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## Mutual Influence of Semantics and Syntax during Language Emergence – A lexicon-syntax coevolution model

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# Outline

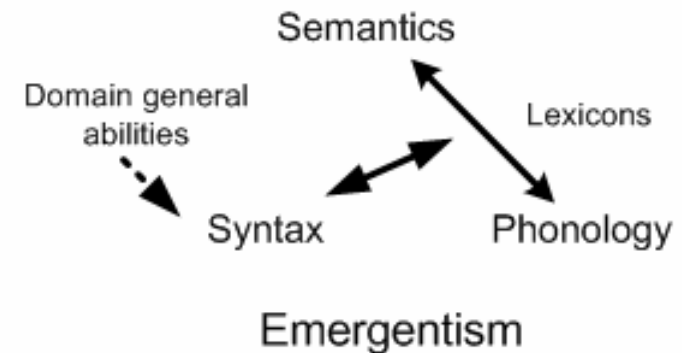
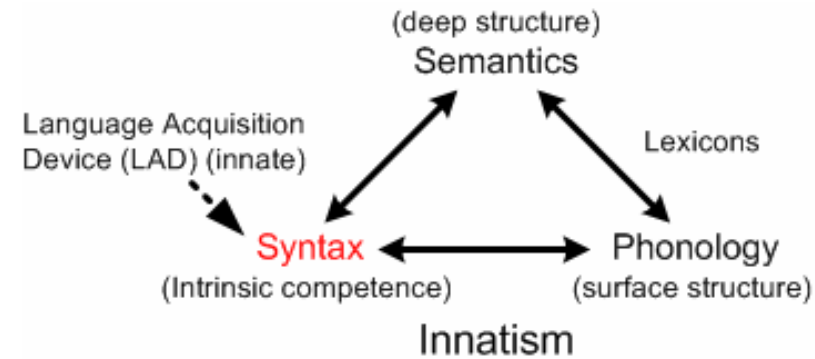
- Background;
  - Hypotheses on language emergence: Innatism and Emergentism;
- Overview of the model;
  - Target questions, objectives and general assumptions;
- Components of the model;
  - Meaning-Utterance mappings;
  - Memory system and rule acquisition mechanisms;
  - Communication with indirect meaning transference;
- Simulation results;
  - Indices to test the performance;
  - Lexicon-syntax coevolution;
- Something about LEL;



# Background

## Hypotheses on language emergence

- **Innatism (Chomskyan school)**
  - Children do not “learn” a language, as such, but use what they hear to set the **parameters** of a **Universal Grammar (UG)** in order to understand and speak a particular language.
  
- **Emergentism (e.g., Hurford et al. 2000; Oller and Griebel 2004)**
  - “[Language] evolved in a **mosaic fashion**, with the emergence of semantics, phonology, morphology and syntax all at different times and according to different schedules ... language is regarded as a kind of **'interface'** among a variety of more basic abilities. These abilities underlie nonlinguistic processes as well.” (*Wang 1978*)





# Lexicon-syntax coevolution model

## ■ Target Questions:

- Could linguistic competences be derived from some domain-general abilities?
- Instead of built-in, could syntax be gradually developed during the acquisition of lexicons?

## ■ Objectives:

- Phylogenetic emergence of language;
- Trace the transition from holistic signaling system to compositional language (*Wray 2002*);
- Study the formation of linguistic knowledge regarding lexicons and simple syntax through **categorization and conventionalization**;
- Discuss the domain-general abilities in semantic and syntactic operations;

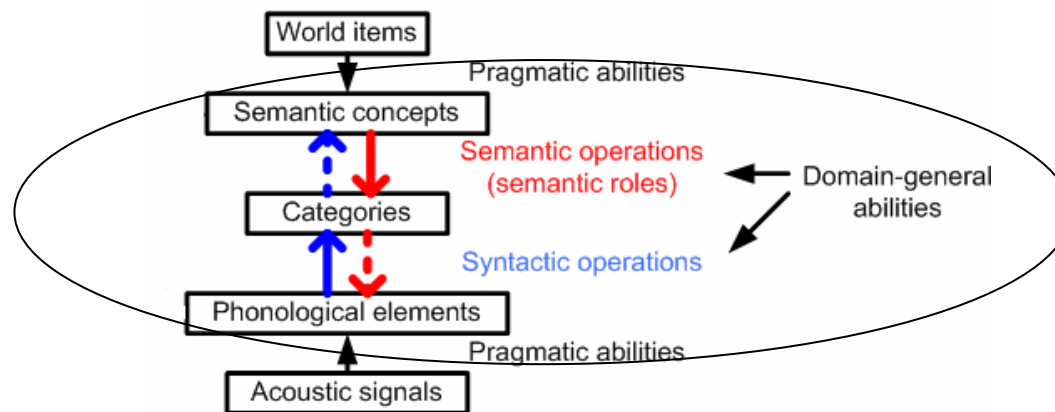
## ■ Research methodology:

- Multi-agent computational model;
- Rule-based system to represent linguistic information;
- Evolutionary computation mechanisms;



