

Mutual understanding requires not only common lexical rules but also a shared syntax to regulate utterances; The sharp increase of UR and strengths of the dominant order rules are almost **synchronized**: the use of compositional rules triggers the convergence of syntax, which in turn boosts the emergence of the lexicon.

Some Conclusions

- Transition from holistic signaling system to compositional language with dominant word order is a process of coevolution of lexicon and syntax.
- Certain heterogeneity do not significantly affect the emergence process.
- Effective transition is found to be possible when adopting:
 - Certain Internal strategies (e.g., homonym avoidance)
 - External requirement (e.g., high reliability of cues)

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Heterogeneity discussion

(10 agents, 500*5 communications, RC=0.7)

Homogeneous condition:

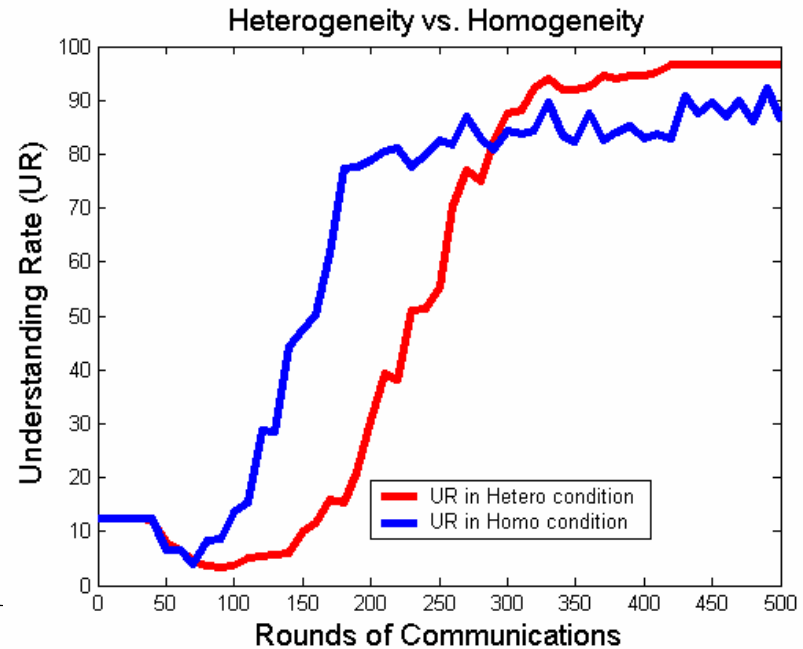
Storage size: $Buffer = 30$
 $Rulelist = 45$

Linguistic abilities: $R_{\text{random creation}} = 0.5$
 $R_{\text{rule generalization}} = 0.5$

Heterogeneous condition:

Storage size: $Buffer = 30 \pm 5$
 $Rulelist = 45 \pm 5$

Linguistic abilities: $R_{\text{random creation}} = 0.5 \pm 0.1$
 $R_{\text{rule generalization}} = 0.5 \pm 0.1$



Statistical result (10 simulations)

	avg UR	std UR	avg CT	std CT
Heterogeneity:	35.1967	7.7568	479	23.3095
Homogeneity:	38.5333	4.7847	449	36.8524

