Statistical Physics of Language Dynamics

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Language Dynamics

- Language is complex adaptive system
- Evolves through the process of self-organization
- Question: How can one explain the interplay of structure and dynamics of such a system?
- => Statistical Physics tools

A Physical System Perspective

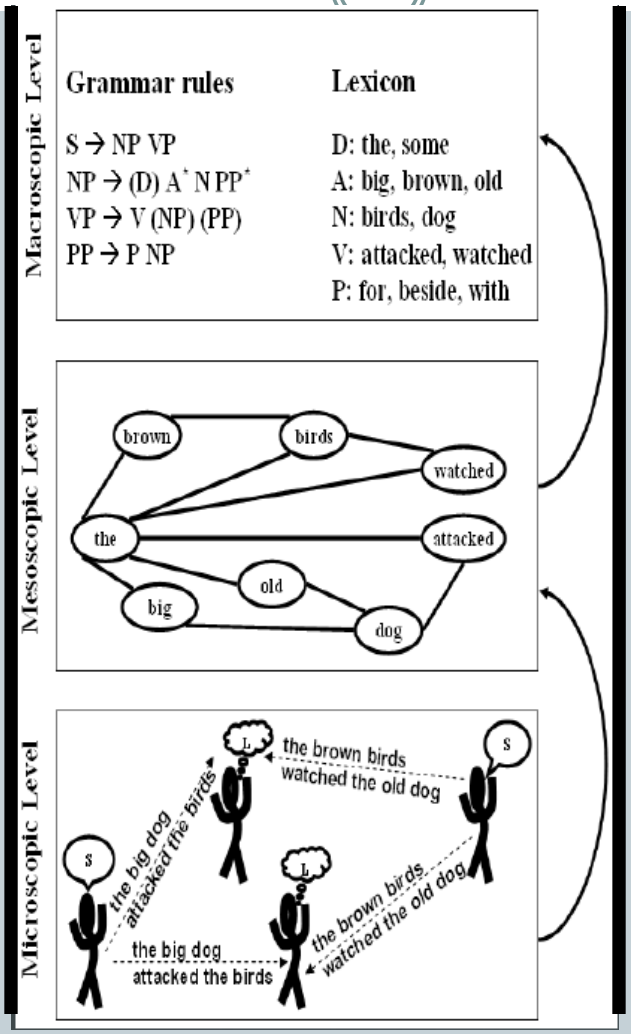
Language as a whole (grammatical constructs)

↓

Language as a collection of interactions among linguistic units

↓

Language as a collection of utterances



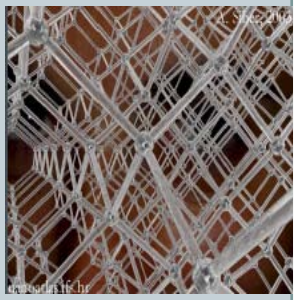
Macroscopic level

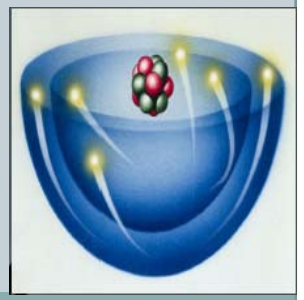
↓

Mesoscopic level

↓

Microscopic level





A Physical System Perspective

Language as a whole (grammatical constructs)

↓

Language as a collection of interactions among linguistic units

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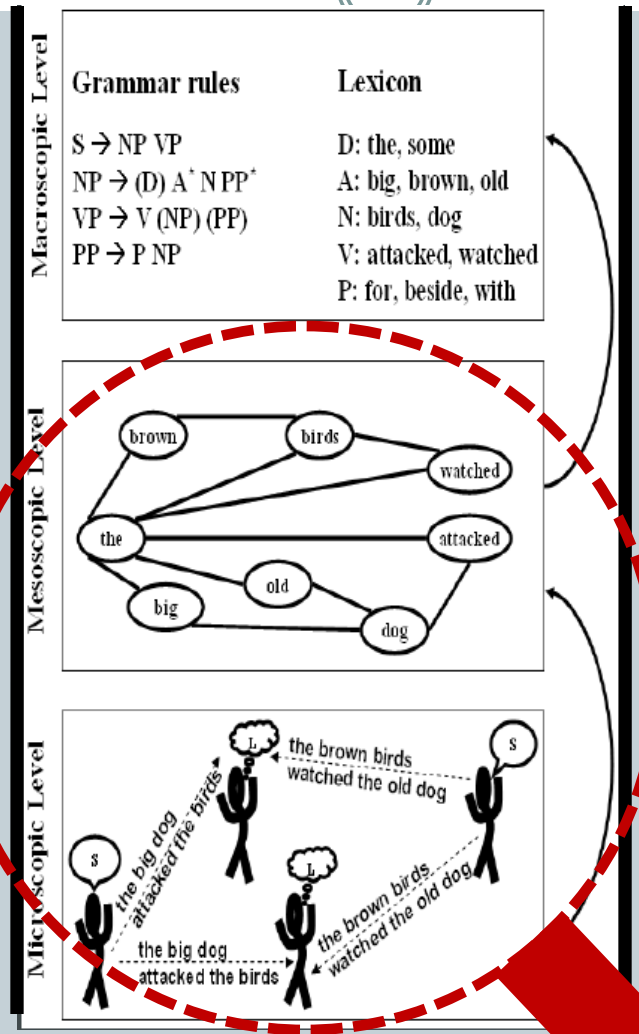
Language as a collection of utterances

dynamic



Macroscopic level

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Mesoscopic level

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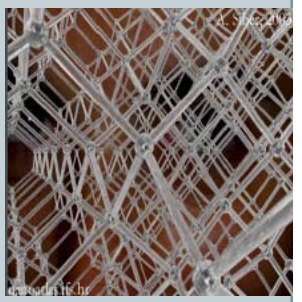
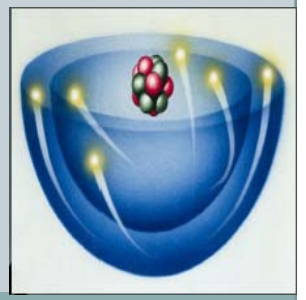
Microscopic level





Names for meanings

SPAM !

Names for meanings

SPAM !

Spiced HAM

Monty Python's spam comedy (1970 TV show)

Mr. and Mrs. Bun enter a cheap pub

Mr. Bun: What have you got, then?

Waitress: egg and SPAM; egg, bacon, and SPAM; egg, bacon, sausage and SPAM; SPAM, bacon, sausage, and SPAM; SPAM, egg, SPAM, SPAM, bacon, and SPAM; SPAM, SPAM, SPAM, egg, and SPAM; SPAM, baked beans, SPAM, SPAM, SPAM, and SPAM....

Mrs. Bun: Have you got anything without SPAM in it?

Waitress: Well, there's SPAM, egg, sausage, and SPAM. That's not got MUCH SPAM in it.

Mrs. Bun: I don't want any SPAM.

Mr. Bun: Why can't she have egg, bacon, SPAM, & sausage?

Mrs. Bun: That's got SPAM in it!

Mr. Bun: Not as much as SPAM, egg, sausage, and SPAM.

Mrs. Bun: Look, could I have egg, bacon, SPAM, and sausage without the SPAM?

Waitress: Uuuuuuuuuggggggh!

Mrs. Bun: What d'you mean uuugggh!? I don't like SPAM.

Vikings: (singing) SPAM, SPAM, SPAM, SPAM..SPAM, SPAM, SPAM, SPAM... Lovely SPAM, wonderful SPAM....

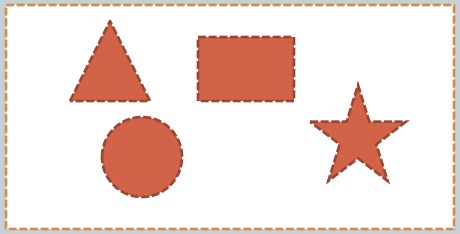
Form meaning association

How do we associate names to objects ((e-)spam to spam)?

The Naming Game

The “Talking Heads” Experiment

Speaker



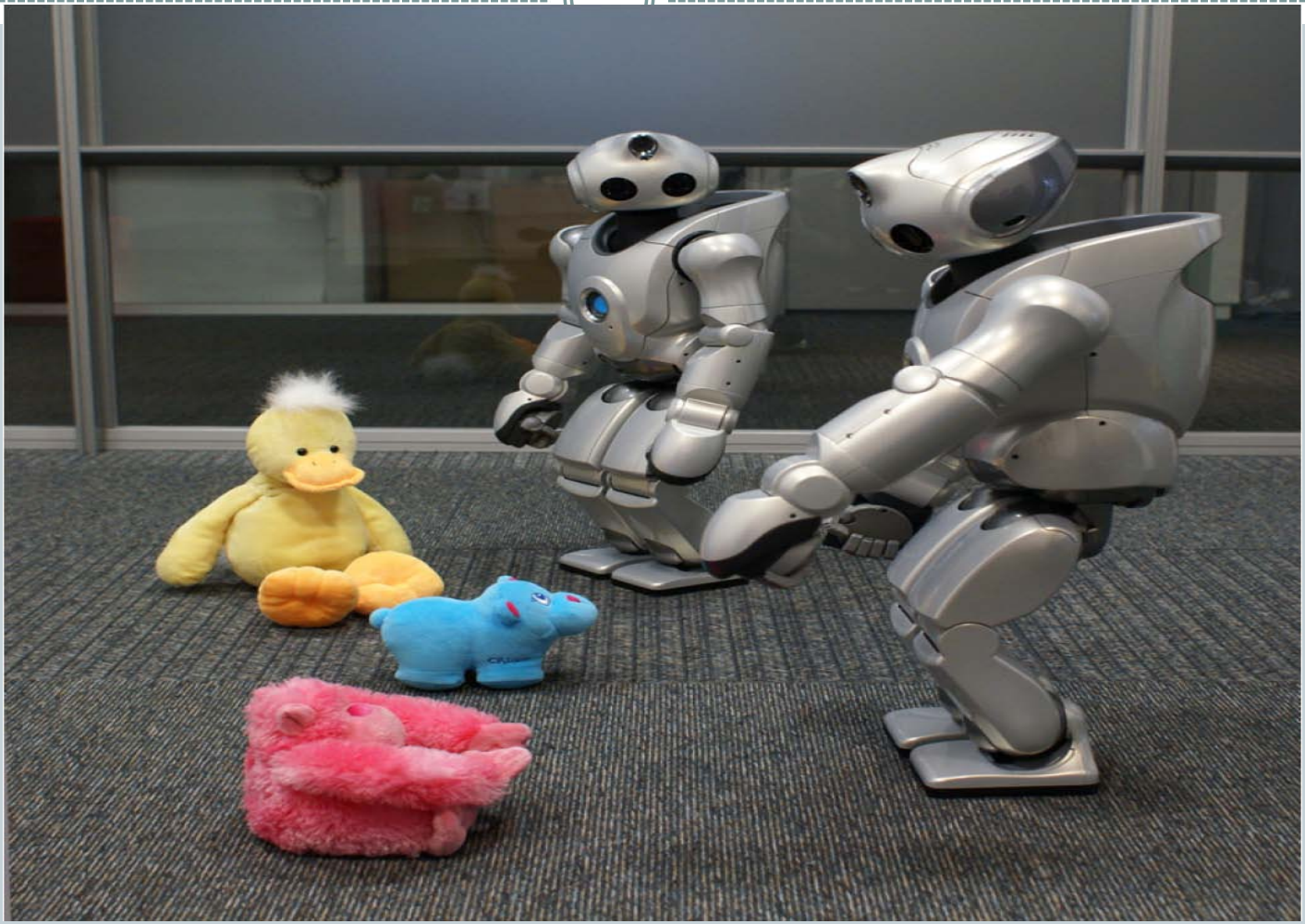
Hearer

- Perceive scene
- Choose topic
- Conceptualize
- Verbalize

interpret utterance
perceive scene
apply meaning
point to referent

Luc Steels, Autonomous Agents and Multi-agent Systems (1998)