## General assumptions

- **EVOLANG5's (Gong & Wang 2005) model:**
  - The coevolution of lexicons and global word orders;
  - Syntax (simple word orders) are global (e.g., SV/VS, SVO/OVS) and built-in;
  - No categories (Syntactic category is equal to the semantic category);
  
- **Current model:**
  - **No global word orders are built-in**, they are gradually formed based on local orders between two categories;
  - Linguistic knowledge, in the form of category, is gradually formed based on **semantic and syntactic operations**, both of which are derived from domain-general abilities;
  - **Categorization and conventionalization** make possible the emergence and convergence of common lexicons and dominant global word orders;





## Components of the model:

### Meaning-Utterance (Meaning-Form) mappings

- **Integrated meanings:**
  - **“Predicate<Agent>”:** e.g., “run<wolf>”;
  - **“Predicate<Agent, Patient>”:** e.g., “chase<wolf, fox>”, “eat<lion, meat>”;
  
- **Utterance:** Combinable syllables from a syllable space;
  
- **Meaning-Utterance mappings:**
  - **Holistic mapping:** the utterance as a whole is mapped to some integrated meaning;
    - e.g., “run<wolf>”  $\leftrightarrow$  /e f g/; “fight<bear, wolf>”  $\leftrightarrow$  /c g/
  - **Compositional mapping:** the meaning mapped by the utterance is a function of the utterance components;
    - e.g., “run<wolf>”  $\leftrightarrow$  /a g c/;
    - “chase<wolf, bear>”  $\leftrightarrow$  /a b c d/

**Semantics operation    Syntactic operation**

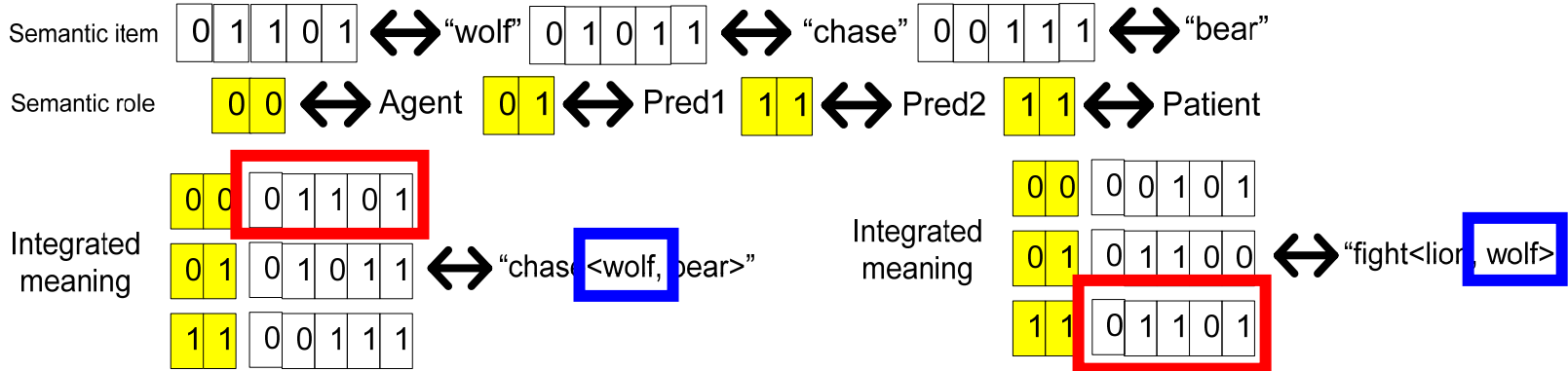


**Category (linguistic knowledge)**



# Semantic operation

- Semantic items, semantic roles and integrated meanings;



Semantic space: integrated meanings + frequency (*personal experience*);

**Semspace1:** M=4, N=4, P=4, Q=4 (=“Ag”):

“Pred1<Ag>”: 4\*4=16;

“Pred2<Ag, Pat>”: 4\*4\*3=48;

**Semspace2:** M=5, N=5, P=5, Q=5 (=“Ag”):

“Pred1<Ag>”: 5\*5=25;

“Pred2<Ag, Pat>”: 5\*5\*4=100;

		Semantic Space			
		Agent	Predicate	Patient	Frequency
<agent>	Predicate	Ag 1	Pred1 1		0.0-1.0
					0.0-1.0
		Ag M	Pred1 N		0.0-1.0
<agent; patient>	Predicate	Ag 1	Pred2 1	Pat 1	0.0-1.0
					0.0-1.0
		Ag M	Pred2 P	Pat Q	0.0-1.0



## Syntactic operation and syntax

- Syntactic roles of compositional utterance syllables:
  - Semantic category  $\neq$  syntactic category.
  - Subject (“Agent”), Verb (“Pred1”, “Pred2”), Object (“Patient”);
  
- Local order: order relations between 2 utterance items with different syntactic roles.
  - Orders: << (before) and >> (after); ▲ (middle) and ▼ (surround)
  - /a b/ << /c/  $\leftrightarrow$  Verb << Subject (VS);
  