Some Conclusions

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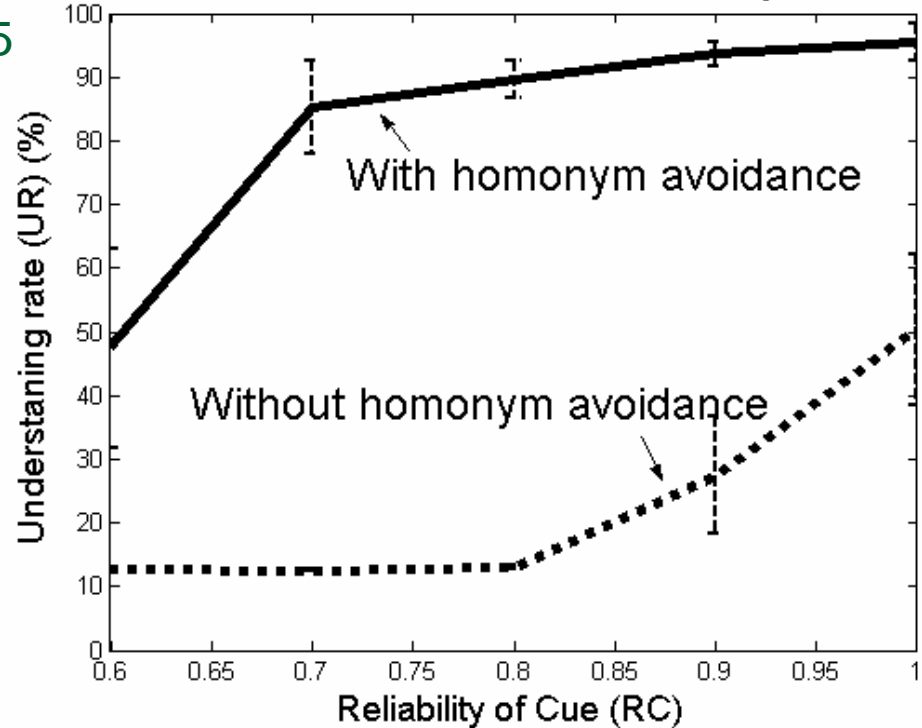
Homonym avoidance and Reliability of cues

(Simulation condition: 10 agents, 500*5 communications, 10 simulations)

Results:

- 1) Without Homonym avoidance, UR is low.
- 2) With Homonym avoidance, not very high RC can already achieve a high UR.

UR under different RC with and without homonym avoidance



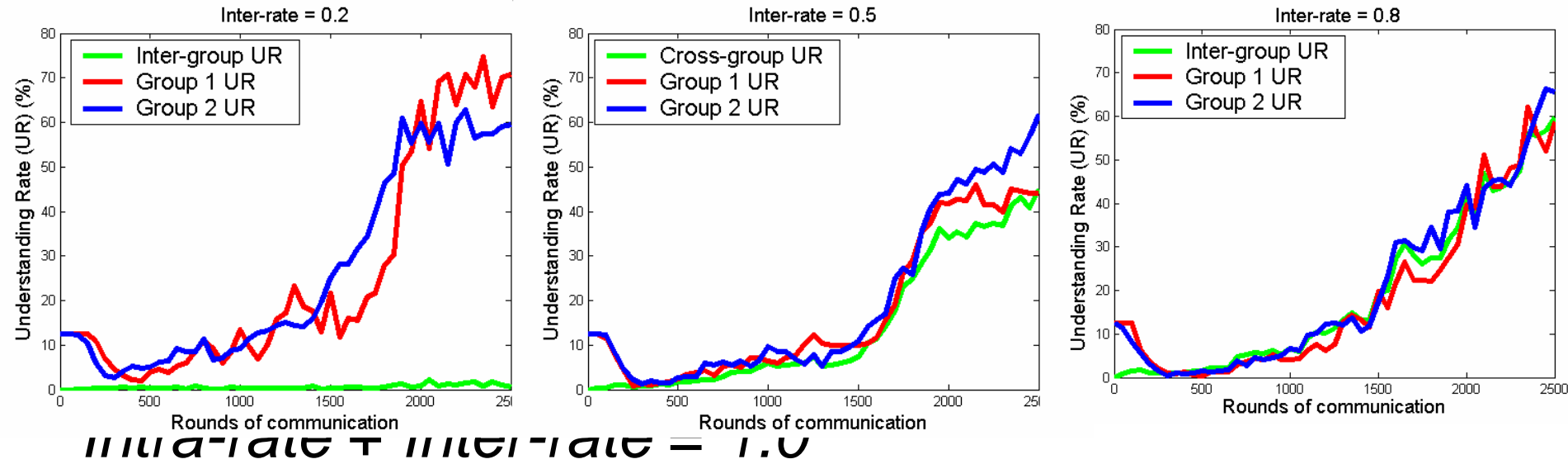
In order to achieve an effective language:

- 1) **Internal strategy to avoid ambiguity is necessary.**
Homonym avoidance is one such strategy that works well.
- 2) **Reliable external (Non-linguistic) information is necessary.**
High RC (over 0.7) is necessary.

