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

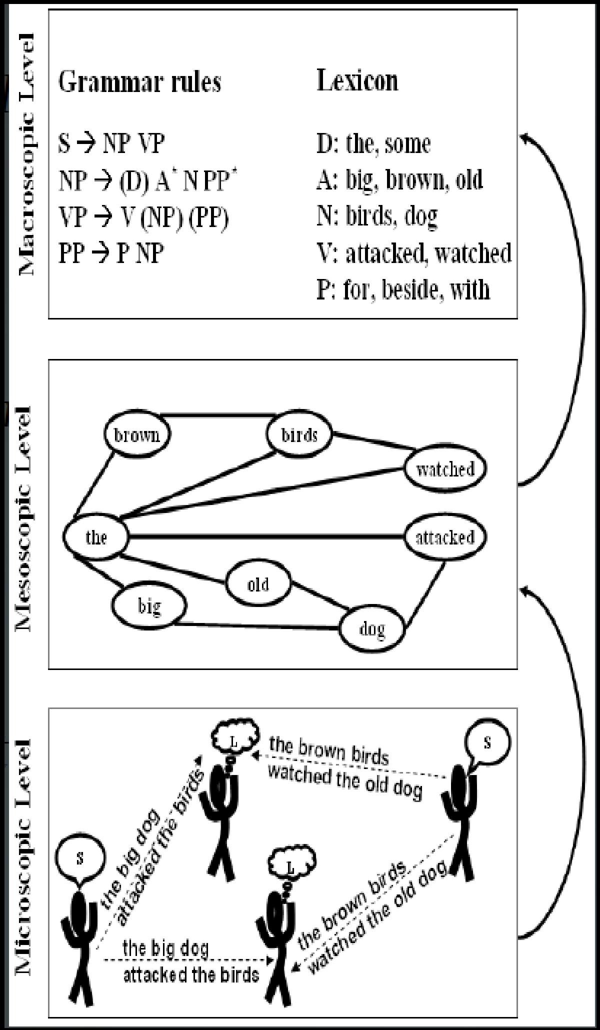
Language as a whole (grammatical constructs)

↓

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)

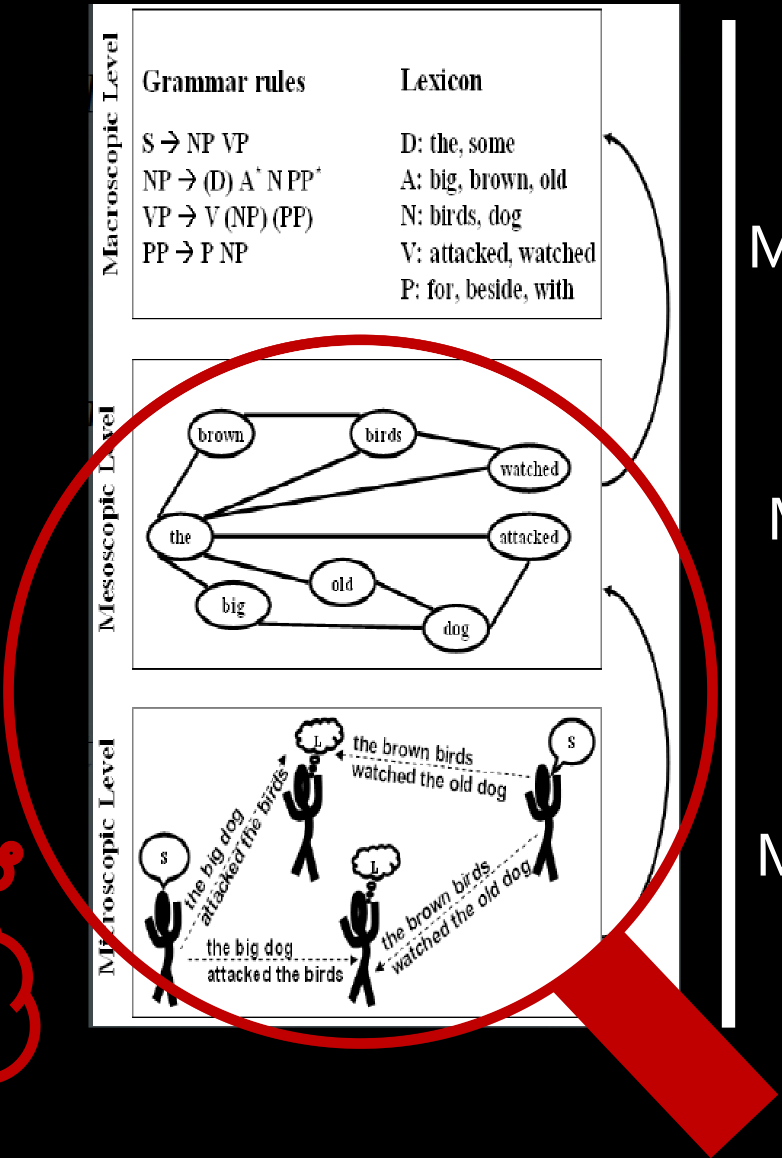
↓

Language as a collection of interactions among linguistic units

↓

Language as a collection of utterances

dynamic



Macroscopic level

↓

Mesoscopic level

↓

Microscopic level

Names for meanings

SPAM !

Names for meanings

SPAM !

Spiced HAM

Monty Python's spam comedy (1970 TV show)

All the customers are Vikings. Mr. and Mrs. Bun enter

Mr. Bun: What have you got, then?

Waitress: Well, there's egg and bacon; egg, sausage, and bacon; 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, SPAM, SPAM, SPAM, 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, and sausage?

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

Mr. Bun: Not as much as SPAM

, egg, sausage, and SPAM.

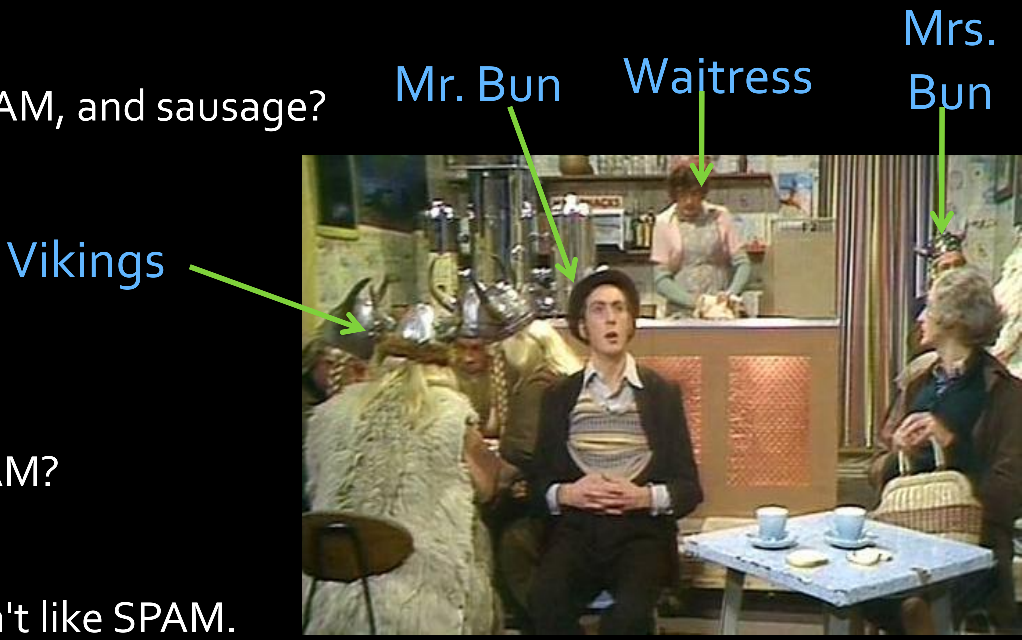
Mrs. Bun: Look, could I have egg,

bacon, SPAM, and sausage without the SPAM?

Waitress: Uuuuuuuuggggh!

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....



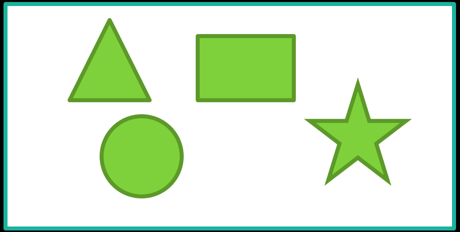
How do we associate names to objects ((e-)spam to spam)?