- Syntactic operation:
  - Generalize local orders among different utterances;
    - “run<wolf>”  $\leftrightarrow$  /a g c/; “chase<wolf, bear>”  $\leftrightarrow$  /a b c d/
  - Build up global orders based on local orders;
    - unique order: V << S + O >> S  $\rightarrow$  VSO;
    - multiple orders: V << S + O << S  $\rightarrow$  VOS or OVS;
    - SV ▼ O  $\rightarrow$  SOV or VOS;



## Linguistic rules and category

- Linguistic rules: (condition + strength);

### 1) Lexical rules (M-U mappings + strength);

- **Strength:** the probability of successful use of that rule (fitness of that rule), which can be updated in successful / failed use of that rule;
- **Holistic rule** (holistic M-U mappings + strength);
  - e.g., “run<wolf>”  $\leftrightarrow$  /a c/ (0.5)
- **Compositional rule** (compositional M-U mappings +strength);
  - **Word rule:** e.g., “wolf”  $\leftrightarrow$  /a/ (0.6); “run<#>”  $\leftrightarrow$  /c/ (0.7);
  - **Phrase rule:** e.g., “#<wolf, fox>”  $\leftrightarrow$  /b d/ (0.8);  
 “chase<wolf, #>”  $\leftrightarrow$  /a X c/ (0.9);  
 “fight<#, fox>”  $\leftrightarrow$  /c/ (0.7);
- **Compositional rules can combine together to map integrated meaning;**

### 2) Syntactic rules (local order + strength);

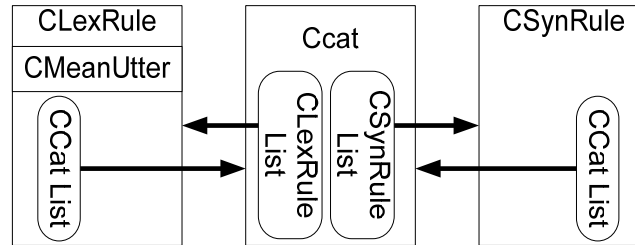
- e.g., # << # (0.5); # ▲ # (0.8);

- Linguistic rule, with strength indicating its fitness, is “real entity”;



## Linguistic rules and category

- Category (lexical rule list + syntactic rule list):
  - Knowledge of how to use lexical rules and syntactic rules to produce/comprehend integrated meaning;



- One lexical rule can be associated into many category with same syntactic roles;
- Operations on category:

### 1) Category formation:

- Available M-U mappings: “run<wolf>”  $\leftrightarrow$  /a g c/, “chase<wolf, bear>”  $\leftrightarrow$  /a b c d/;
- lexical rules: “run<#>”  $\leftrightarrow$  /a g/ (0.7); “chase<#, #>”  $\leftrightarrow$  /a b/ (0.6); “wolf”  $\leftrightarrow$  /c/ (0.6);
- Formed category: Lex-rule list: “run<#>”  $\leftrightarrow$  /a g/ (0.7) [0.5]; “chase<#, #>”  $\leftrightarrow$  /a b/ (0.6) [0.5];  
Syn-rule list: V << S (0.5);

### 2) Category merge:

- Cat1: Lex-rule list: “run<#>”  $\leftrightarrow$  /a g/ (0.7) [0.6]; “chase<#, #>”  $\leftrightarrow$  /a b/ (0.7) [0.5];  
Syn-rule list: Cat3>>Cat1 (0.9); Cat1<<Cat4 (0.6);
- Cat2: Lex-rule list: “fight<#, #>”  $\leftrightarrow$  /c/ (0.6) [0.5]; “run<#>”  $\leftrightarrow$  /a g/ (0.7) [0.3];  
Syn-rule list: Cat2<<Cat3 (0.8); Cat2>>Cat5 (0.3);
- Cat3: Lex-rule list: “wolf”  $\leftrightarrow$  /g/ (0.8) [0.7]; Syn-rule list: Cat3>>Cat1 (0.9); Cat2<<Cat3 (0.8);
- Cat1 and Cat2 merge!

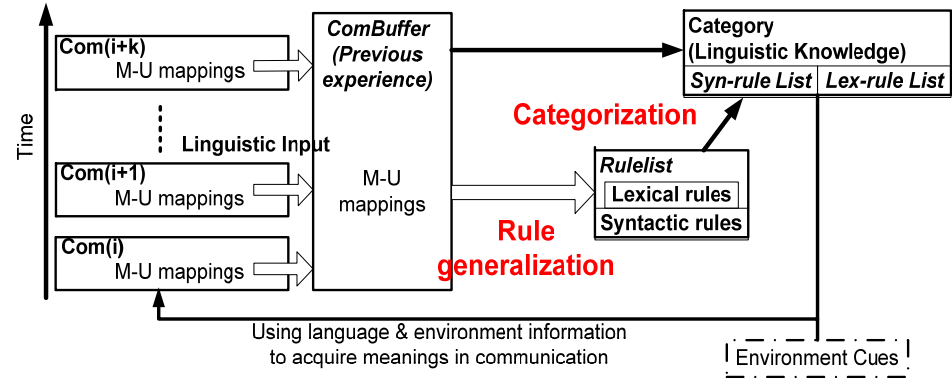
- Category has no fitness, it is “virtual property”, easily formed and updated;