Social structure's influence on language emergence

1. Inter/Intra Group Communication

(Simulation condition: 20 agents, 2500 com., RC=0.7, 10 simulations)



Inter-group UR:

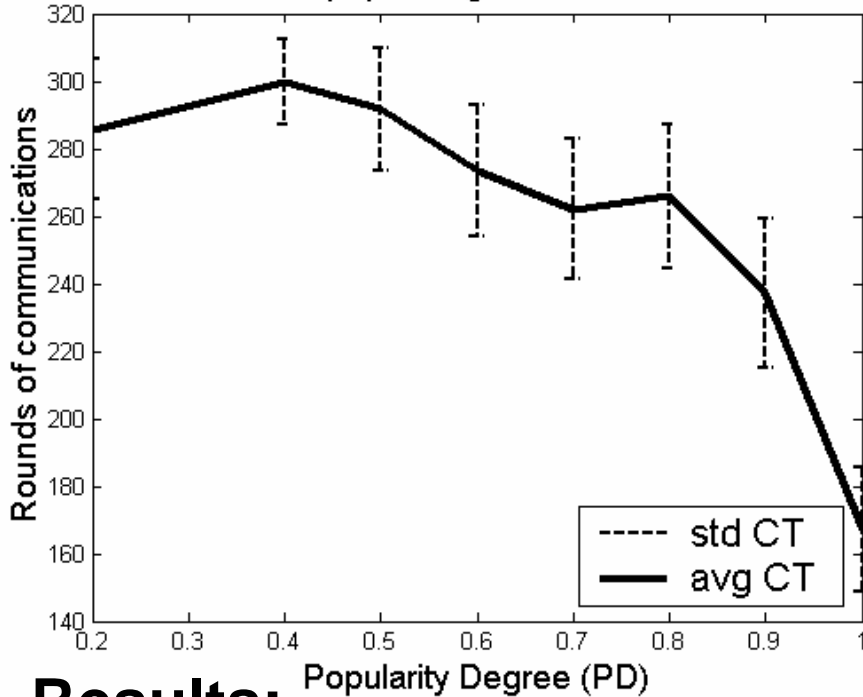
Results: The frequency of inter-group communication decides the emergence process and the similarity of the language between the two groups.

$UR_{inter-group} = \frac{\text{number of understandable meanings between agent } i, j}{\text{number of all possible pairs of agent } i \text{ (in group 1) and agent } j \text{ (in group 2)}}$