The Grounded Naming Game



Bleys et al., Roman-09 (2009)

Minimal Naming Game

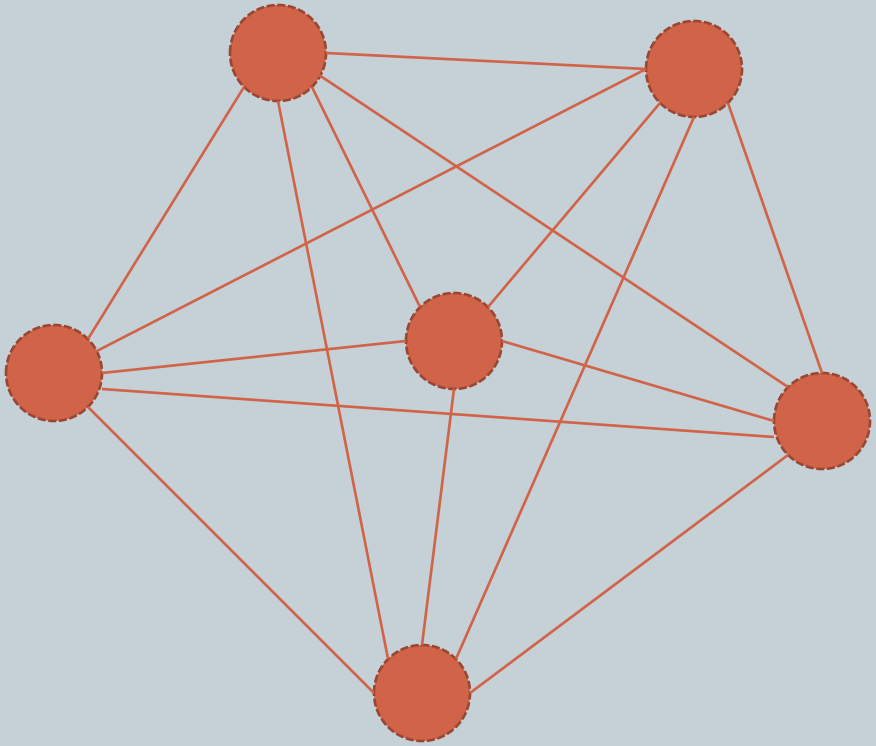
Interactions of N agents who communicate on how to associate a name to a given object

Agents:

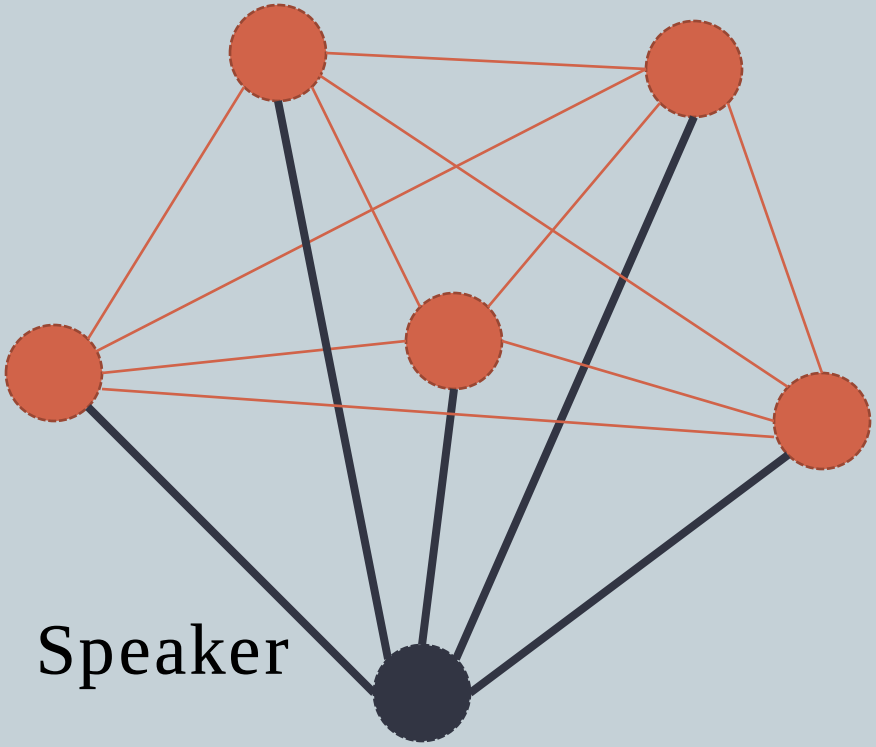
- can keep in memory different words
- can communicate with each other

Baronchelli et. al, J. of Stat Mech. (2006)

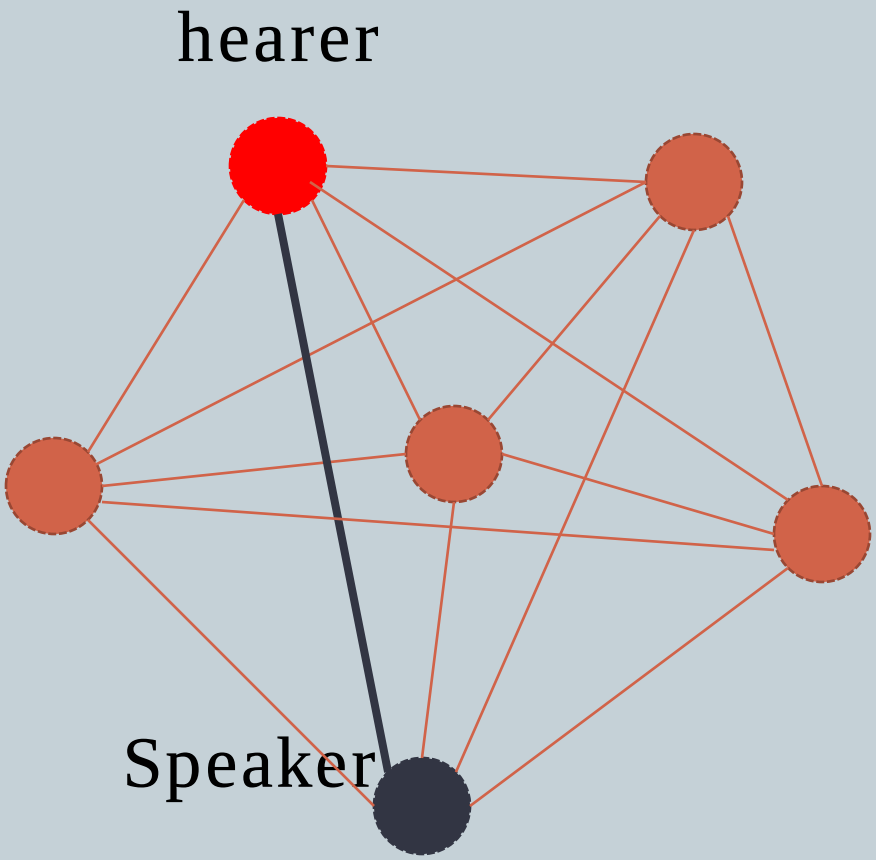
Minimal NG on fully-connected network



Choosing agents



Choosing agents



Game dynamics

Speaker

Bottle
Apple
Tiger
Car

Hearer

Bag
Blackberry
Tree

Game dynamics

Speaker

Hearer

Bottle
Apple
Tiger
Car

Bag
Blackberry
Tree

randomly chosen from speaker's inventory

Game dynamics

Speaker

Bottle
Apple
Tiger
Car

Hearer

Bag
Blackberry
Tree

Search for Apple

Not Found
→ Failure!!!

Game dynamics

Speaker

Bottle
Apple
Tiger
Car

Hearer

Bag
Blackberry
Tree
Apple

Add: Apple

Game dynamics

Speaker

Hearer

Bottle
Apple
Tiger
Car

Bag
Apple
Tree

randomly chosen from speaker's inventory

Game dynamics

Speaker

Bottle
Apple
Tiger
Car

Hearer

Bag
Apple
Tree

Search
for Apple

Found

→ Success!!!

Game dynamics

Speaker

Apple

Retain: Apple
Delete: Others

Hearer

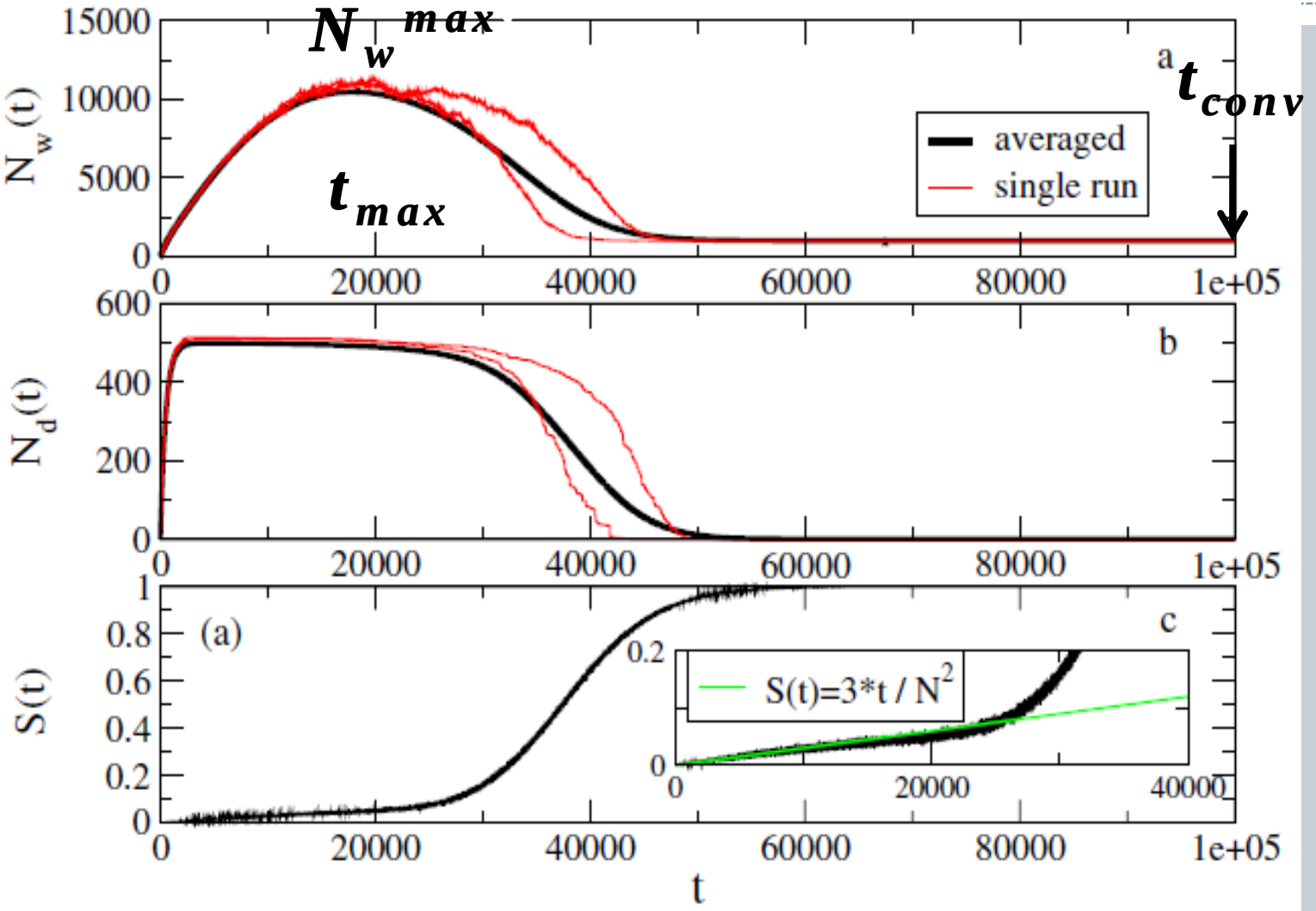
Apple

Retain: Apple
Delete: Others

Phenomenology

- $N_w(t)$ – total number of words in the system at time t
- $N_d(t)$ – number of different words in the system at time t
- $S(t)$ - average success rate at time t
- N_w^{max} - maximum memory required by the system
- t_{max} - the time required to reach the memory peak
- t_{conv} - the time required to reach the global consensus