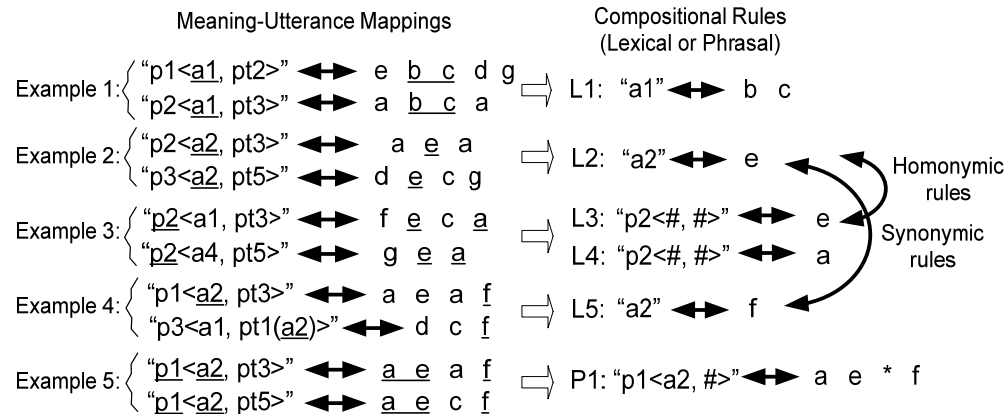
# Components of the model:

## Memory system and rule acquisition mechanisms;

- Memory system:
  - 2-level memory: **buffer** (short-term); **rule list** (long-term);
  - “Learning from experience”;
  - Inspired by Classifier Systems (*Holland 2002*).



- Rule acquisition mechanisms:
  - **Random creation** (similar to Iterative Learning Model (*Kirby 2002*));
  - **Detection of recurrent patterns:** simplified pattern-recognition;
  - Synonyms and homonyms are possible;





## Components of the model:

### Communication with indirect meaning transference

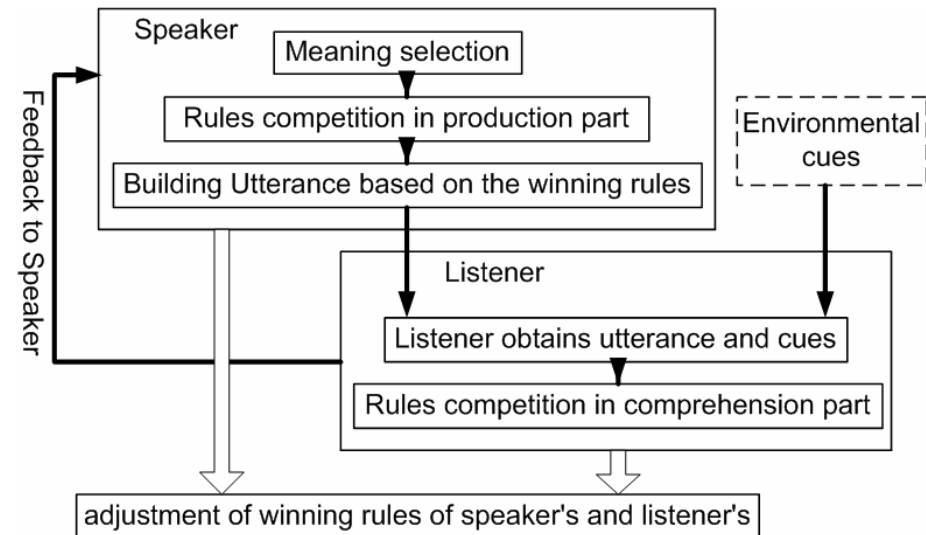
- **Cue: (integrated meaning + same strength):**
  - Environmental information, as hints for comprehension: “chase<wolf, dog>” (0.75);
  - Cues are not reliable: **Cue Reliability:** the probability that the speaker’s intended meaning contained in one of the cues available to the listener;
- **Communication:**
  - In one communication, many meanings are produced / comprehended between the speaker and the listener;
  - **Indirect feedback:** if the winning rules combined strength exceeds certain threshold, a positive feedback is sent; otherwise, a negative feedback is sent;

### Combined strength in Production

$$CS_{speak} = \text{Str}(\text{available rules}) + \text{Str}(\text{applicable word order rules})$$