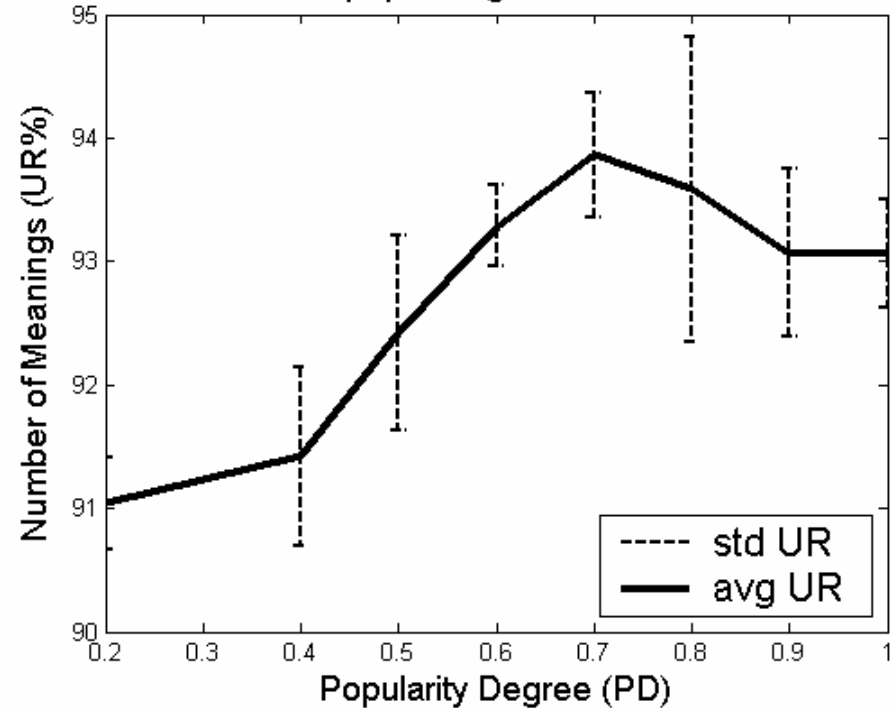
2. Popular agent effects

(Simulation condition: 10 agents, 500*5 com., RC=0.7, 10 simulations)

one popular agent effect: CT



One popular agent effect: UR



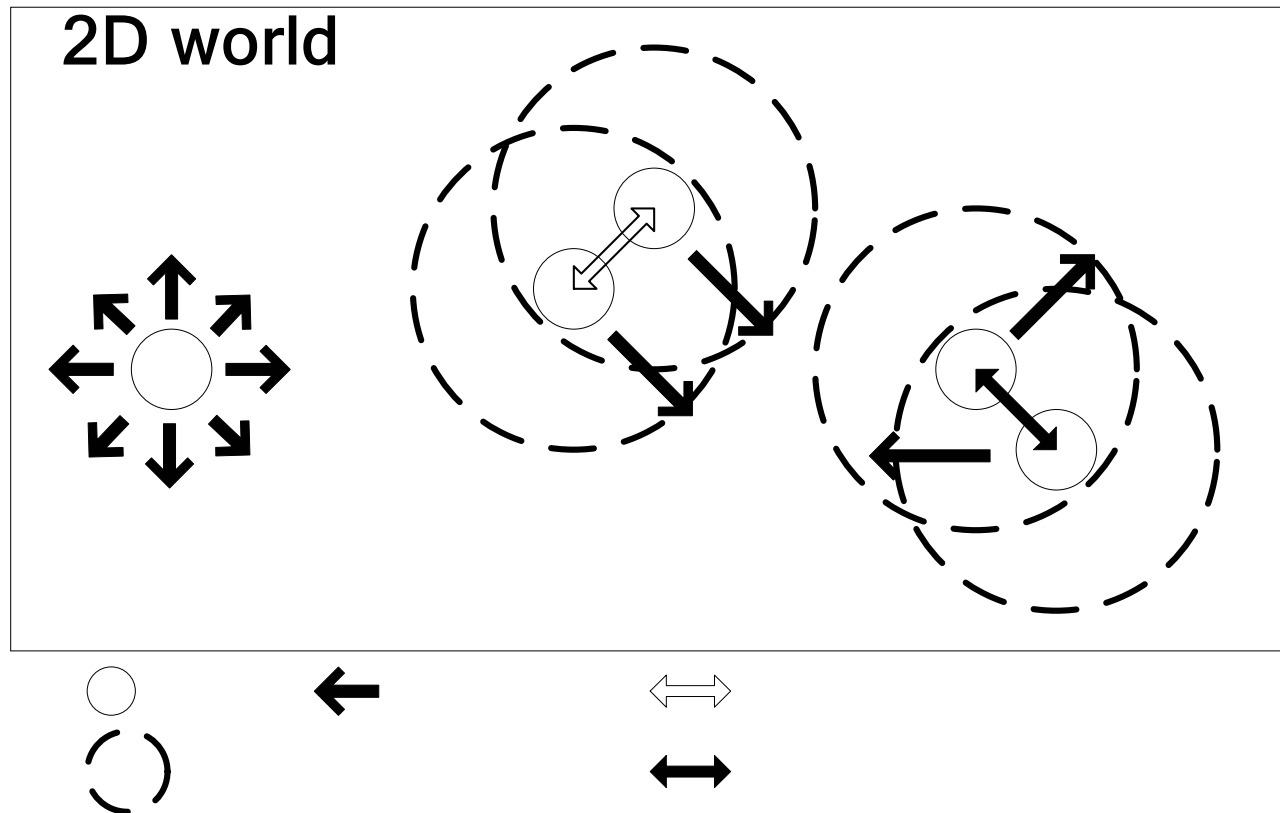
Results:
communicate with the popular agent.