Temporal evolution of the emergent properties



Baronchelli et al . J. of Stat. Mech. (2006)

Scaling Relations

- Assume when total # words is close to maximum, each agent has on average cN^a words
- probability for the speaker to play a given word is $1/(cN^a)$
- probability that the hearer knows that word is $2cN^a/N$ (where $N/2$ is the number of different words present in the system)

$$\frac{dN_w(t)}{dt} \propto \frac{1}{cN^a}\left(1-\frac{2cN^a}{N}\right) - \frac{1}{cN^a}\frac{2cN^a}{N}2cN^a$$

Unsuccessful interaction Successful interaction

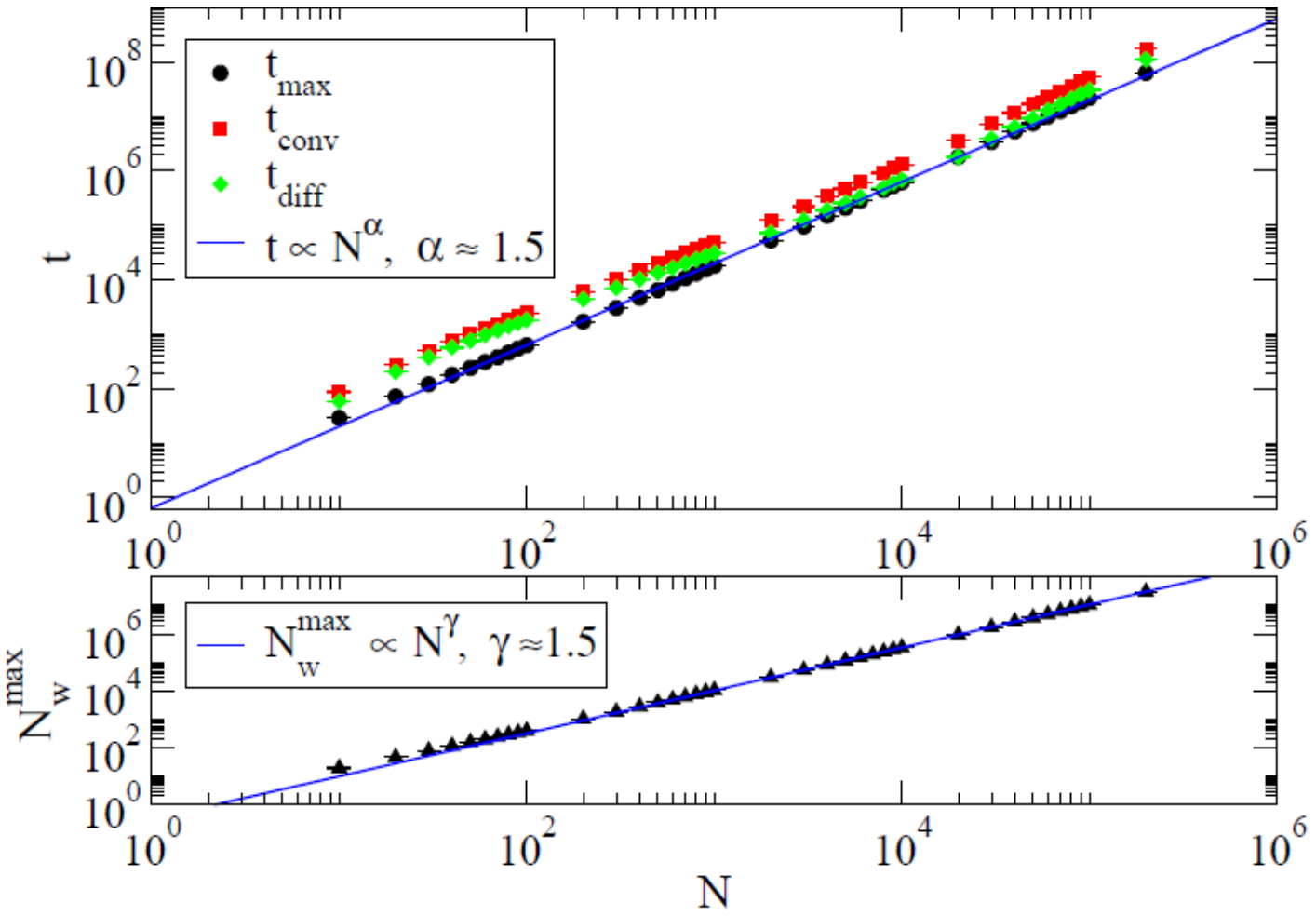
Scaling Relations

- At the maximum, $dN_w(t_{max})/dt = 0$
- only possible value for exponent a is a =1/2
- So, $N_w^{max} \sim N^{3/2}$
- rewriting the same evolution equation as

$$\frac{dN_w(t)}{dt} \propto \frac{1}{cN^{1/2}}\left(1 - \frac{ct}{N^2}\right) - \frac{1}{cN^{1/2}}\frac{ct}{N^2}2cN^{1/2}$$

and imposing $dN_w(t)/dt = 0$, we get $t_{max} \sim N^{3/2}$

Scaling with population size N



Baronchelli et al., IJMPC (2008)

Scaling relations for various topologies

	N^w_{max}	t_{max}	t_{conv}
Mean-field	$N^{1.5}$	$N^{1.5}$	$N^{1.5}$
Scale-free	N	N	$N^{1.4}$
Erdos-Renyi	N	N	$N^{1.4}$
Small-world	N	N	$N^{1.4}$

Applications

- As an opinion formation model in social networks
- As a "leader election" model in sensor networks
- Autonomous development of a common language among sensor nodes at exploration stage after network deployment
- In social tagging systems like del.icio.us, flickr.com etc.

Category Game

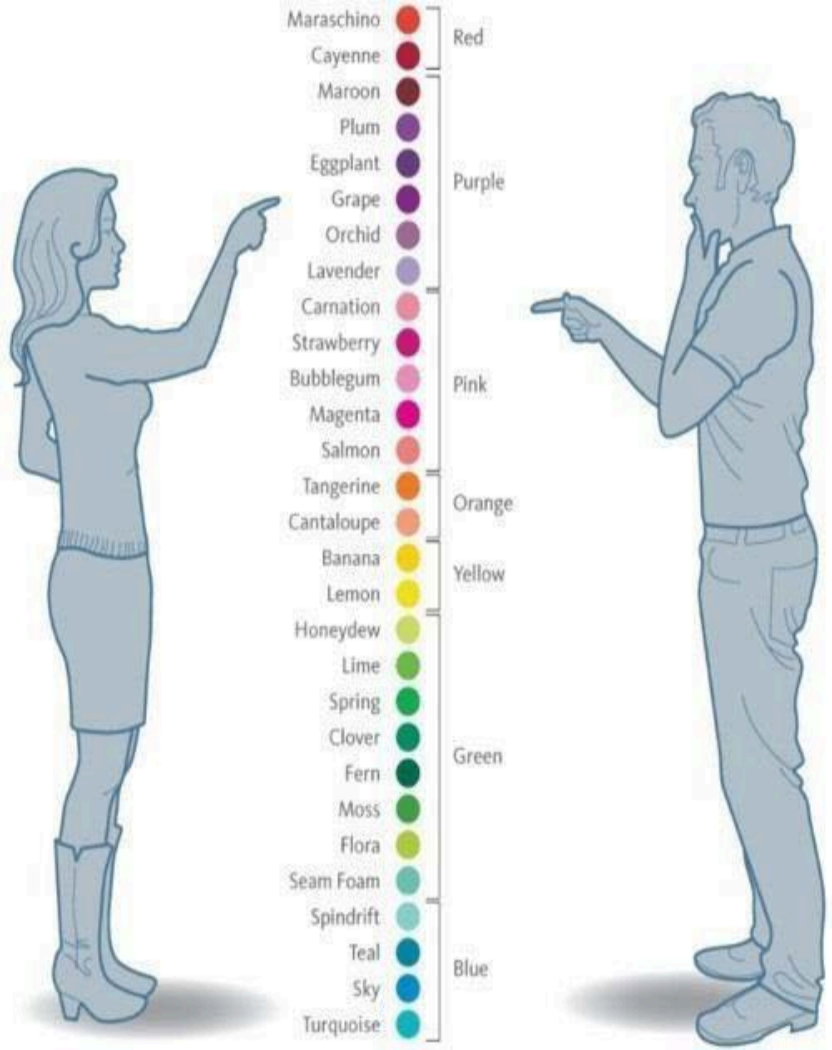
- Emergence of categorization from scratch
- No pre-existing categorization in a group of individuals
- Emerge a categorization through pairwise interactions without any central coordination

Motivation

- Color categorization (a central issue both in linguistics and in cognitive science)

- evolution of English color categories

  [English color terms gradual semantic shift from largely brightness color concepts (Old English) to almost exclusively hue concepts (Middle English)]

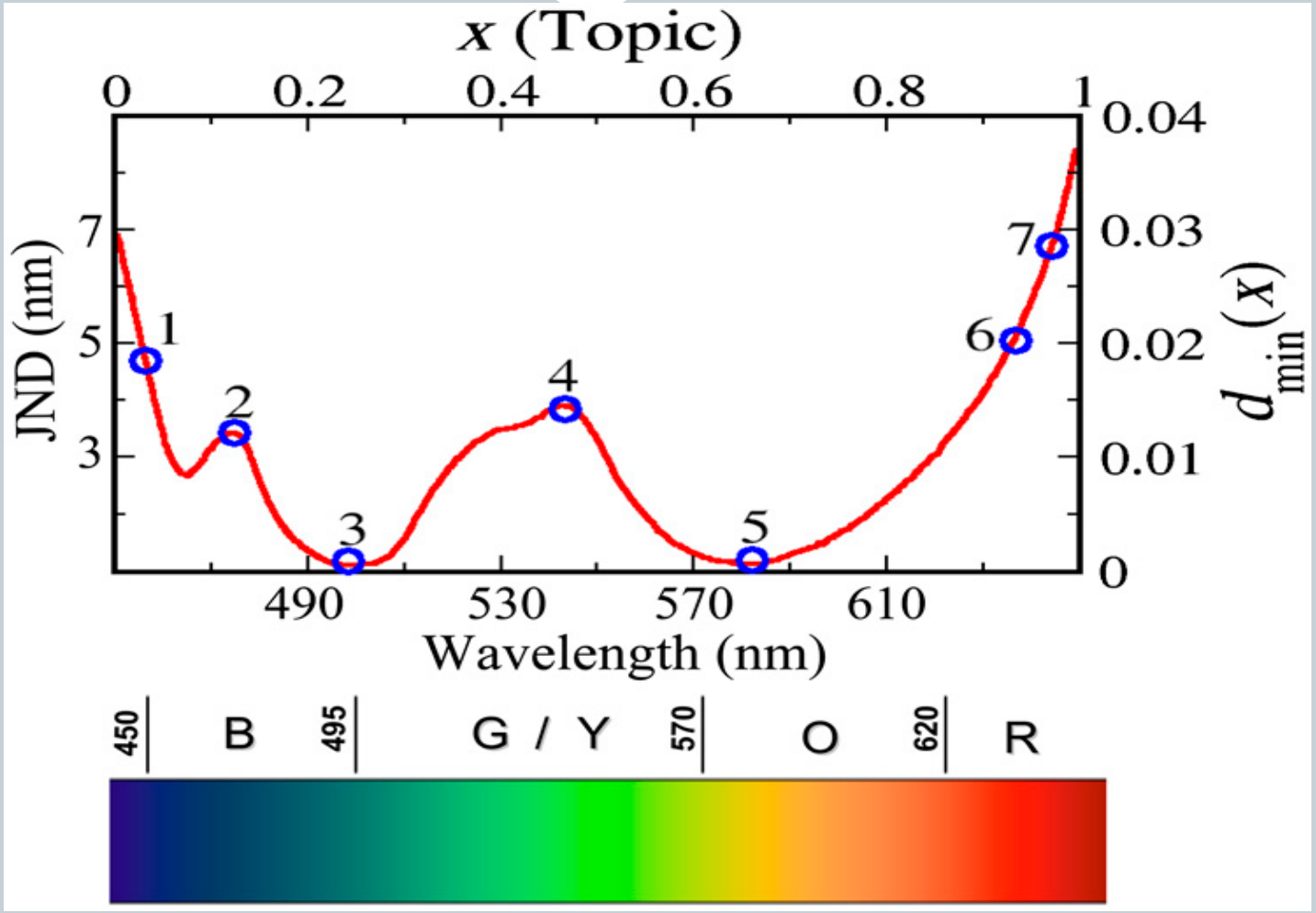


The Model

- Both the speaker and hearer are presented with a scene of $M >= 2$ stimuli (objects)