↓

The Naming Game

The “Talking Heads” Experiment

Speaker



Hearer

- Perceive scene
- Choose topic
- Conceptualize
- Verbalize

interpret utterance

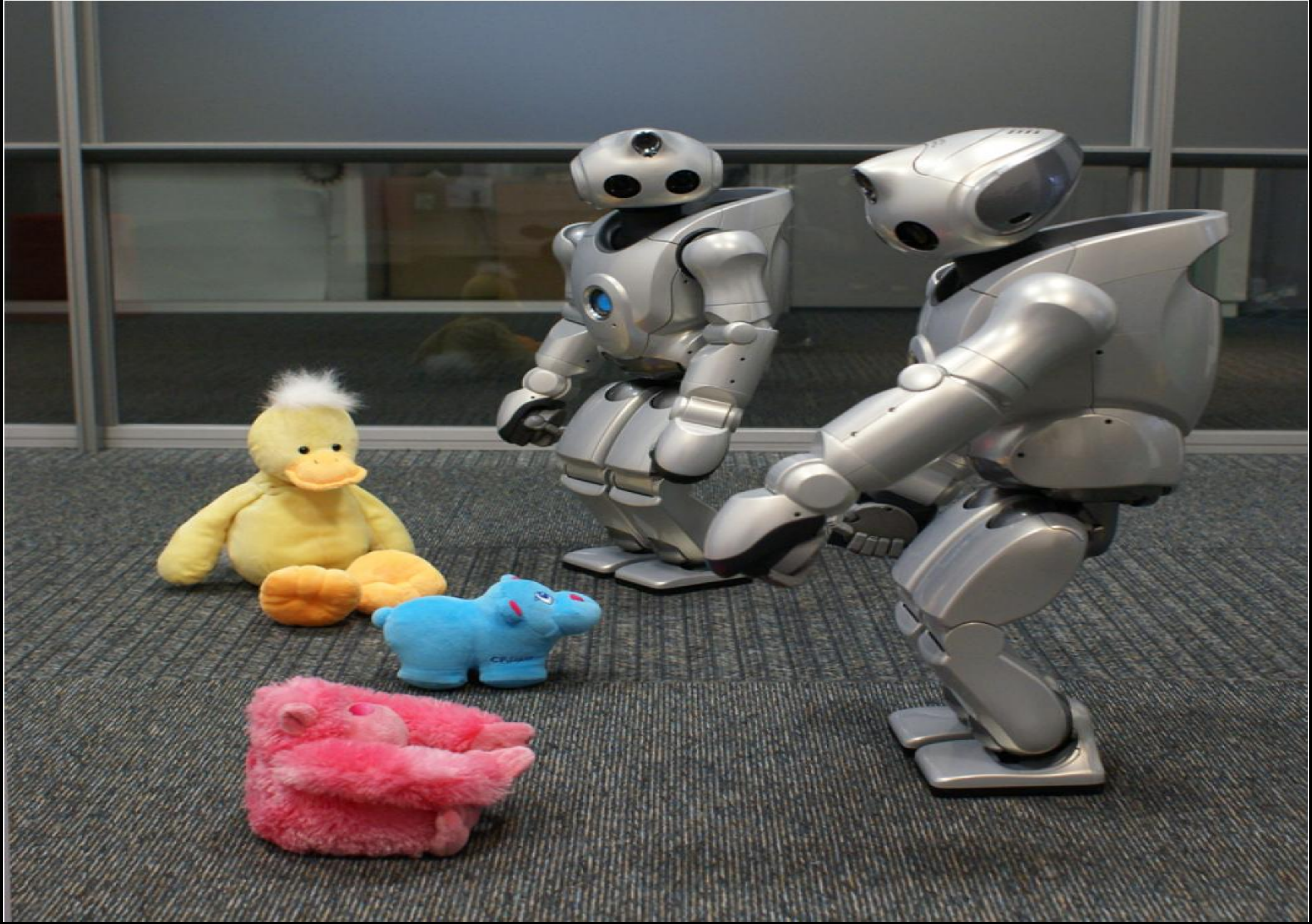
perceive scene

apply meaning

point to referent

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

The Grounded Naming Game



Bleys et al.

Minimal Naming Game

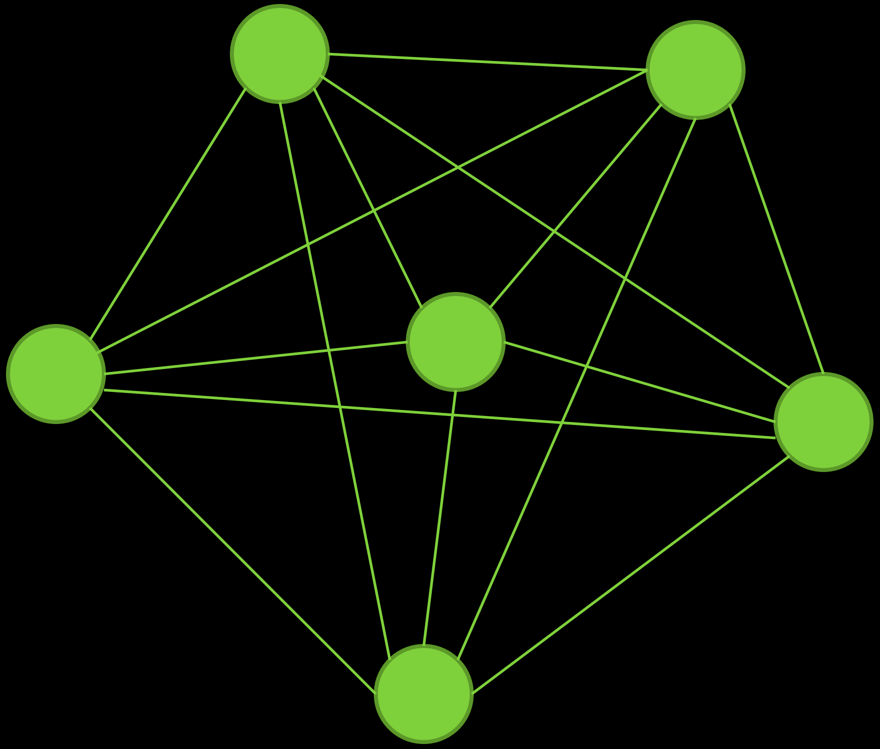
Interactions of N agents who communicate on how to associate a name to a given object

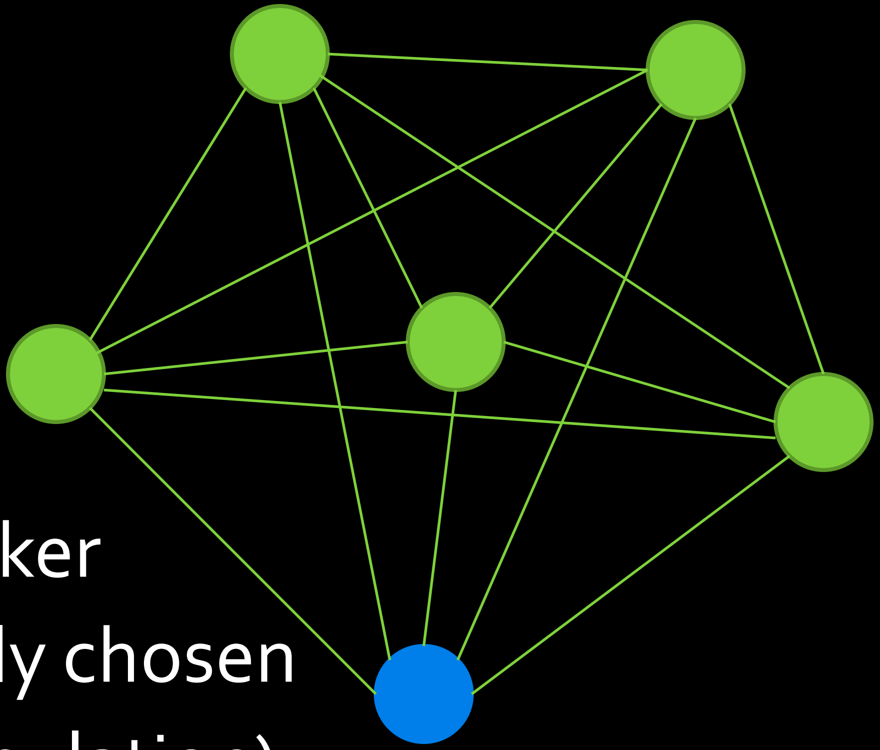
Agents:

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

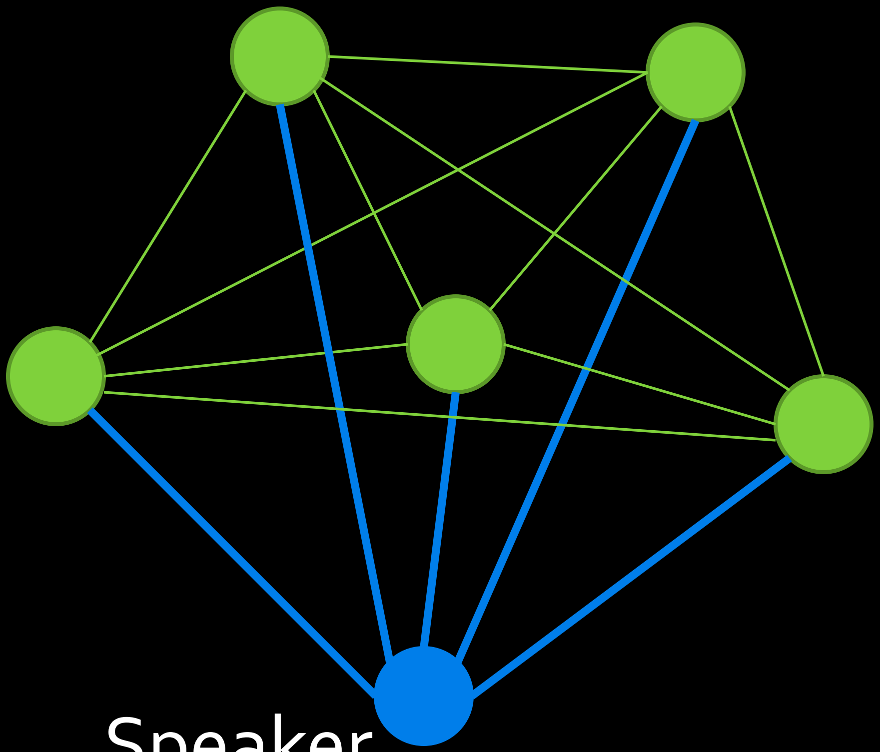
Baronchelli et. al (2006)

Minimal NG on fully-connected network

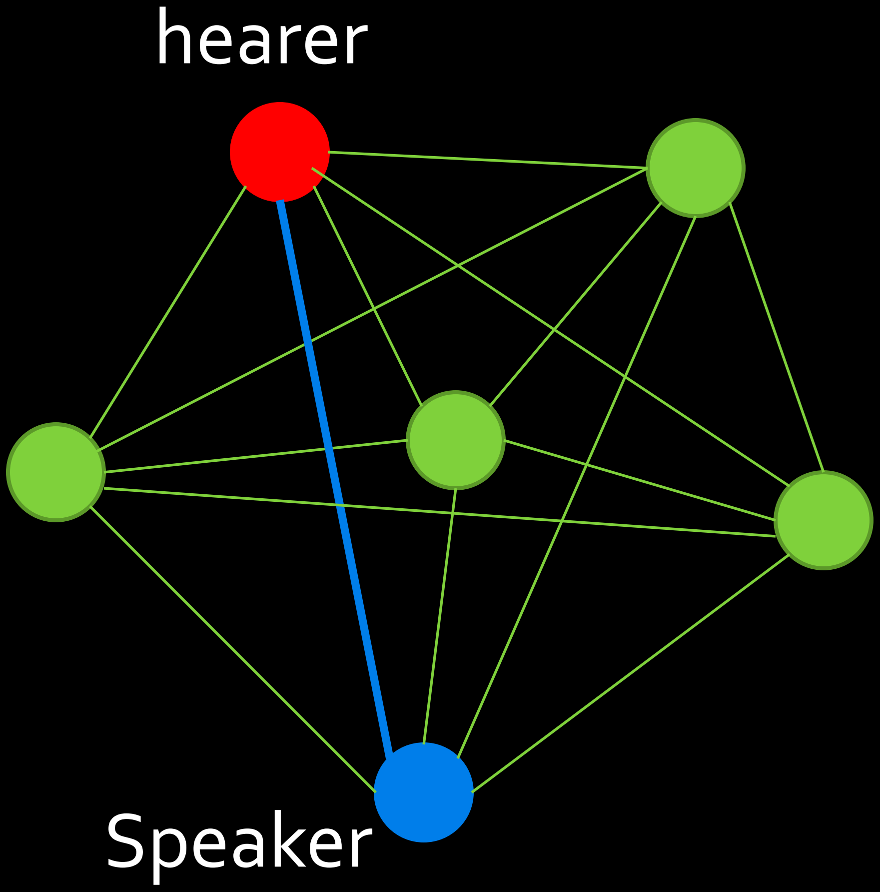




Speaker
(randomly chosen
From population)



Speaker


hearer
Speaker

Speaker

Bottle
Apple
Tiger
Car

Hearer

Bag
Blackberry
Tree

Speaker

Bottle

Apple

Tiger

Car

Hearer

Bag

Blackberry

Tree

randomly chosen from speaker's inventory

Speaker

Bottle
Apple
Tiger
Car

Searched in hearer’s inventory

Hearer

Bag
Blackberry
Tree

Not Found!!

Speaker

Bottle

Apple

Tiger

Car

Failure !

Hearer

Bag

Blackberry

Tree

Speaker

- Bottle
- **Apple**
- Tiger
- Car

Hearer

- Bag
- Blackberry
- Tree
- **Apple**

Add the word

Speaker

Bottle
Apple
Tiger
Car

randomly chosen from speaker's inventory

Hearer

Bag
Apple
Tree

Speaker

Bottle

Apple

Tiger

Car

Hearer has it in its inventory

Hearer

Bag

Apple

Tree

Speaker

- Bottle
- **Apple**
- Tiger
- Car

Success

Hearer

- Bag
- **Apple**
- Tree

Speaker

Apple

Hearer

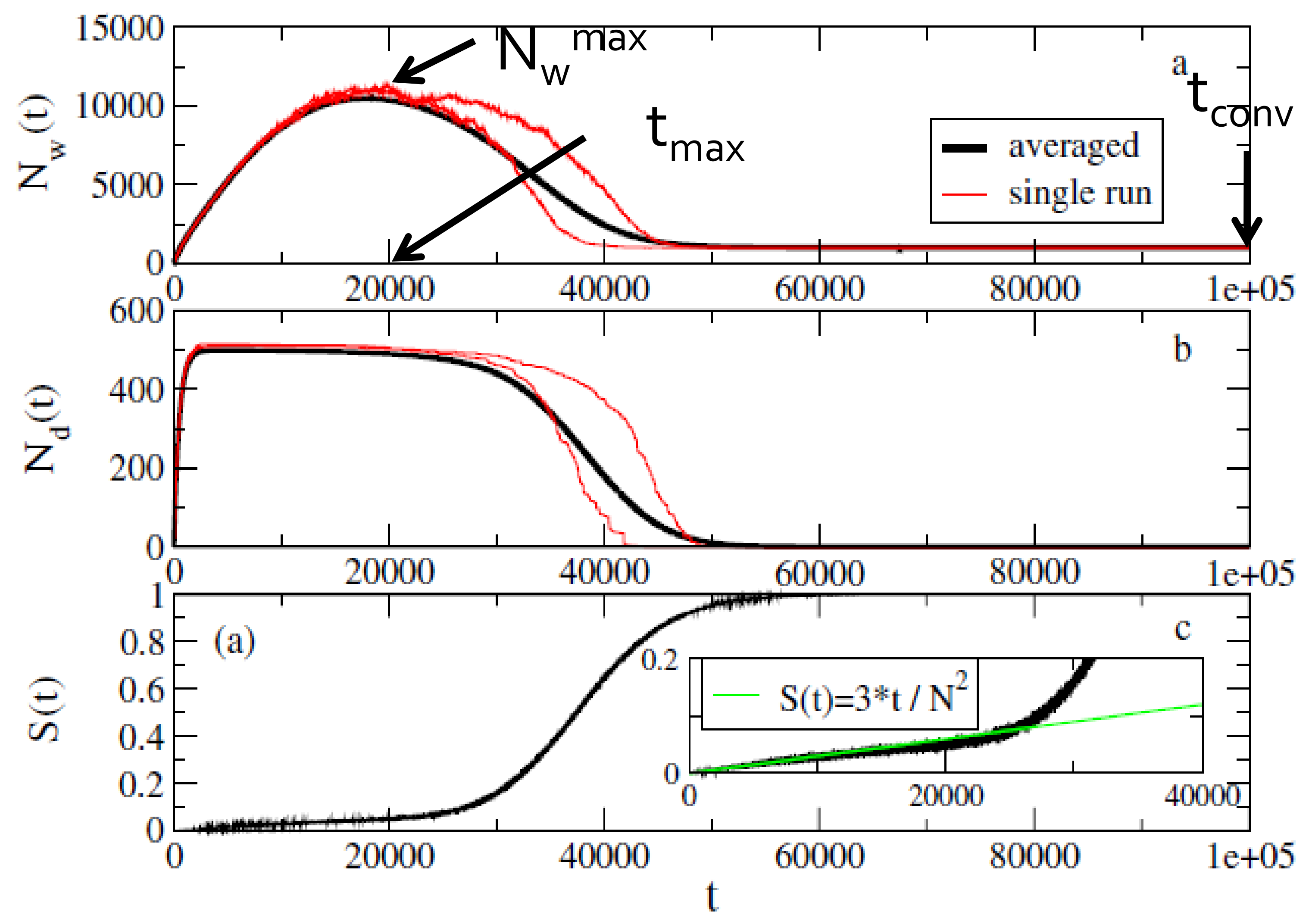
Apple

Retain only the successful word

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 (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)

$$\frac{dN_w(t)}{dt} \propto \underbrace{\frac{1}{cN^a}\left(1 - \frac{2cN^a}{N}\right)}_{\text{Unsuccessful interaction}} - \underbrace{\frac{1}{cN^a}\frac{2cN^a}{N}2cN^a}_{\text{Successful interaction}}$$