- 1) High Popularity Degree (PD) reduces Convergence Time;
- 2) Intermediate PD (neither absolute "dictatorship" (PD=1.0) nor "democracy" (PD=1/GroupSize) achieves the best performance).

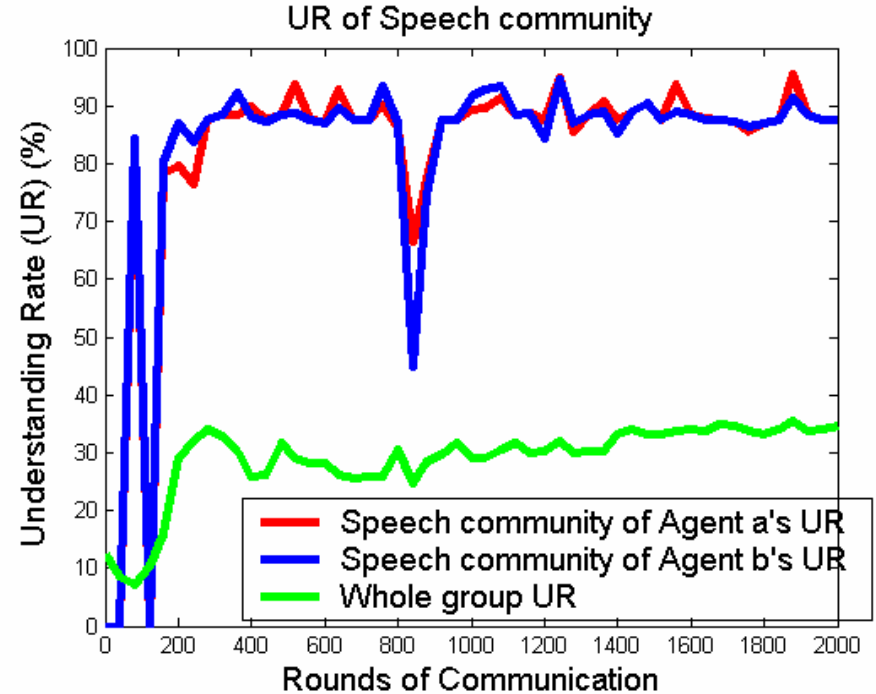
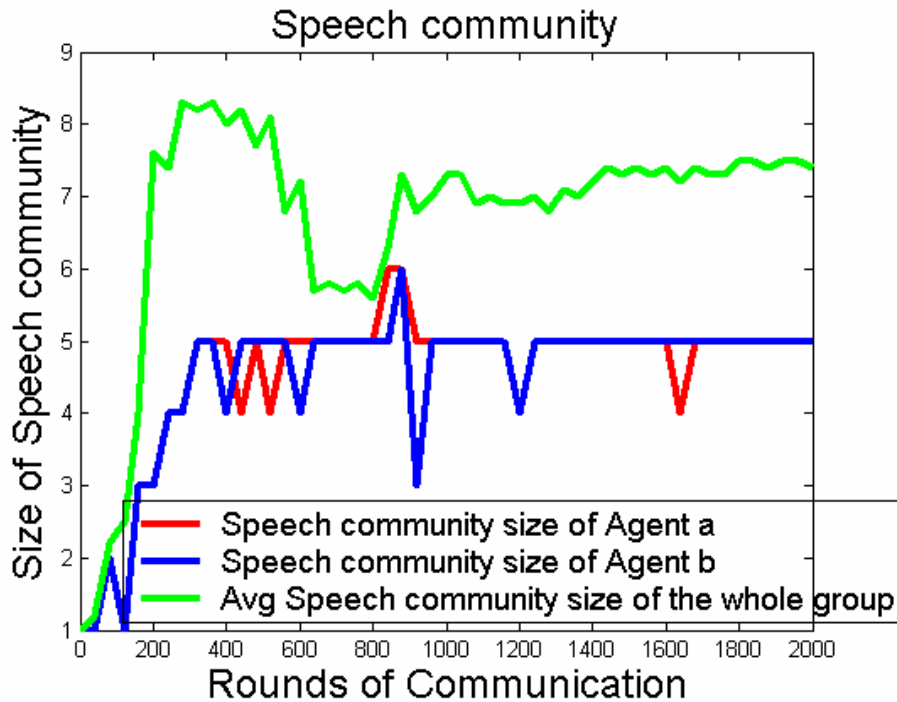
Similar result is found in groups with more than one popular agent.