- No two stimuli appearing in the same scene can be at a distance closer than $d_{min}(x)$ → the only parameter of the model encoding the finite resolution power of any perception: the human Just Noticeable Difference (JND).

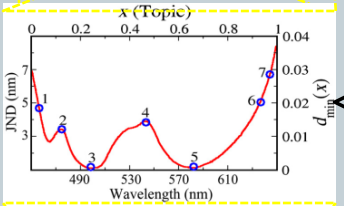
Just Noticeable Difference



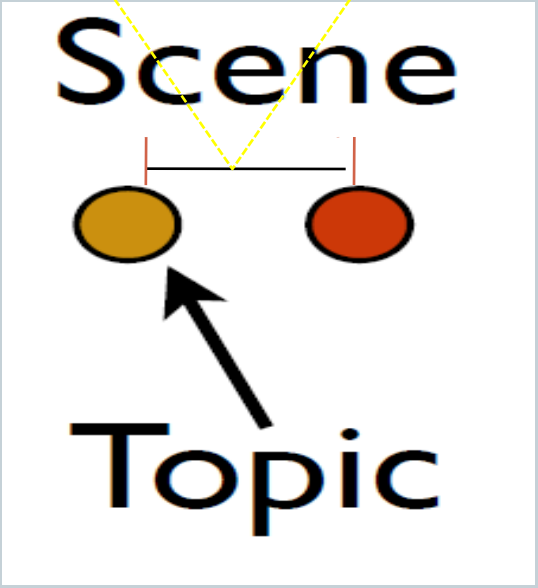
Scene Perception

Speaker (S)

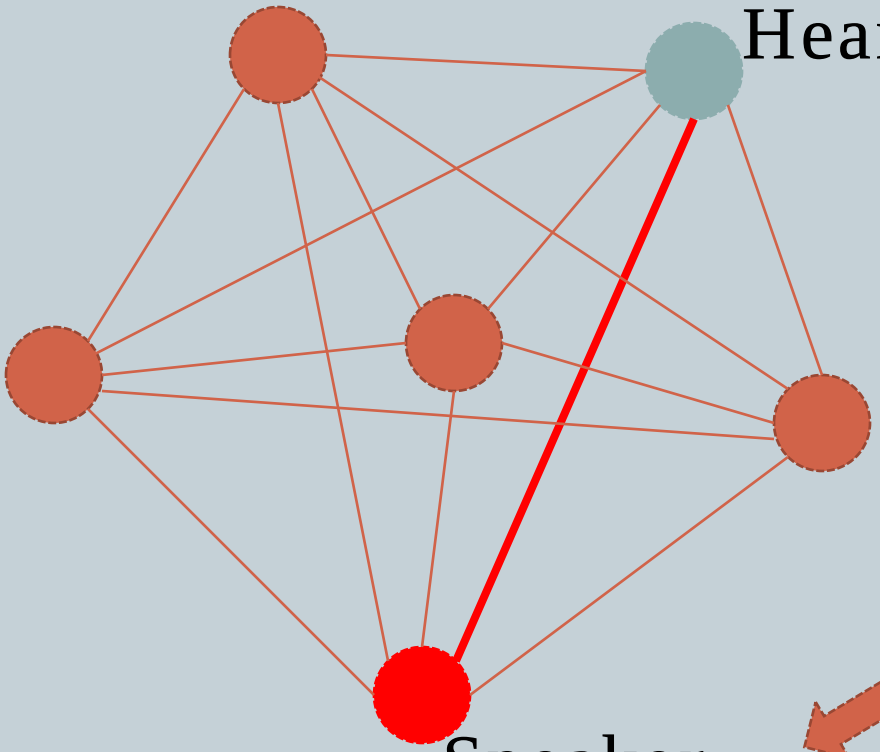
Hearer (H)