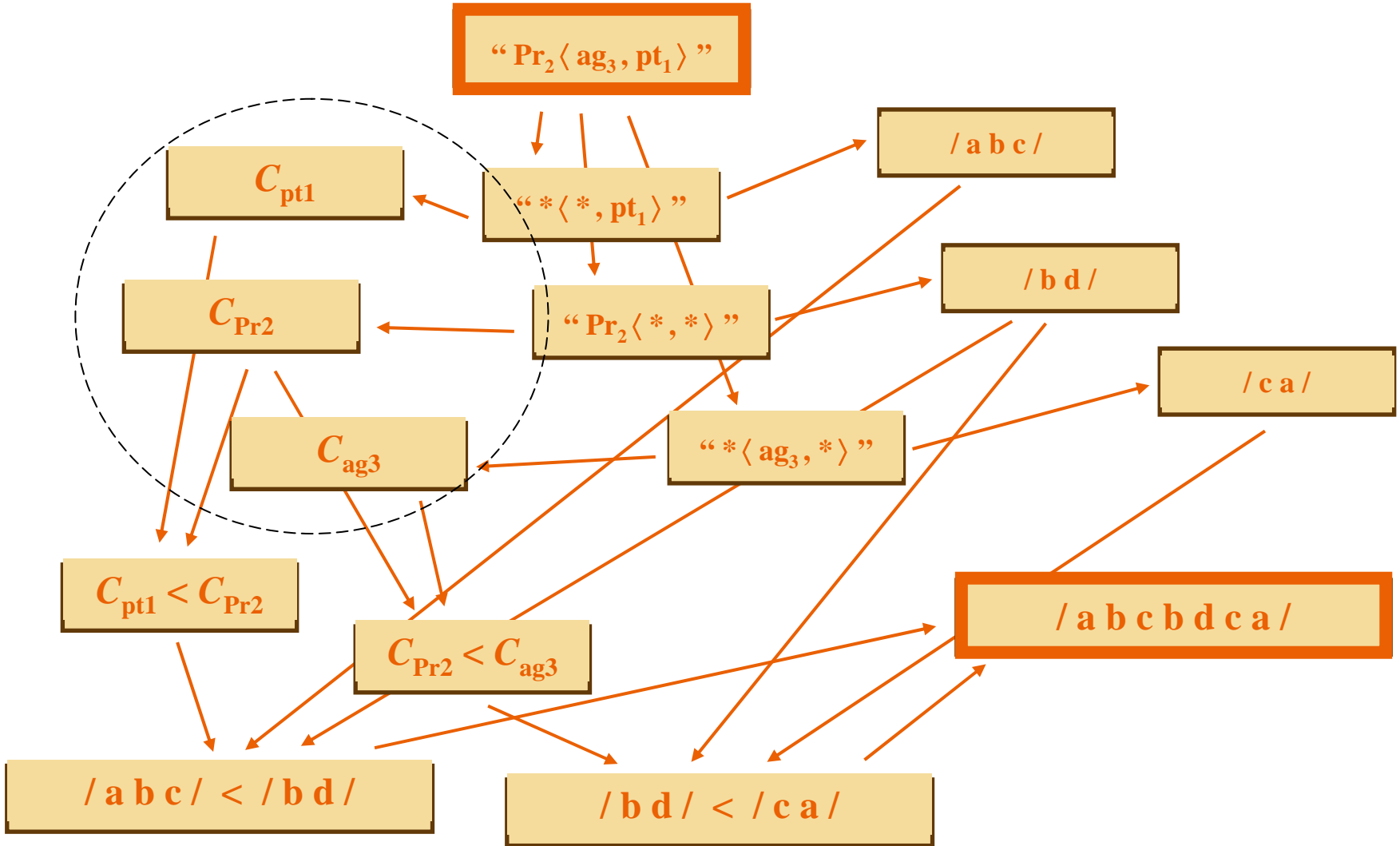
### Combined strength in Perception

$$CS_{listen} = \text{LangWeight} \left\{ \begin{array}{l} \text{Str}(\text{activated rules}) \\ + \text{Str}(\text{applicable word order rules}) \end{array} \right\} + \text{EnvWeight} \left\{ \text{Str}(\text{related Cues}) \right\}$$