3. *Geographic restricted communication*

- Agents, in a 2D world, are moving randomly .
- Communications happen **within a geographic distance**.
- Successful communication links the speaker and the listener as **Speech community**. Failed communication will break this connection.



(Simulation condition: 180*80 world, 20 agents, 2000*20 com., RC=0.7)



Results:

- 1) Mutual understanding, a force for group cohesion, can separate group members into different speech community during language emergence.
- 2) A phenomenon of “**Global Polarization, Local Convergence**” (Axelrod 1997) seen during language evolution.

Acknowledgements

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Danke schön! - Thank you!
Comments are welcome

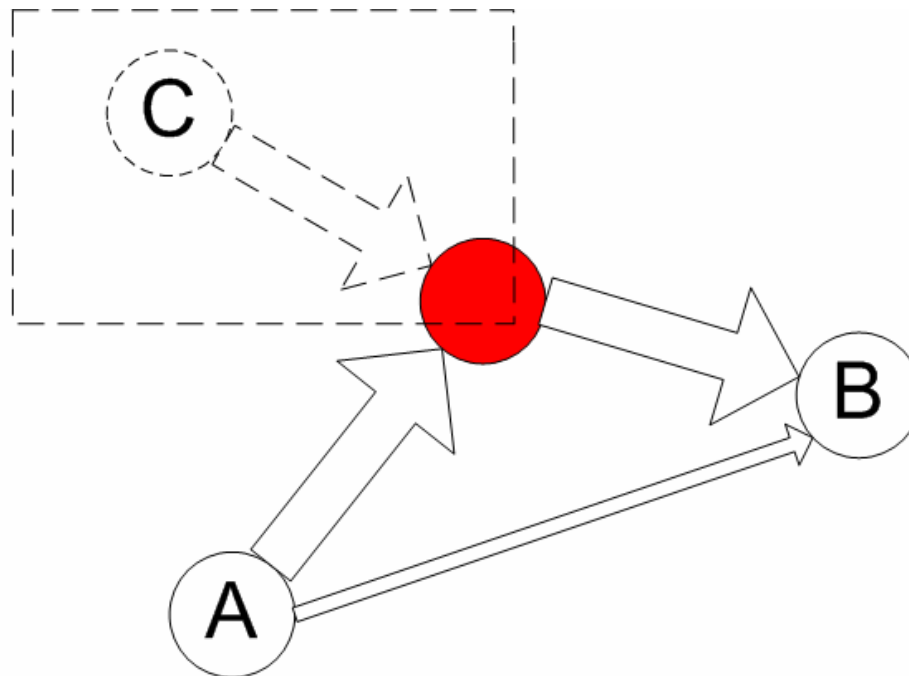
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Popularity Degree effects

With the increase of Popularity Degree (PD)

- **Good effect:** increase the chances for normal two agents to exchange information through the popular agent.
- **Bad effect:** the linguistic competence of the popular agent, who is also a language learner as other normal agents, can be influenced by other normal agents.