<-- $d_{min}(x)$

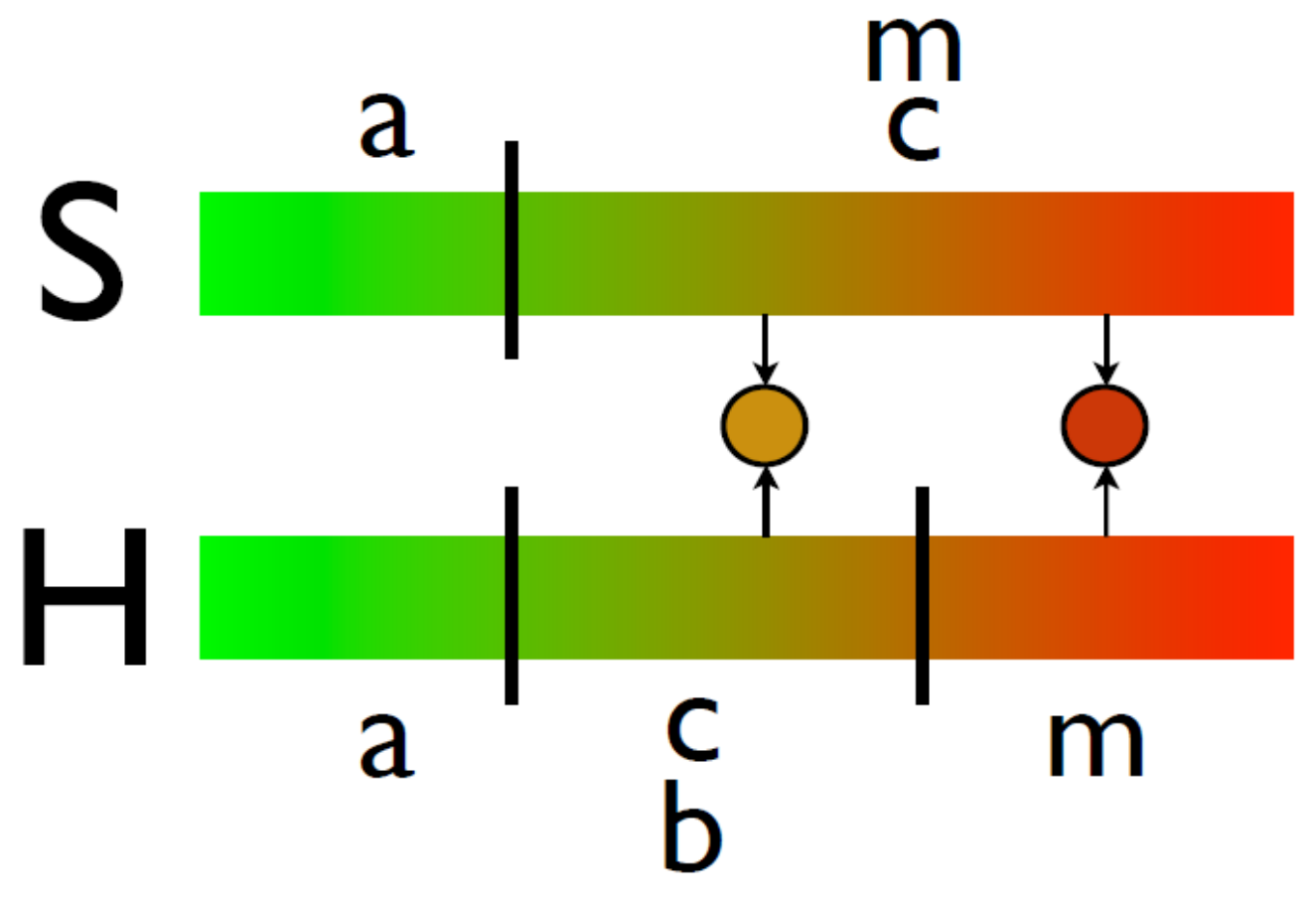


Choice of agents



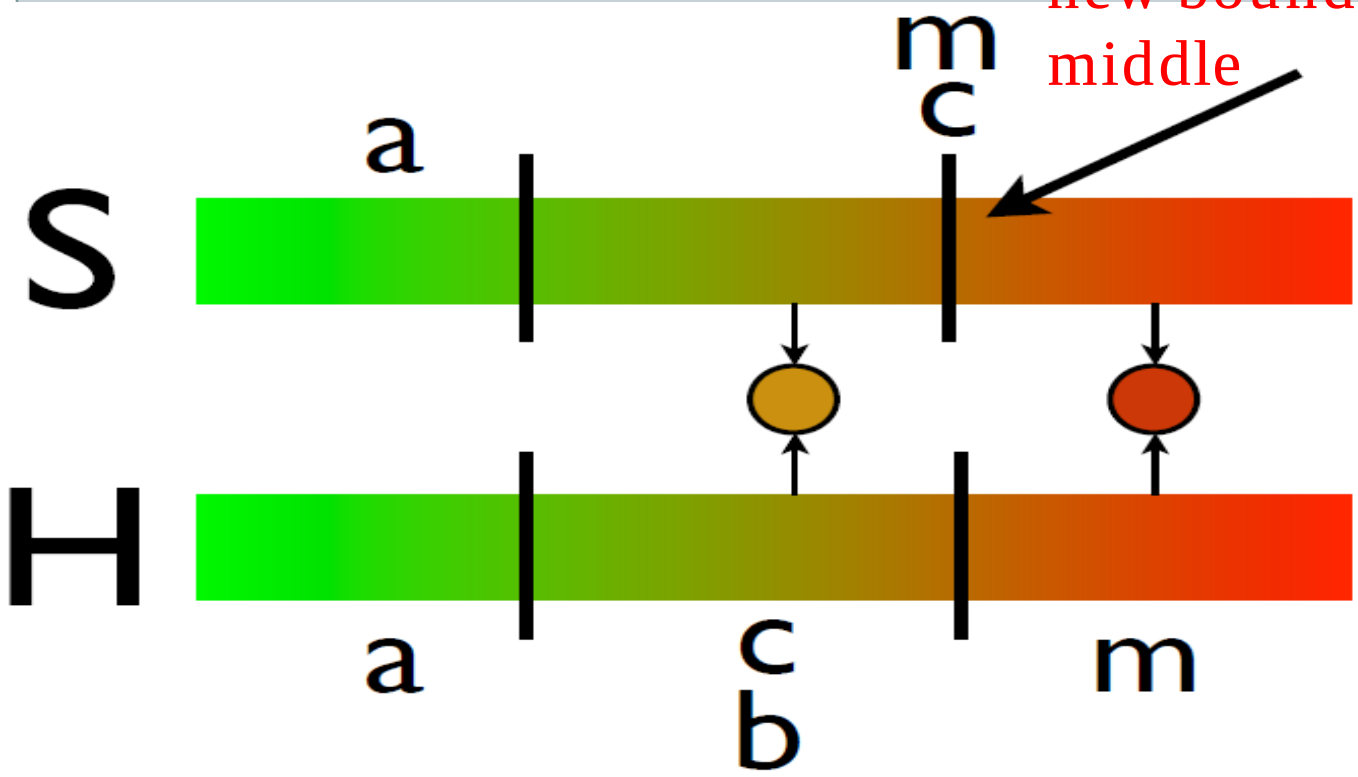
randomly chosen from population

Locating stimuli in perceptual space



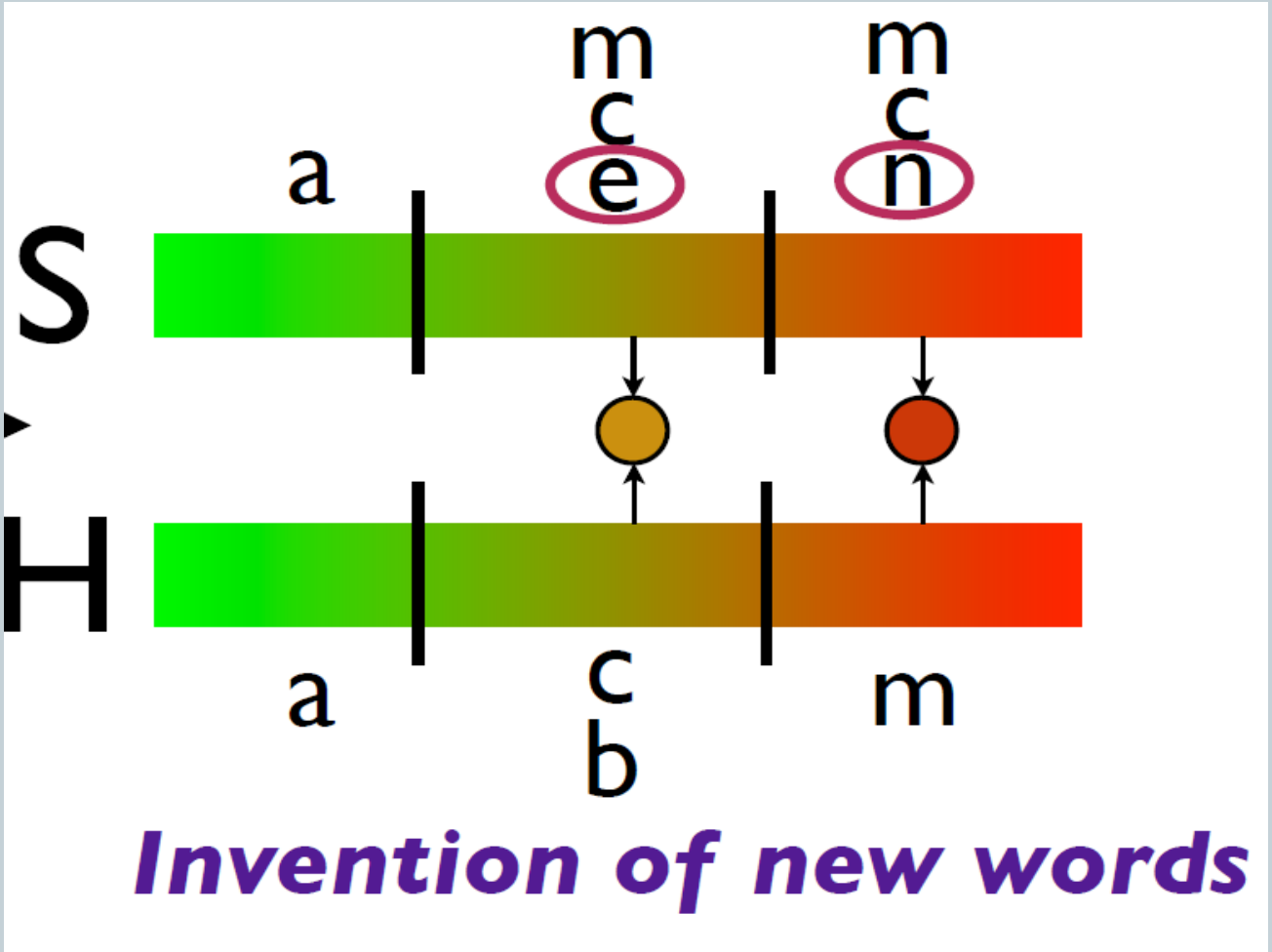
Word Invention

two stimuli colliding on the same perceptual category → new boundary created in the middle



Discrimination

Word Invention

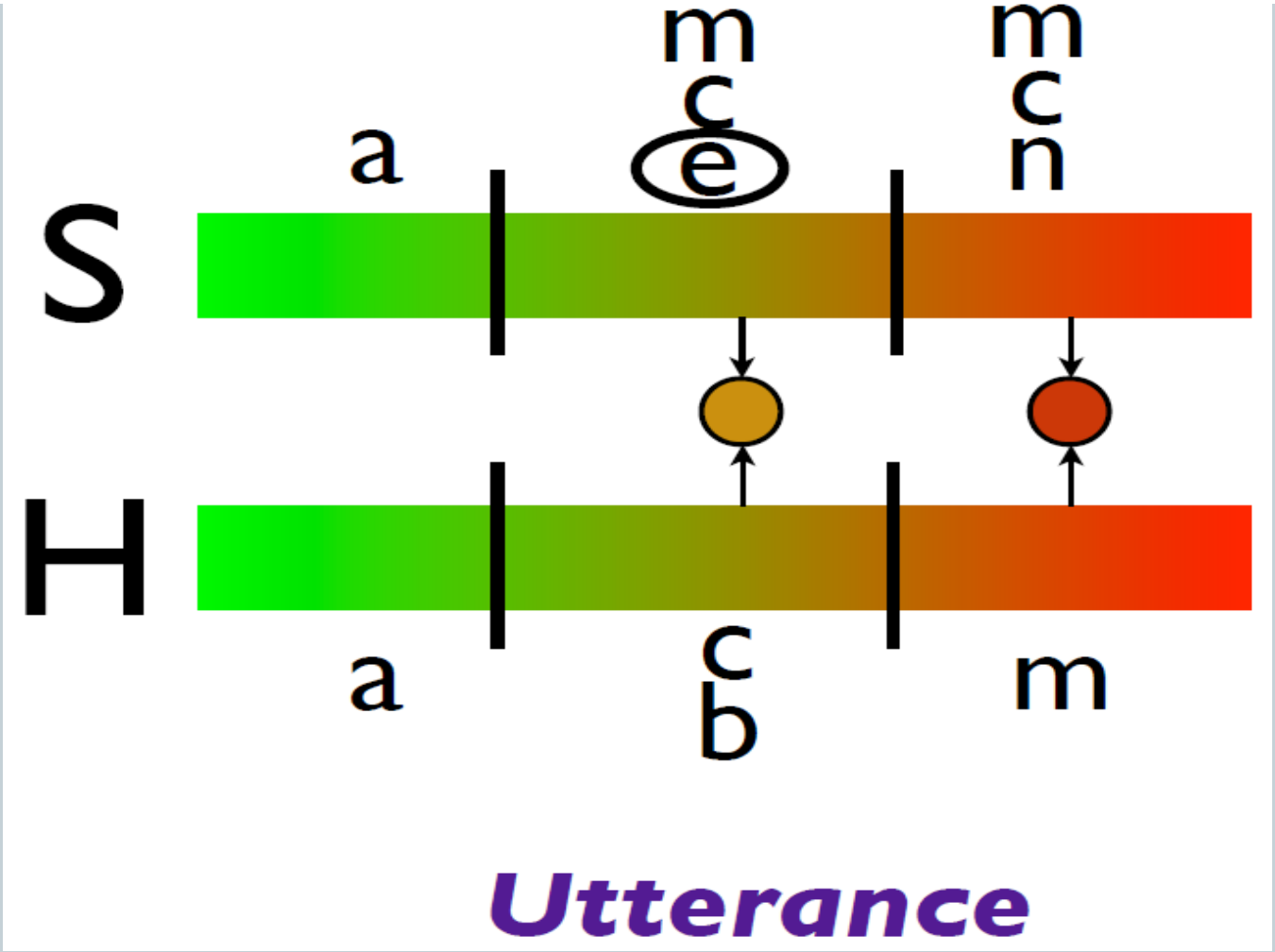


Word Selection

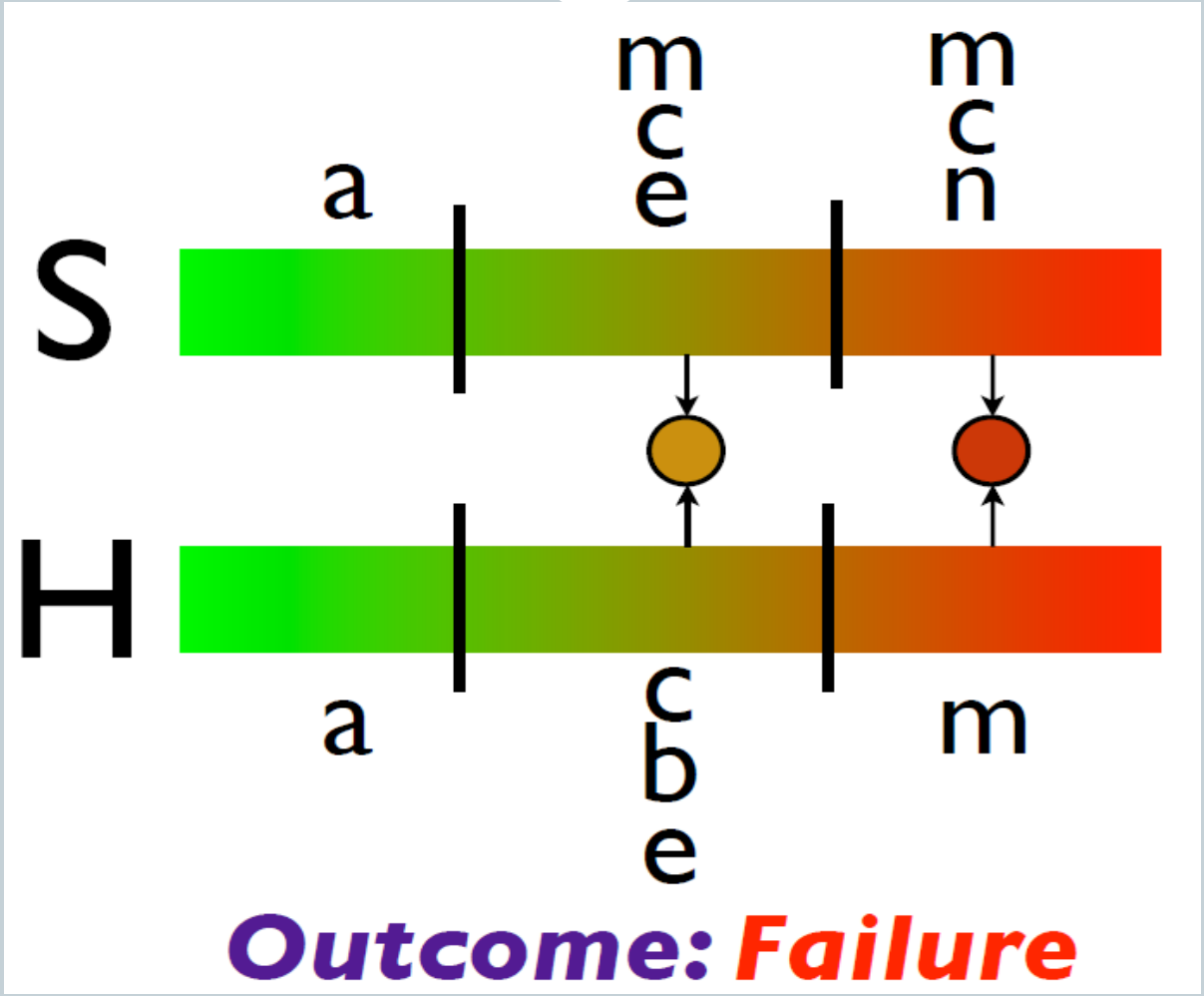
- Speaker browses its list of words associated with the perceptual category containing the topic