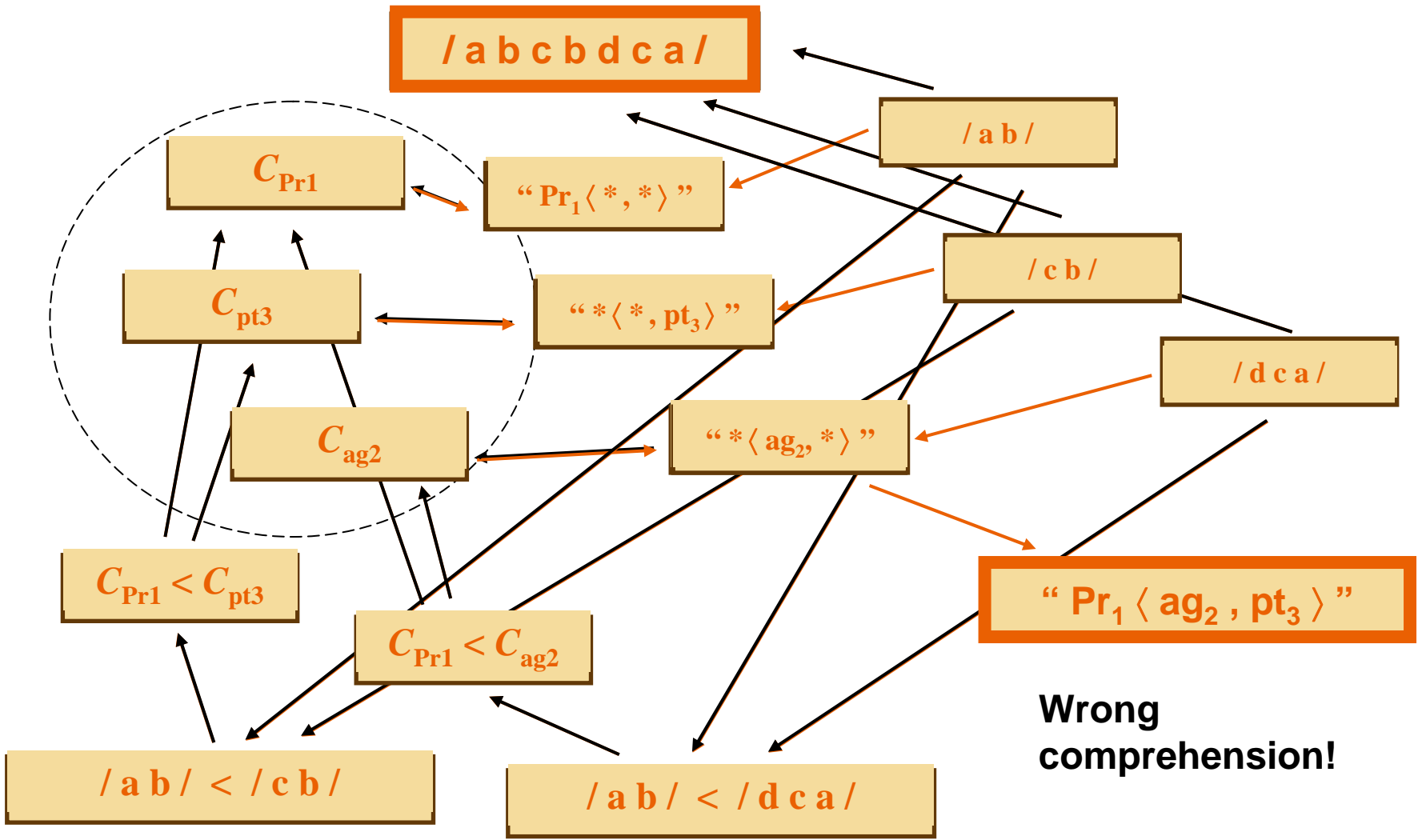


# Speaker's production





# Listener's perception



**Wrong comprehension!**



## Simulation Results

- Simulation scenario:
  - From **holistic signaling system** to **compositional language** (*Wray 2002*);
  - **Initial stage**: holistic signaling system, all agents share some common holistic rules, with no syntactic rules nor categories;
  - **Random communication**: on each step, 2 randomly chosen agents communicate with each other.

- Indices to test the performance:

- **Rule expressivity (RE)**: “how many meanings on average one agent can express”:

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

- **Understanding rate (UR)**: “how many meanings on average one agent can accurately understand based on linguistic information only (**displacement** (*Hockett 1960*))”:

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

- **Number and type of common lexical rule;**
- **Global word orders' productivity and understandability;**

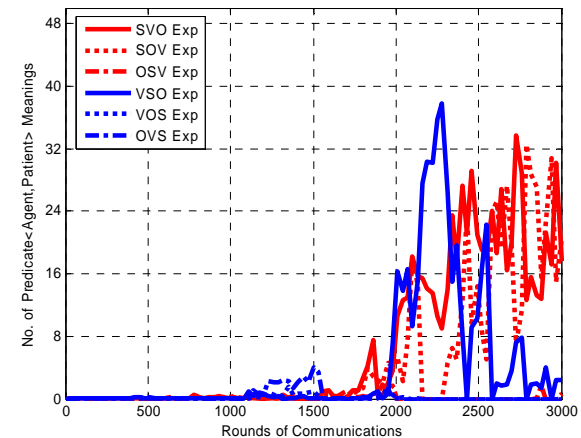
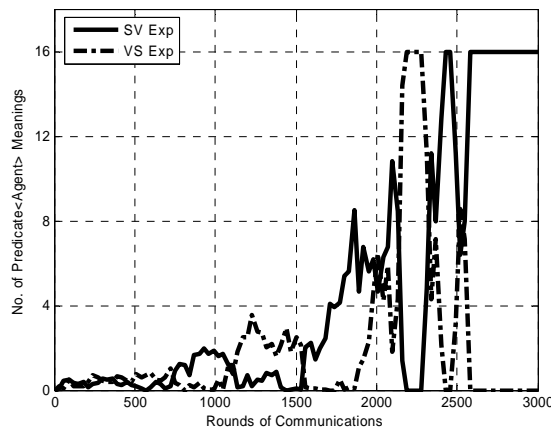
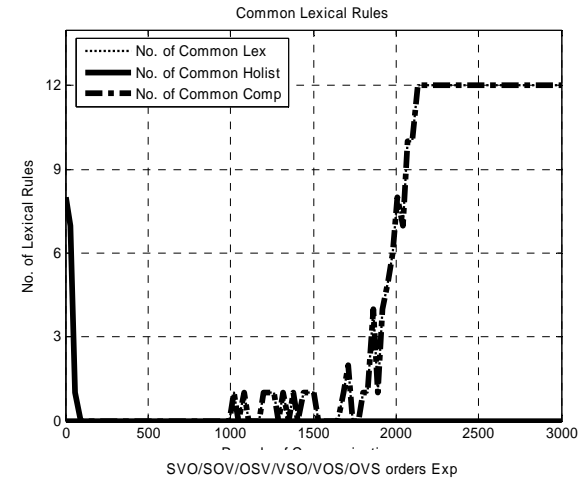
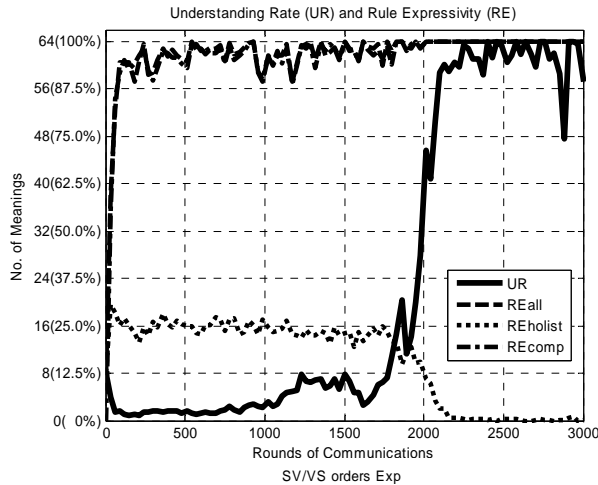