Scaling Relations

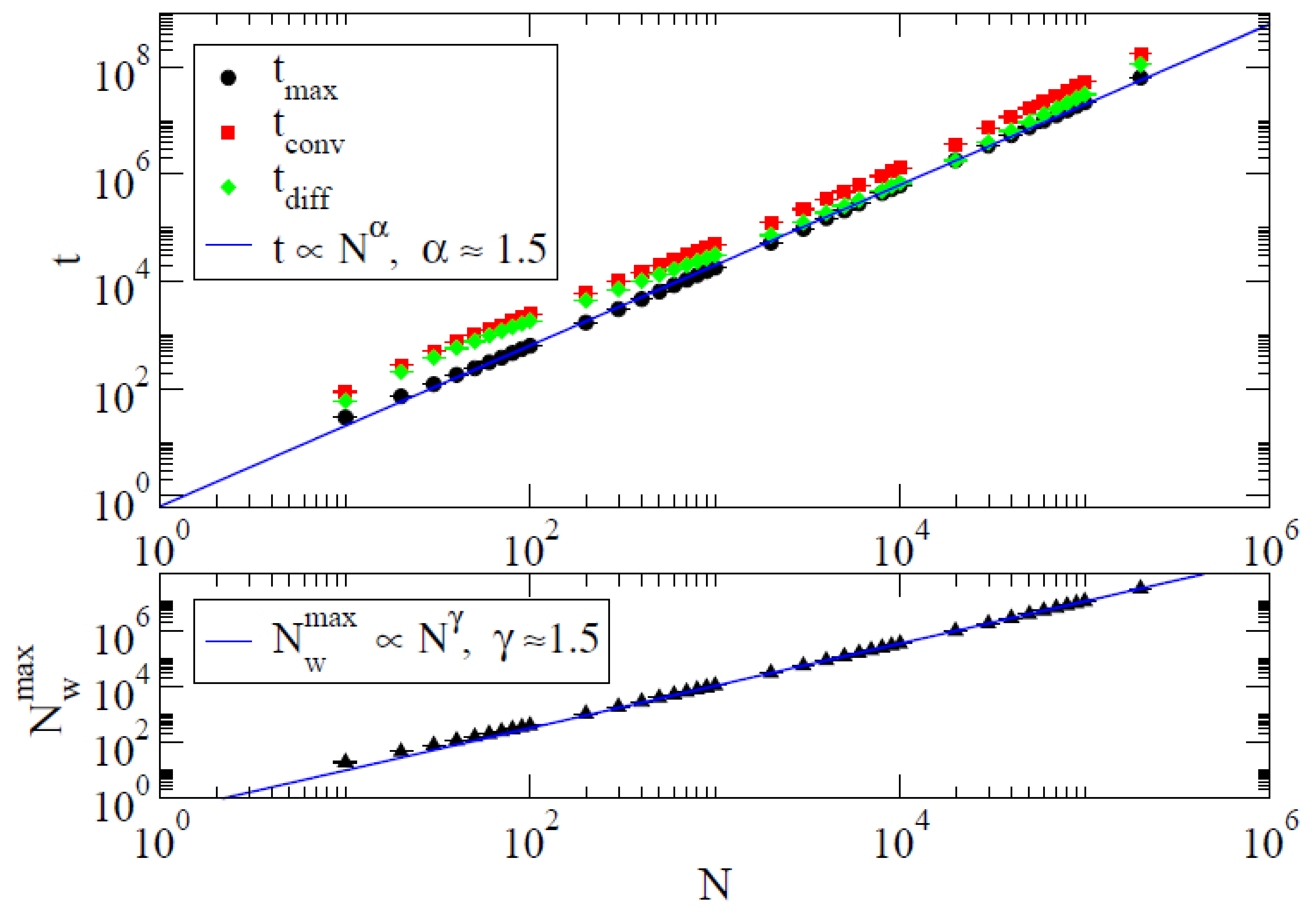
- At the maximum, $dN_w(t_{max})/dt = 0$
- only possible value for exponent α is $\alpha = 1/2$
- So, $N_w^{max} \sim N^{3/2}$

- 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. (2008)

Another extreme case: agents on regular lattices

Local consensus is reached very quickly through repeated interactions. (few neighbors)

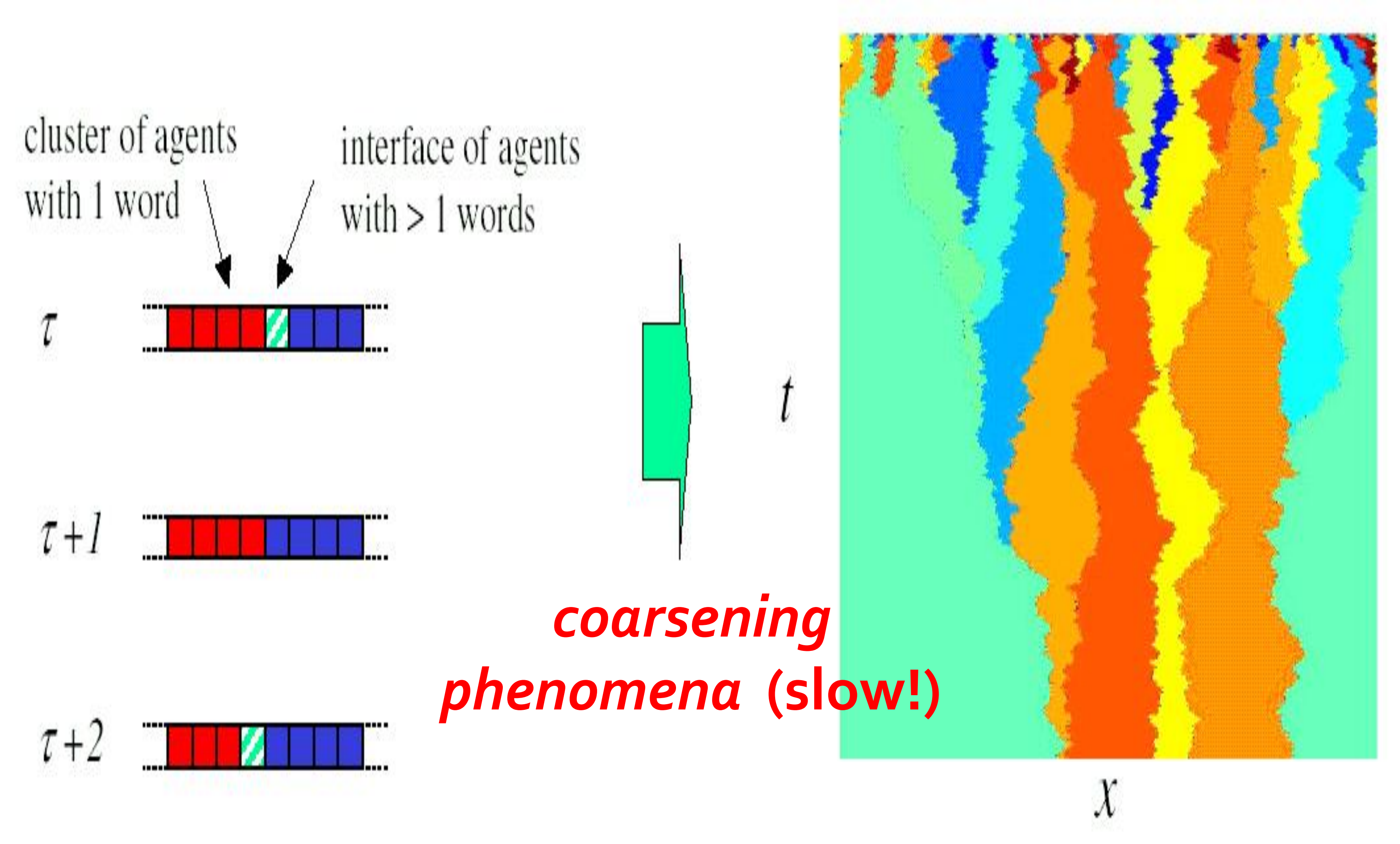
Then:

- clusters of agents with the same unique word start to grow,

- at the interfaces series of successful and unsuccessful interactions take place.