- 2 possibilities (the most relevant name):
  - Chooses the last winning word
  - Otherwise, choose the newly created one

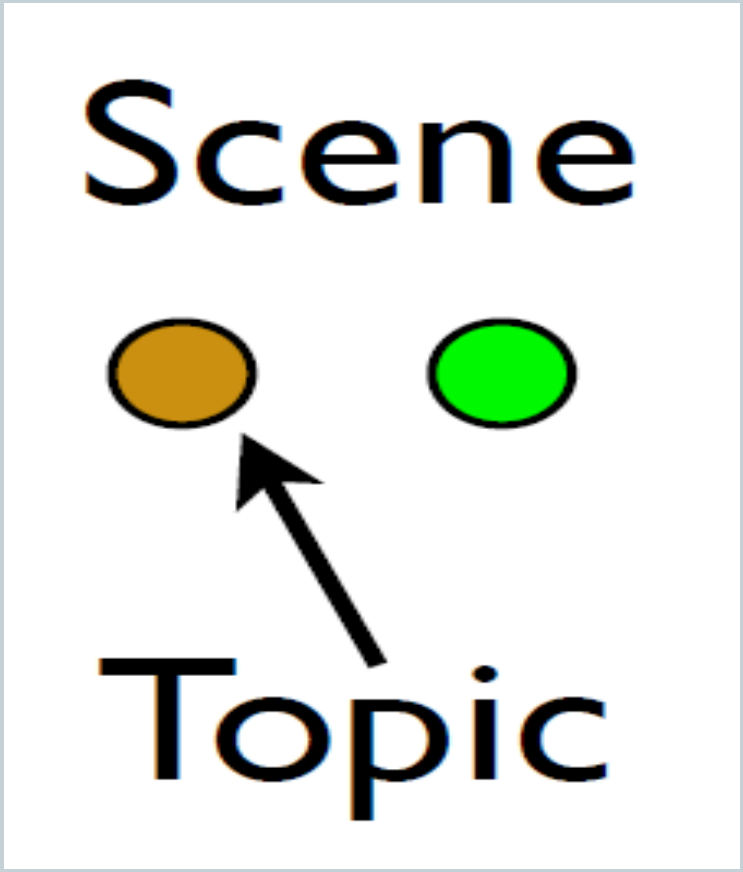
Word Selection



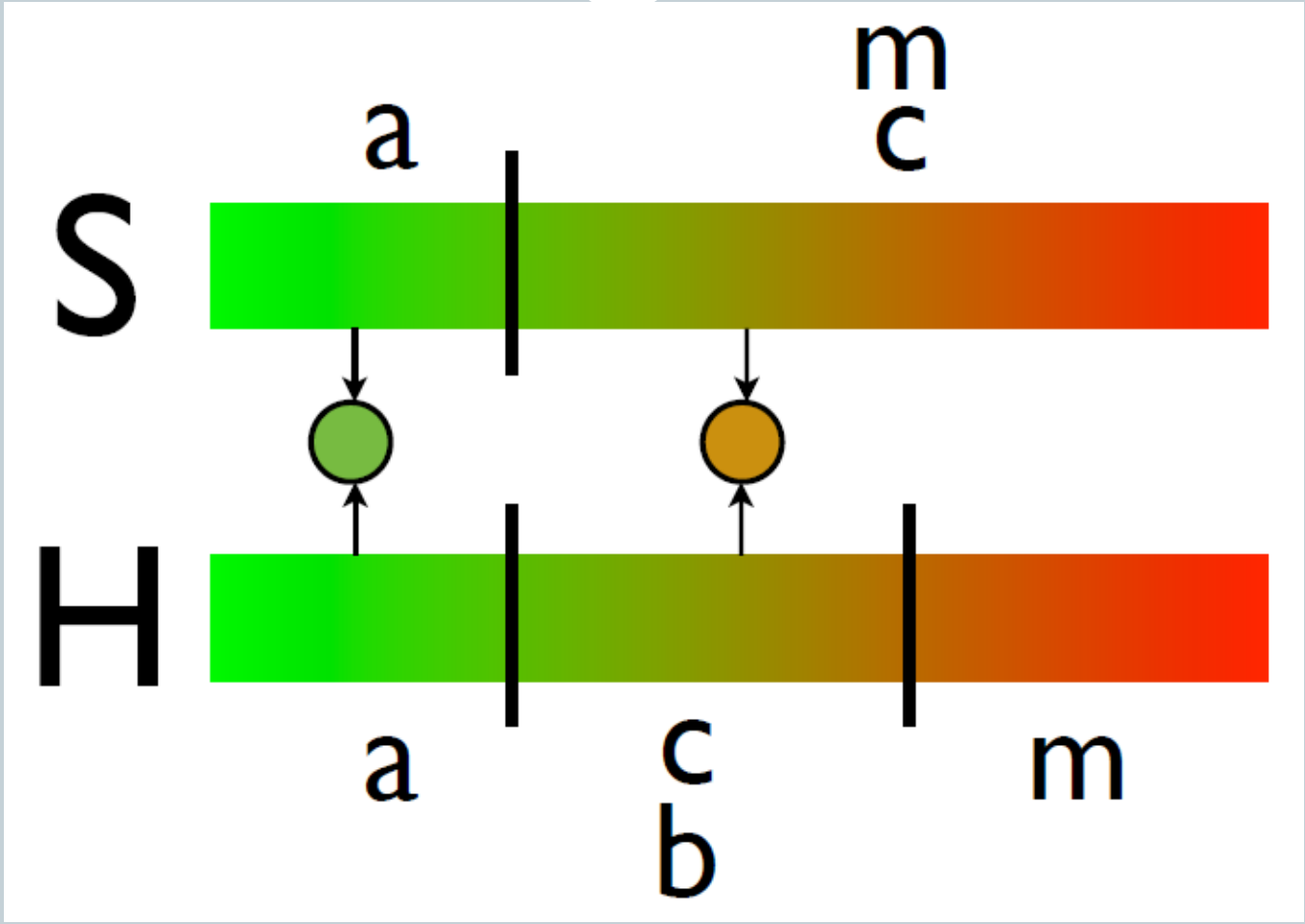
Failure in Communication



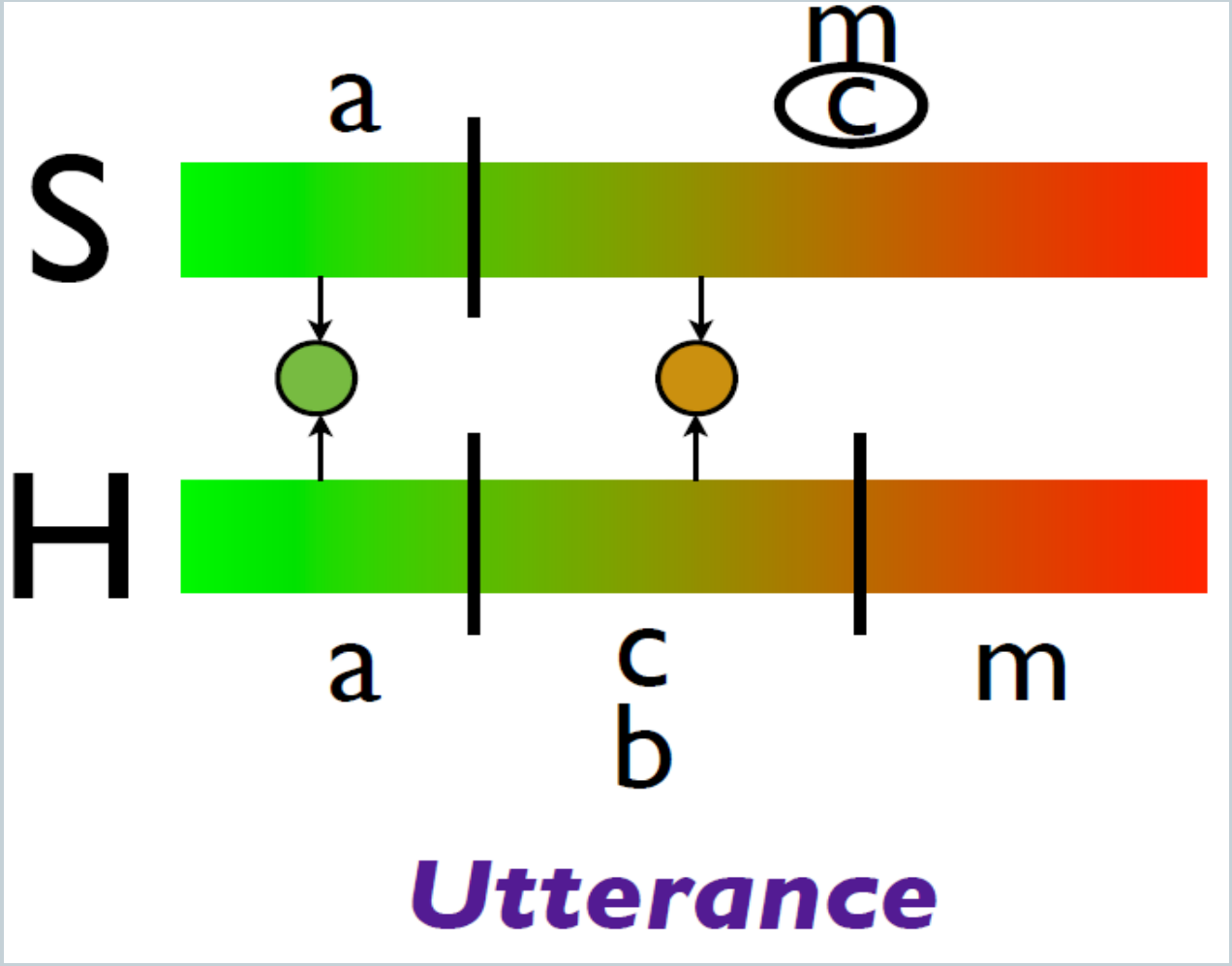
Other side of the coin



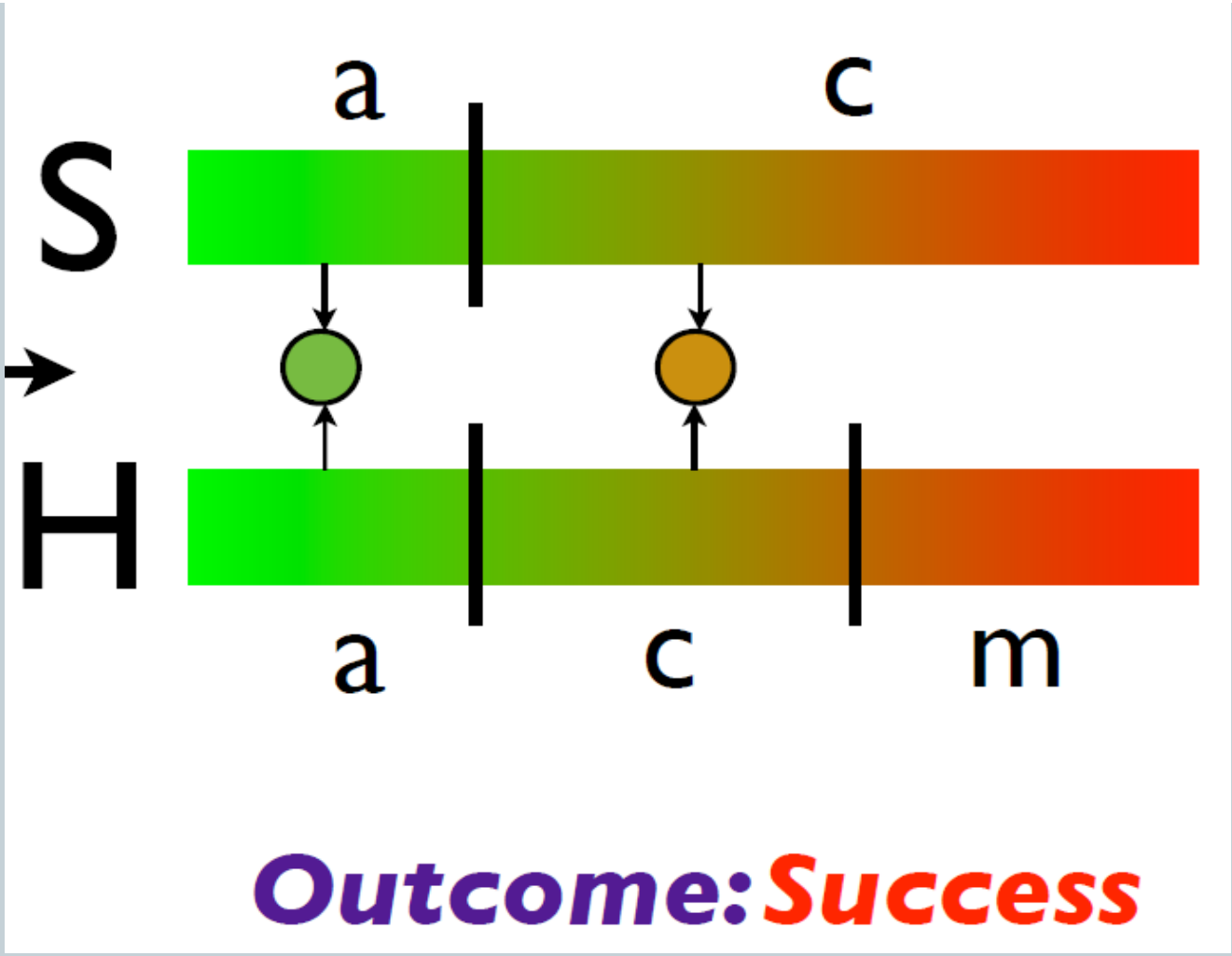
State of the agents



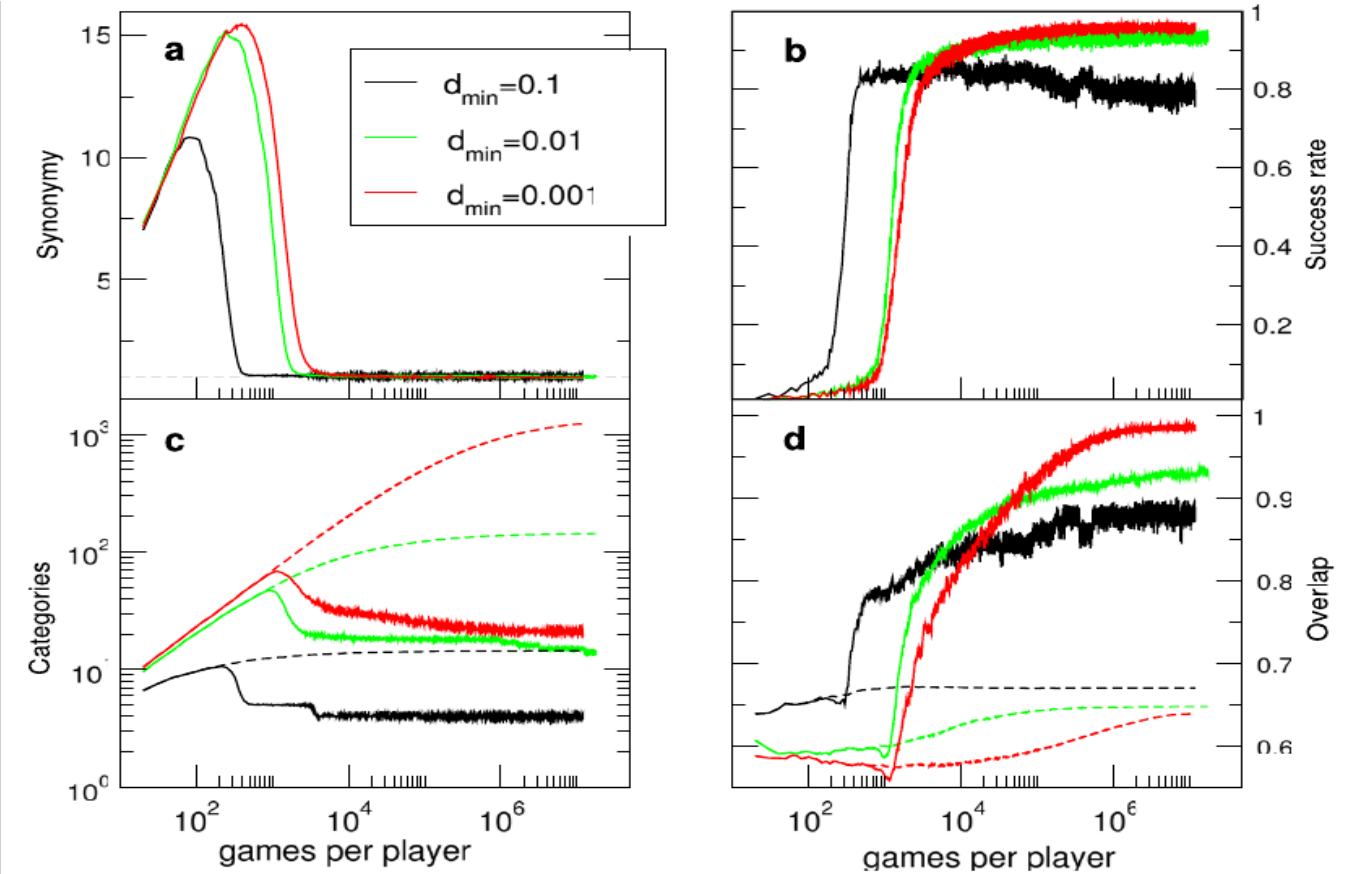
Word Selection