# Simulation Results: Lexicon-Syntax Coevolution

## Simulation conditions:

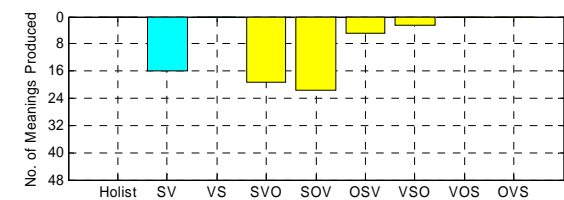
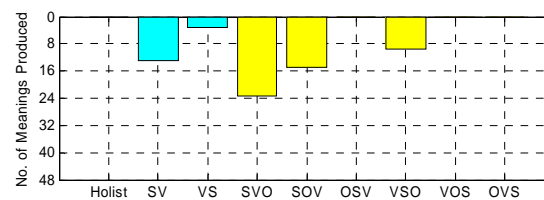
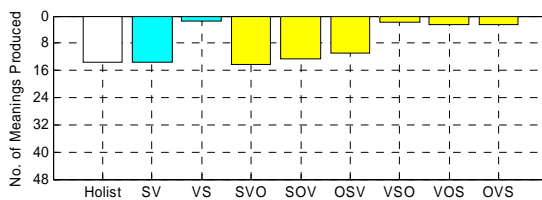
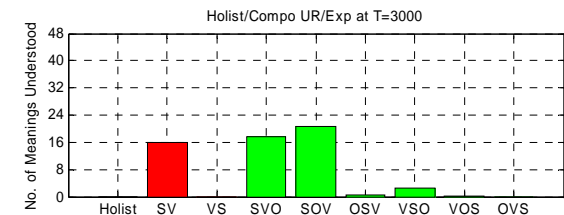
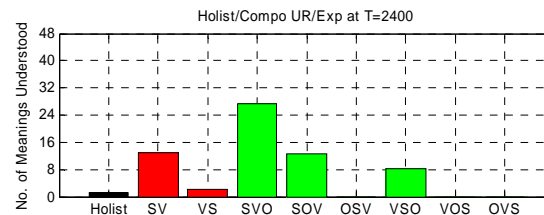
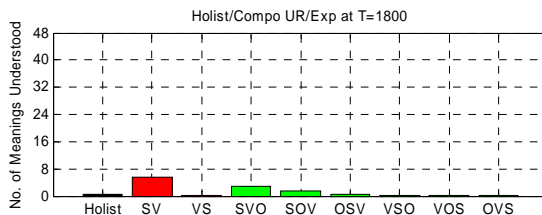
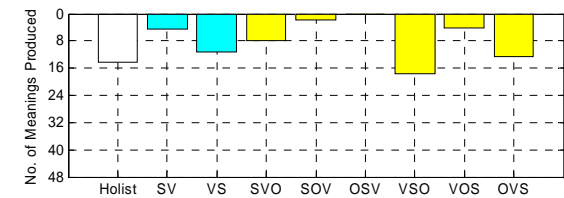
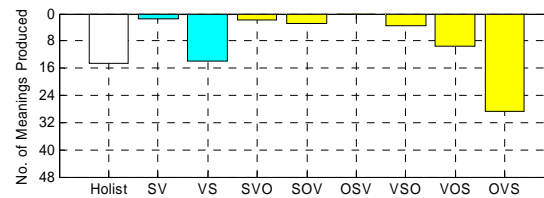
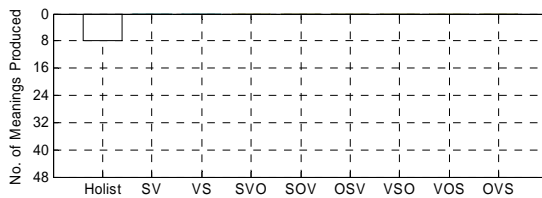
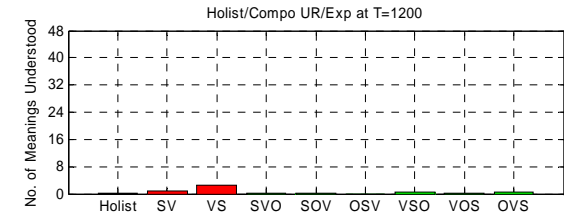
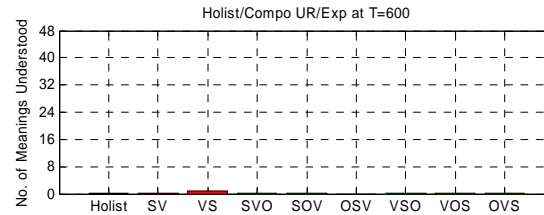
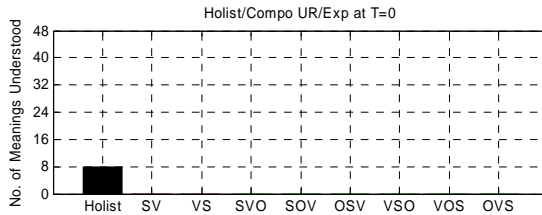
- $N_{Agent}=10$ ;  $N_{Com}=3,000$ ;  $N_{MeanExc}=20$ ;  $S_{buffer}=30$ ;  $S_{Lex}=40$ ;  $S_{Cat}=20$ ;  $S_{Syn}=20$ ;
- Strength (Lex-rule/Syn-rule str, Asso-Weight): [0.0 1.0]; InitStr=0.5; AdjStr=0.1; ForgetStr=0.01;
- CueReliab=0.8; Confidence Threshold=0.75;
- Semantic Space: 64 (16+48) Mean; Type ratio = 1:3; **Token ratio = 3:1**;