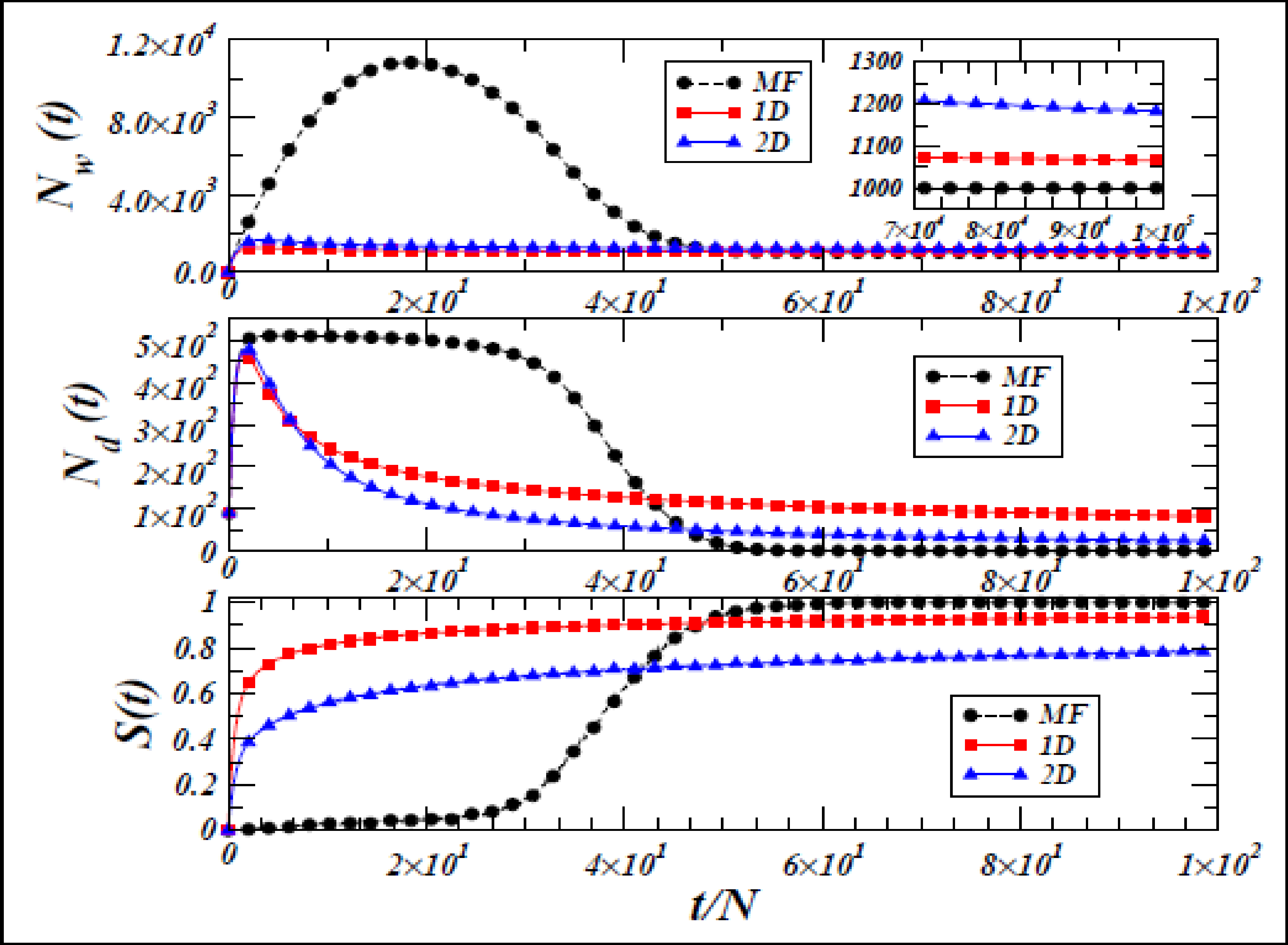
Baronchelli et al., PRE **73** (2006) 015102(R)

Another extreme case: agents on regular lattices



coarsening phenomena **(slow!)**

Agents on regular lattices



Regular lattice: dependence on system size N

- Memory peak

$N_{max}^{w} \sim N$

$t_{max} \sim N$

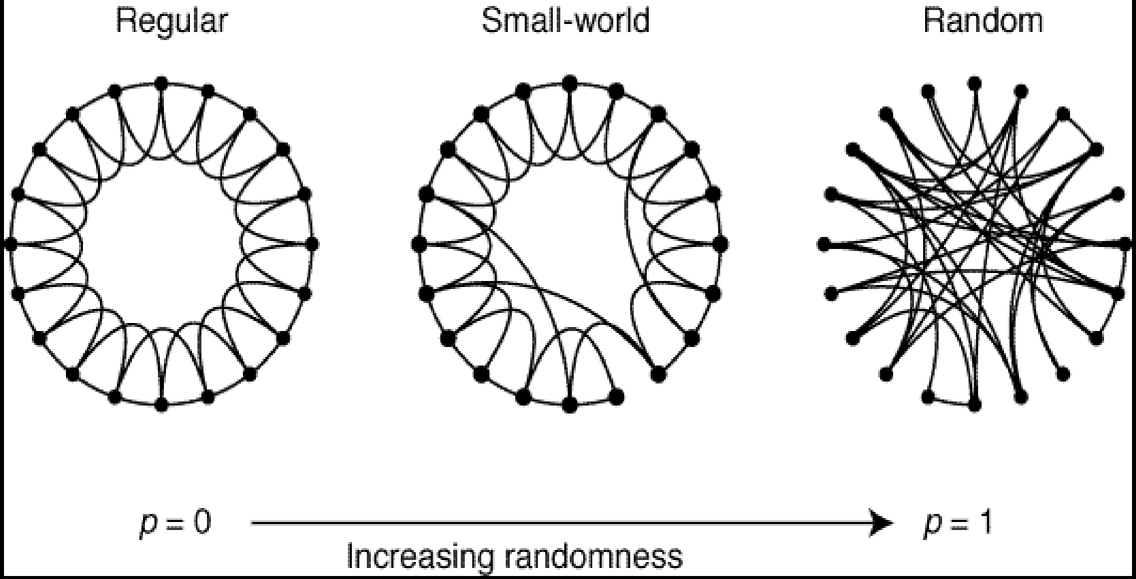
average maximum memory per agent: finite!

- Convergence time: $t_{conv} \sim N^3$

=> Slow process!

(in d dimensions $\sim N^{1+2/d}$)

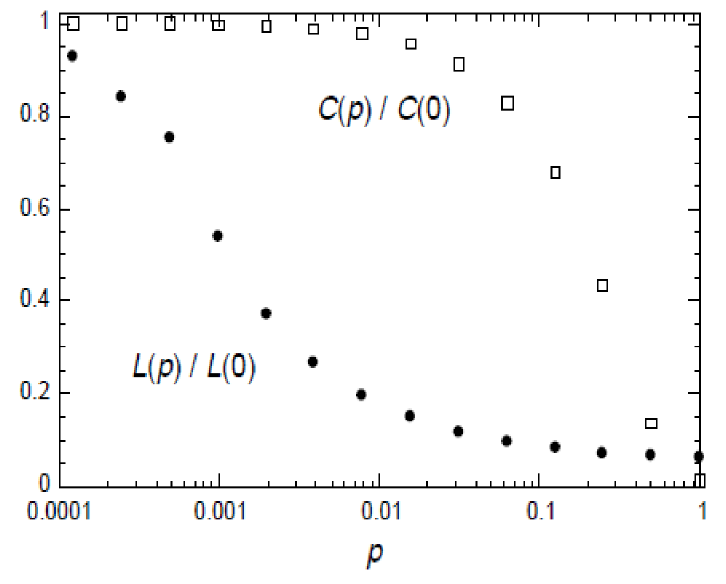
Small-world



N nodes forms a regular lattice. With probability p, each edge is rewired randomly