Successful Communication



Phenomenology



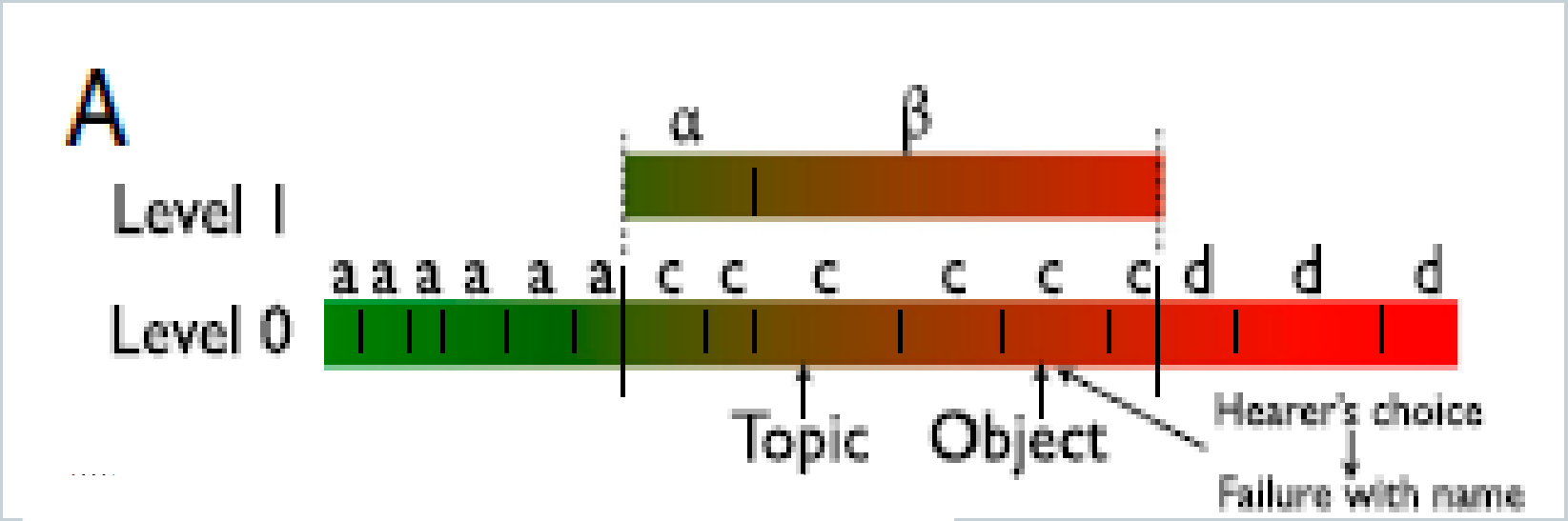
---- perceptual category

—— linguistic category

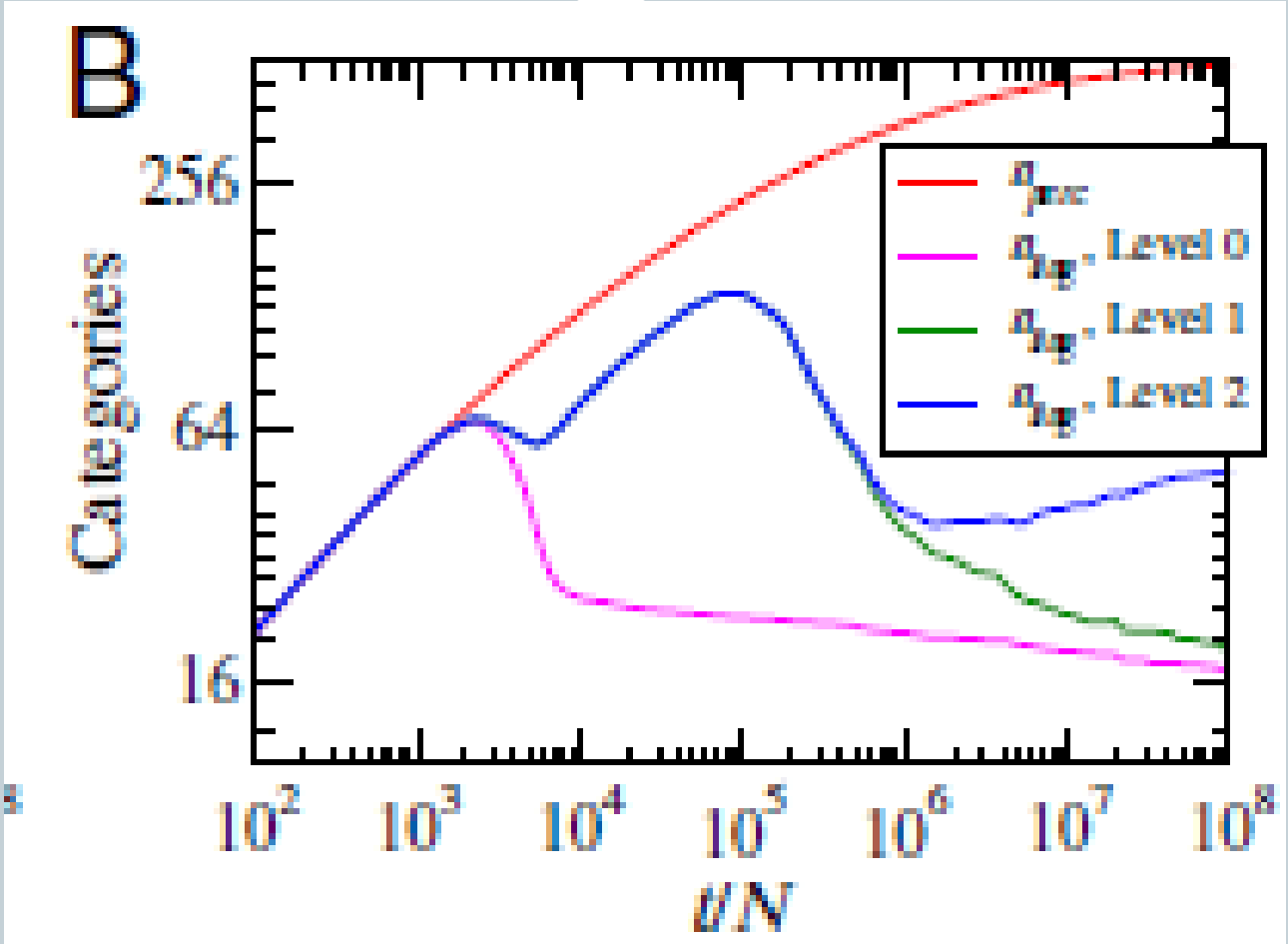
Puglisi et al., PNAS, 2008

Multi-level hierarchy

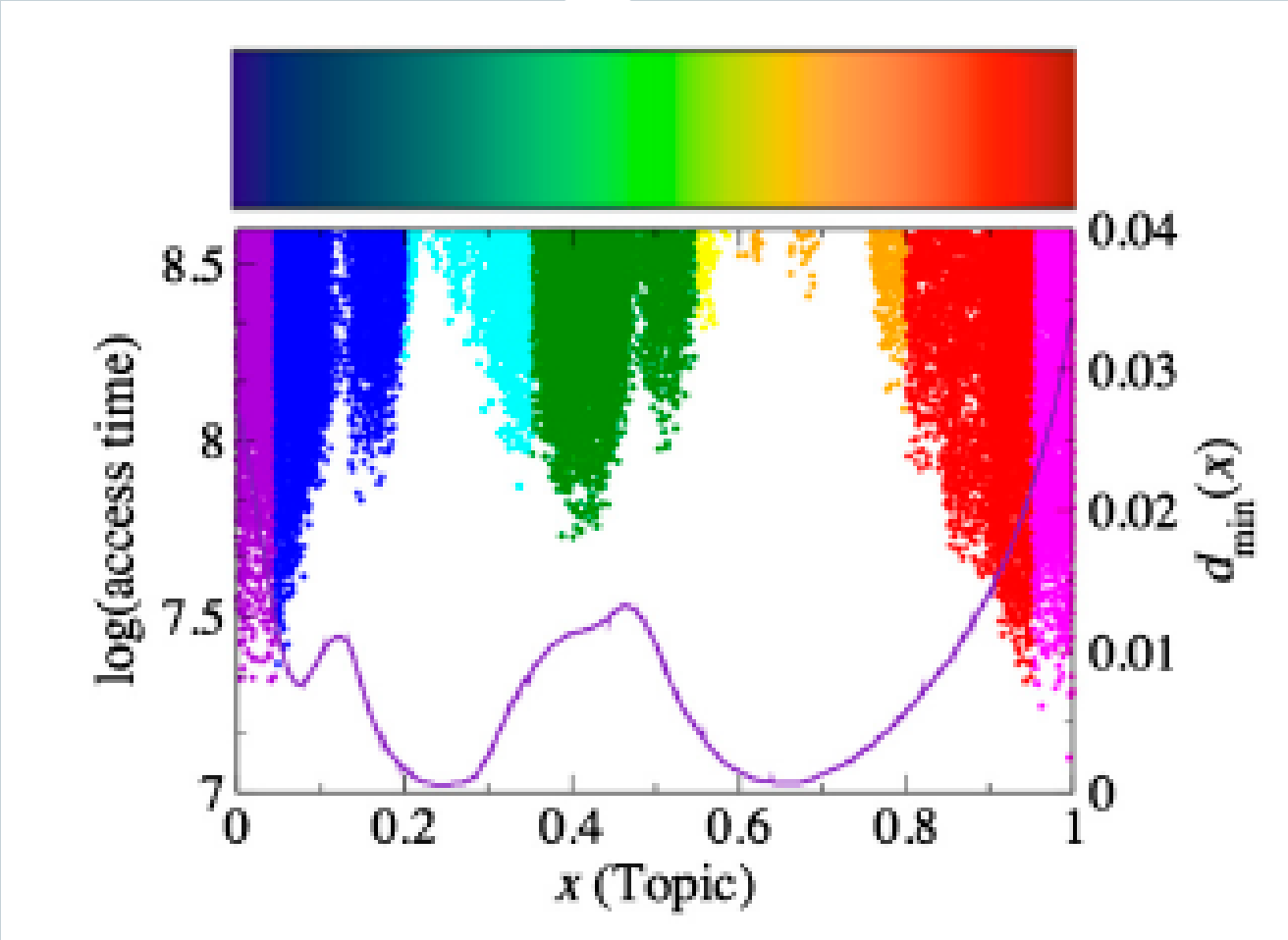
- Failure with name → Failure due to confusion → Create a new level → A more complex reference for the corresponding region



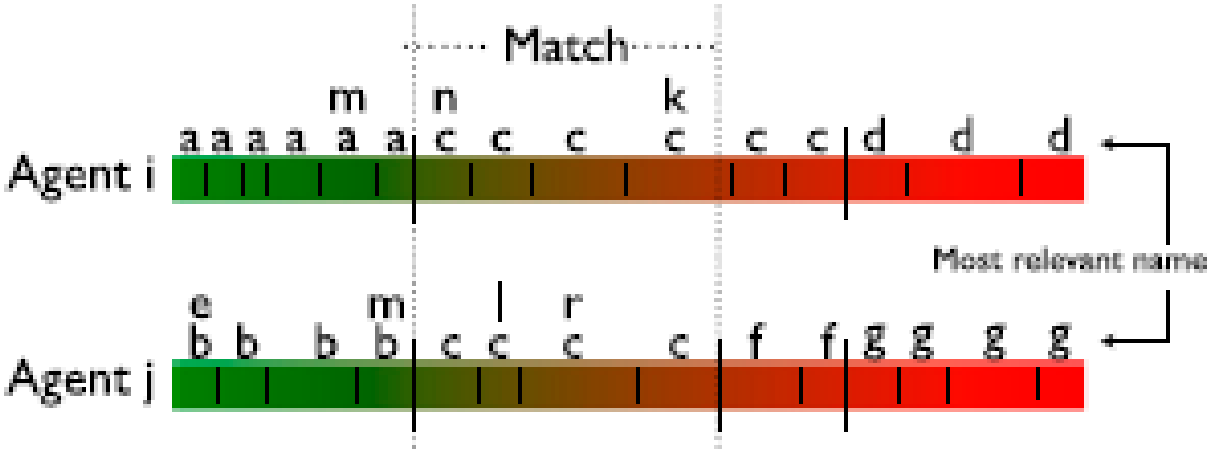