## Lexicon-Syntax coevolution





# Simulation Results: Coexistence of multiple global orders





## Explanation of coexistence of multiple orders

- Semantic category  $\neq$  syntactic category;
  - Modern languages with flexible orders, e.g., French.
  
- Instance frequency's influence on creation of local orders:
  - Inst ("Ag") > inst ("Pred1") = inst ("Pred2") > inst ("Pat")  $\rightarrow$  SV/VS >> SO/OS >> VO/OV;
  
- Parsimony in using local orders in production and perception:
  - **Multiple orders are possible:** In production, 2 relative orders are enough to produce stable/multiple global orders;
    - e.g.,  $V \ll S + O \gg S \rightarrow$  VSO;  $V \ll S + O \ll S \rightarrow$  VOS or OVS;
  - **Multiple orders are stable:** In perception, 2 relative orders are enough to distinguish S, V and O and get an accurate comprehension;
    - e.g., utterance with VOS or OVS global order can be accurately comprehended using local orders:  $V \ll S + O \ll S$ ;
  - Examples of language with flexible orders: e.g., French, Chinese;



## Preliminary results and future work

- The transition from holistic signaling system to compositional language is a **conventionalization** process of acquiring linguistic knowledge (**categorization**).
- This transition is a **coevolutionary process** of the emergence of common lexicons and similar global orders (both of which are achieved within same period);
- Understanding rate follows a **“S-curve” with a sharing increasing stage**;
- **Global orders can emerge based on local orders and categorization:**
  - Coexistence of multiple orders for “Pred2<Ag, Pat>” meanings;
  - Order shift based on mutual influence of global orders for “Pred1<Ag>” and those for “Pred2<Ag, Pat>” meanings;
- **Mutual influence in semantic and syntactic operations:**
  - Semantic roles  $\leftrightarrow$  Syntactic roles;
  - Global orders for “Pred1<Ag>”  $\leftrightarrow$  Global orders for “Pred2<Ag, Pat>”;
  - Global orders  $\leftrightarrow$  Common lexical rules;



## Something about LEL

[http://dsp.ee.cuhk.edu.hk/lel/;](http://dsp.ee.cuhk.edu.hk/lel/)

first founded in 1994 in City U of HK; moved to CUHK in Sep. 2004.

- **Supervisor:** Prof. Wang, W. S-Y.;
- **Pos-doc:** Dr. Minett, J. W., Peng, G.;
- **Current members:** Wong, F., Gong, T., Shuai, L., Zheng, H. Y.;
- **Evolutionary linguistic topics in LEL:**
  - **Language emergence;**
    - Phylogenetic emergence of language (*Gong, T & Minett, J.*);
    - Ontogenetic emergence of language (*Wong, F. & Au, B.*);
  - **Language change;**
    - Language contact (*Ke, J.*); Linguistic innovation & social structure (*Gong, T., Minett, J. & Ke, J.*);
  - **Language death;**
    - Language competition on users; Endangered languages (*Minett, J. & Wang, F.*);

Minett, J. W. & Wang, W. S-Y., eds. (2005) *Language Acquisition, Change and Emergence: Essays in Evolutionary Linguistics*. Hong Kong: City University of Hong Kong Press.

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