=>Shortcuts

N = 1000

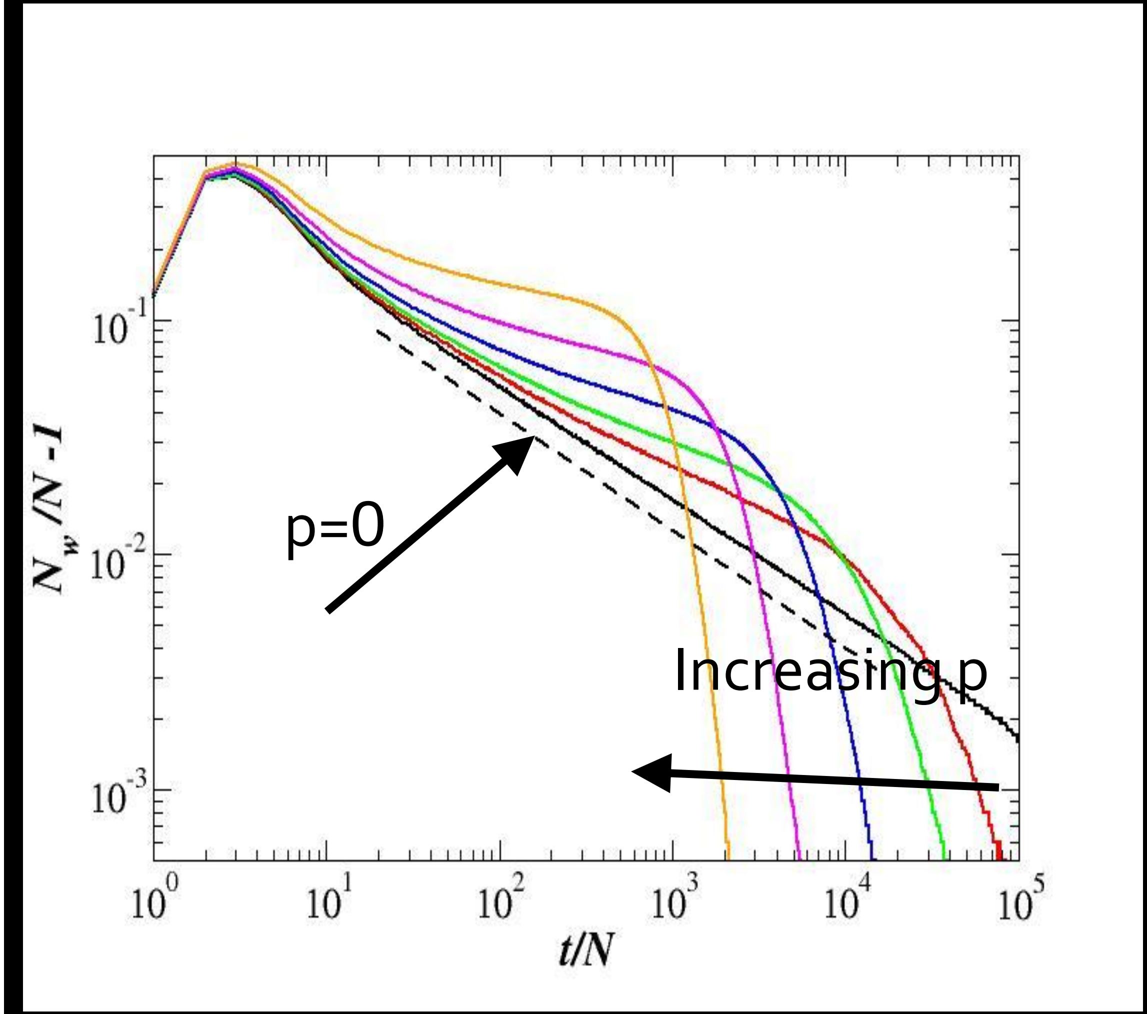


- Large clustering coeff.
- Short typical path

Watts & Strogatz,

Nature **393**, 440 (1998)

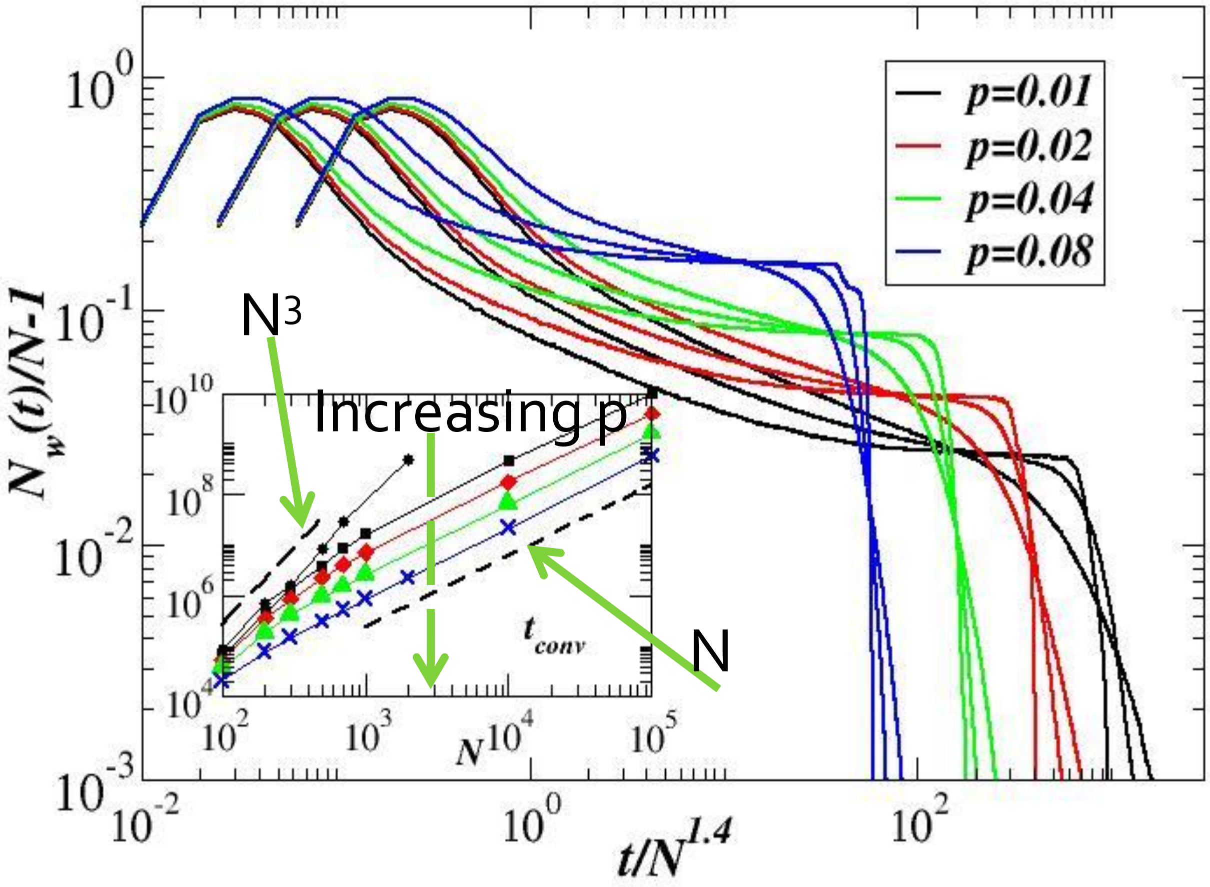
Naming Game on a Small-world



p=0 : linear chain

p~1/N :Small world

Naming Game on a small-world



N^3

Increasing p

N

Maximum memory ~ N

Convergence time ~$N^{1.4}$

	Complete graph	dimension 1	small-world
maximum memory	**$N^{1.5}$**	N	**N**
convergence time	$N^{1.5}$	**N^3**	**$N^{1.4}$**

Better not to have all-to-all communication, nor a too regular network structure

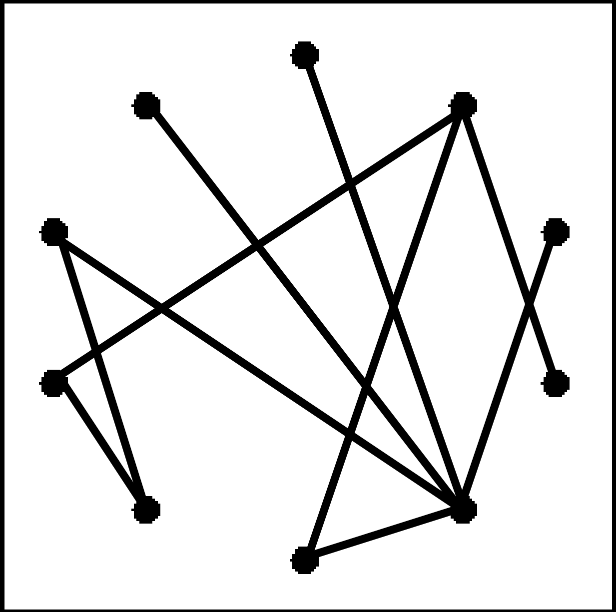
What about other types of networks ?