Communication example

Production Part	Activated rules	Applicable word order rules	Combined Strength (CS)
1 holistic rule	"fight<dog, fox>" \leftrightarrow /a b/ (0.6)		CS1 = 0.6
3 word rules	"dog" \leftrightarrow /b/ (0.8) "fight<#, #>" \leftrightarrow /c e/ (0.5) "fox" \leftrightarrow /g/ (0.3)	VSO (0.6)	CS2 = $1/2(1/3(0.8+0.5+0.2)+0.6) = 0.55$
1 word rule 1 phrase rule	"dog" \leftrightarrow /b/ (0.8) "fight<#, fox>" \leftrightarrow /e * f/ (0.8)	VSO (0.6) OSV (0.5)	CS3 = $1/2(1/2(0.8+0.8)+0.6) = 0.7$

Utterance built up: /e b f/

Comprehension Part	Activated rules	Related cues	Detectable word order rules	Combined Strength (CS)
	Utterance heard: /e b f/			
1 holistic rule	"eat<dog, meat>" \leftrightarrow /e b f/ (0.4)	"eat<dog, meat>" (0.5)		CS1 = $1/2(0.5)+1/2(0.5) = 0.45$
3 word rules	"cat" \leftrightarrow /e/ (0.7) "fight<#, #>" \leftrightarrow /b/ (0.8) "dog" \leftrightarrow /f/ (0.6)		SVO (0.6)	CS2 = $1/2(1/3(0.7+0.8+0.6)+0.6)+1/2(0) = 0.65$
1 word rules	"run<#, #>" \leftrightarrow /b f/ (0.7)	"run<cat>" (0.5)		CS3 = $1/2(0.3)+1/2(0.5) = 0.4$

Interpreted Meaning: "fight<cat, dog>"

Language emergence process

Rounds of communication = 0

gen=0;

Order convergence result: **Rounds of communication = 250**

No order for meaning type 1: 10 agents

No order for meaning type 2: 10 agents

SV word order: 0 agents

VS word order: 0 agents

SVO word order: 0 agents

VSO word order: 0 agents

Lexicon convergence result: 0 agents

Same Holistic rules among all agents: 0

"cry < bear > "->| 24 |

"run < wolf > "->| 7 |

"suck < dog , water > "->| 19 |

"chew < fox , meat > "->| 19 |

"fight < bear , wolf > "->| 19 |

"chase < dog , fox > "->| 19 |

Same Compositional rules among all agents: 0

Same phrase rules: 0

Same word rules: 0

Rules expressivity result: 0

Holistic rules expressivity: 0

Compositional rules expressivity: 0

Mean Understand rate: 0

Rounds of communication = 250

No order for meaning type 1: 10 agents

No order for meaning type 2: 10 agents

Order convergence result:

no order for meaning type 1: 0 agents
no order for meaning type 2: 0 agents

SV word order: 8 agents

VS word order: 2 agents

SVO word order: 0 agents

VSO word order: 0 agents

Lexicon convergence result: 10 agents

Same Holistic rules among all agents: 10

"suck < dog , water > "->| 19 |

"chase < dog , fox > "->| 19 |

Same Compositional rules among all agents: 10

Same phrase rules: 0

Same word rules: 10

"suck < # , # > "->| 25 |

"chase < # , # > "->| 14 |

"dog "->| 25 |

"bear "->| 4 |

"fox "->| 14 |

"wolf "->| 9 |

Rules expressivity result: 5.60

Holistic rules expressivity: 48.00

Compositional rules expressivity: 48.00

Mean Understand rate: 46.40 (96.67%)

Rounds of communication = 500

gen=500;

Order convergence result:

no order for meaning type 1: 0 agents
no order for meaning type 2: 0 agents

SV word order: 10 agents;

VS word order: 0 agents;

SVO word order: 0 agents, SOV word order: 0 agents, OSV word order: 0 agents

VSO word order: 0 agents, VOS word order: 0 agents, OVS word order: 10 agents

Lexicon convergence result:

Same Holistic rules among all agents: 0

Same Compositional rules among all agents: 10

Same phrase rules: 0

Same word rules: 10

"suck < # , # > "->| 25 |

"chew < # , # > "->| 14 |

"fight < # , # > "->| 4 |

"chase < # , # > "->| 7 |

"dog "->| 25 |

"bear "->| 4 |

"fox "->| 14 |

"wolf "->| 9 |

"water "->| 1 |

"meat "->| 15 |

Rules expressivity result:

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