Multi-level Categories



Frequency of higher level access

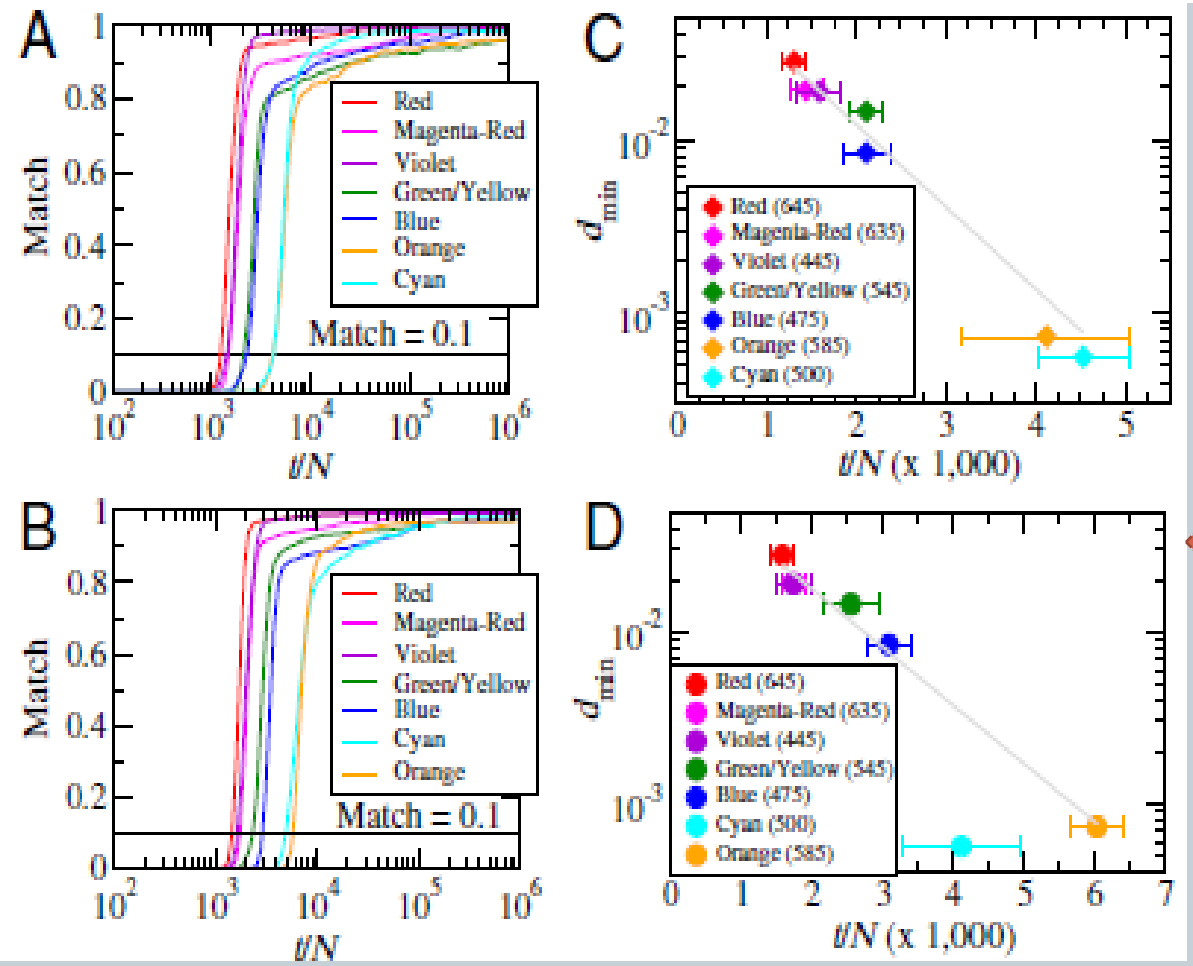


Measuring agreement



$$\frac{2\sum_{i=1}^{N}\sum_{j=i+1}^{N}\text{match}(i,j)}{N(N-1)}.$$

Emergence of color hierarchy



[white, black] < [red] < [green, yellow] < [blue] < [brown] < [purple, pink, orange, gray]

Loreto, Mukherjee and Tria, On the origin of the hierarchy of color names, *PNAS* May 1, 2012 vol. 109 no. 18 6819-6824

Thank You