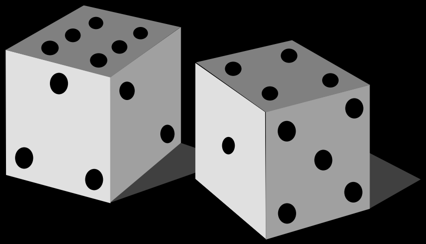
Networks: Homogeneous and Heterogeneous

1.Usual random graphs: Erdös-Renyi model (1960)

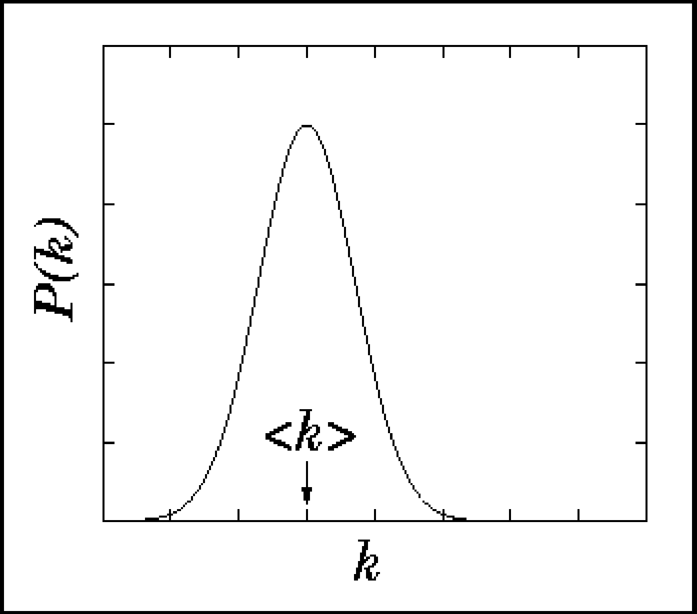
N points, links with probability p: static random graphs

Poisson distribution





(p=O(1/N))



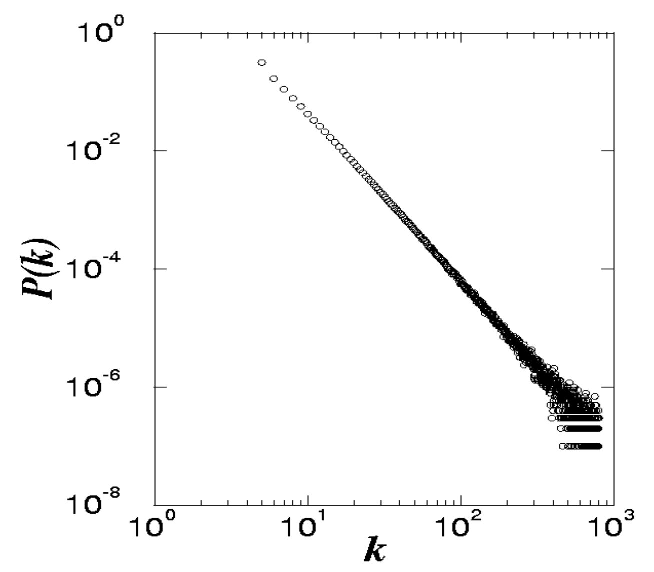
Networks: Homogeneous and Heterogeneous

2.Scale-free graphs: Barabasi-Albert (BA) model

(1) GROWTH : At every timestep we add a new node with *m* edges (connected to the nodes already present in the system).

(2) PREFERENTIAL ATTACHMENT : The probability **Π** that a new node will be connected to node *i* depends on the connectivity k_i of that node

$$\Pi(k_i) = k_i/\Sigma_j k_j$$



A.-L.Barabási, R. Albert, Science 286, 509 (1999)

NG on heterogeneous networks

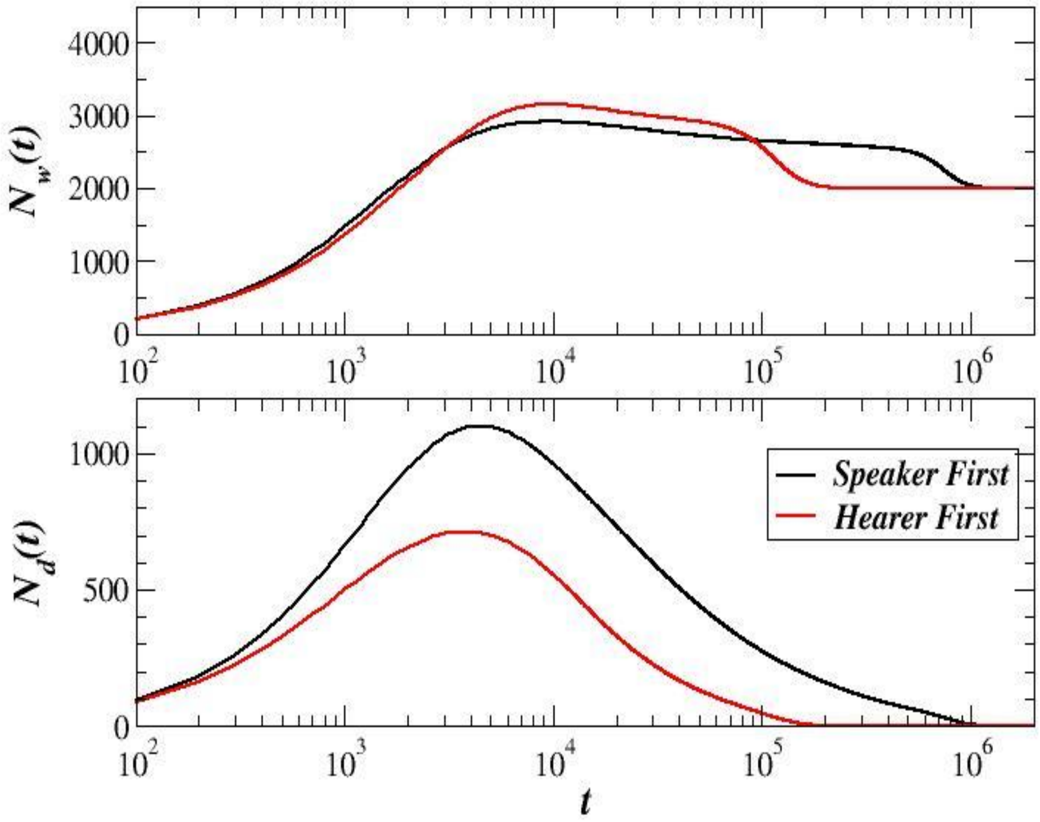
Pair selection strategies:

- select first a speaker i and **then a hearer** among i's neighbors
- select first a hearer i and **then a speaker** among i's neighbors
- select an edge at random and its two extremities at random as hearer and speaker

can be important in heterogeneous networks because:
-a randomly chosen node has typically small degree
-the neighbor of a randomly chosen node has typically large degree

NG on heterogeneous networks

agents on a BA network

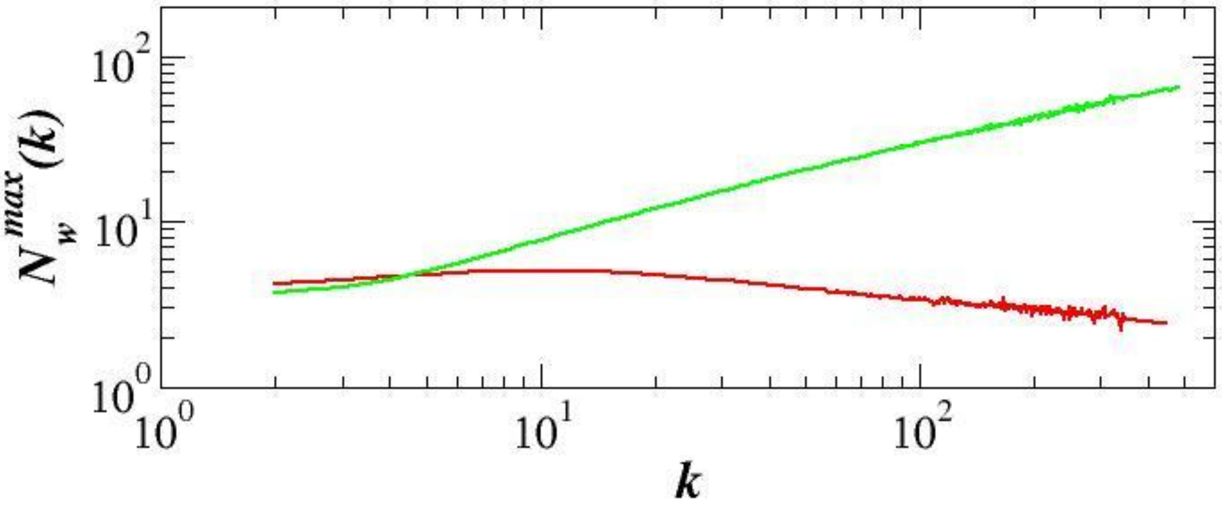


Different behaviours

↓

shows the importance
of understanding the rol
of the hubs!

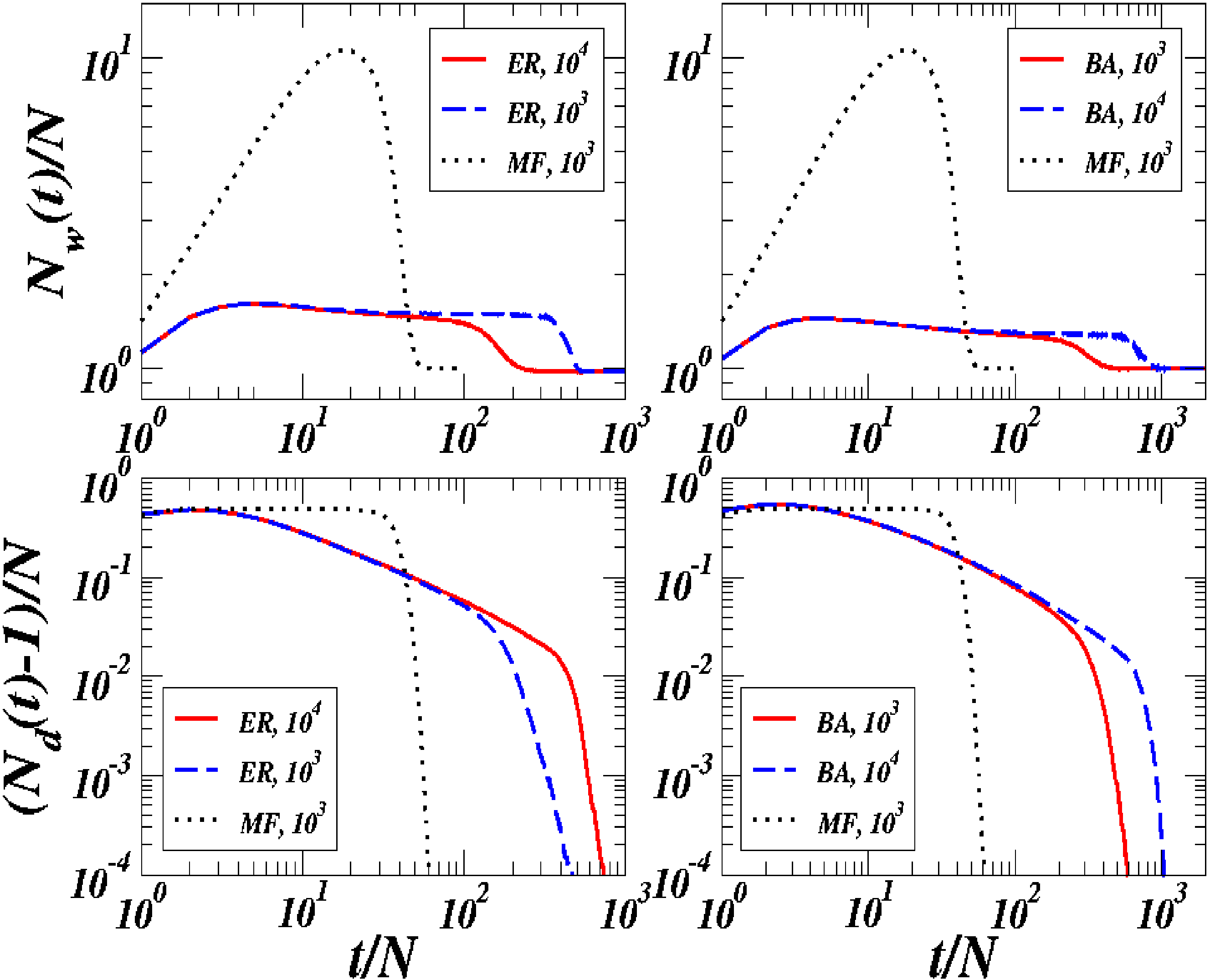
NG on heterogeneous networks



Speaker first: hubs accumulate more words

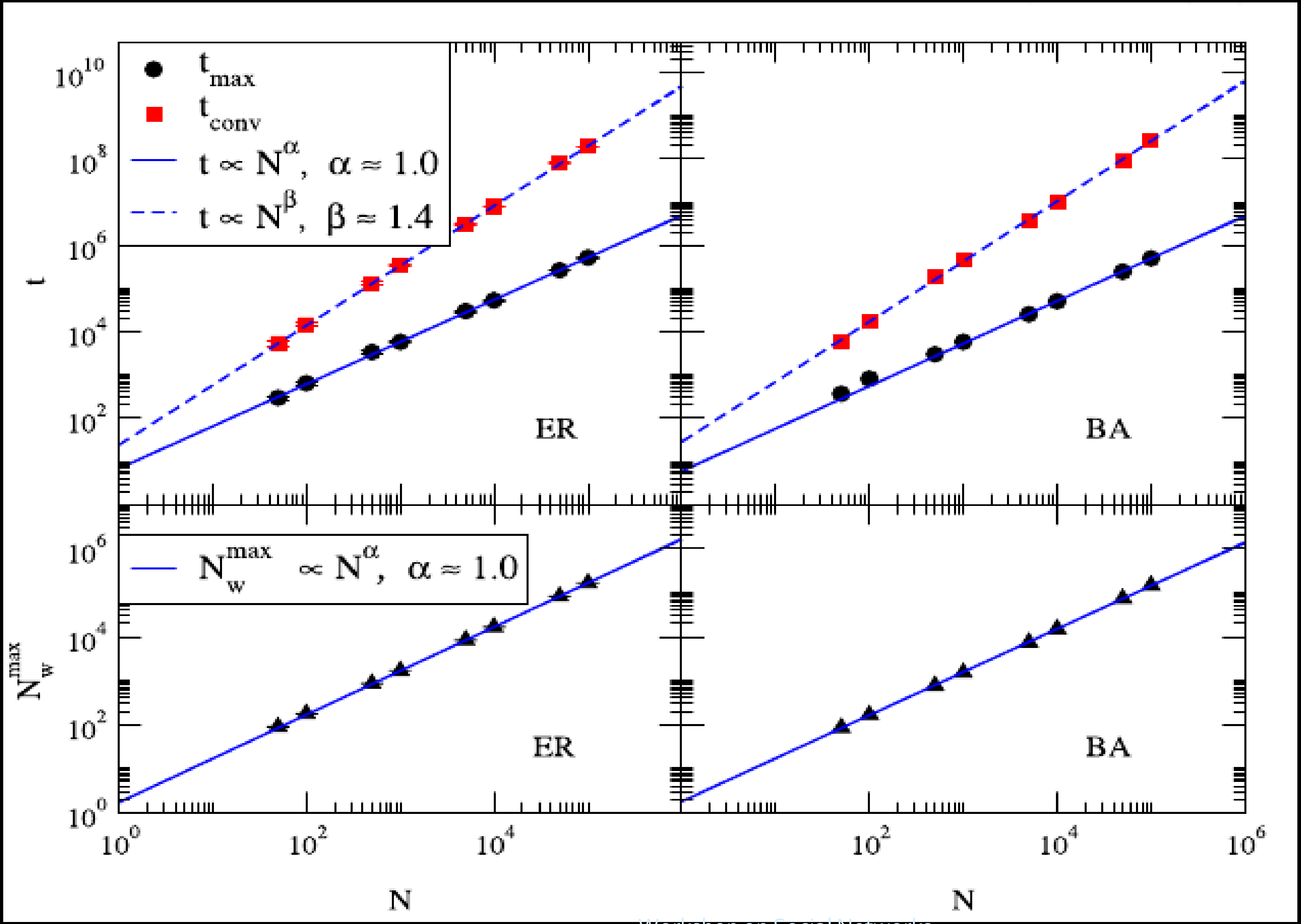
Hearer first: hubs have less words and “polarize” the system, hence a faster dynamics

NG on homogeneous and heterogeneous networks



- ➢Long reorganization phase with creation of correlations, at almost constant N_w and decreasing N_d
- ➢similar behaviour for BA and ER networks

Scaling on BA and ER networks



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

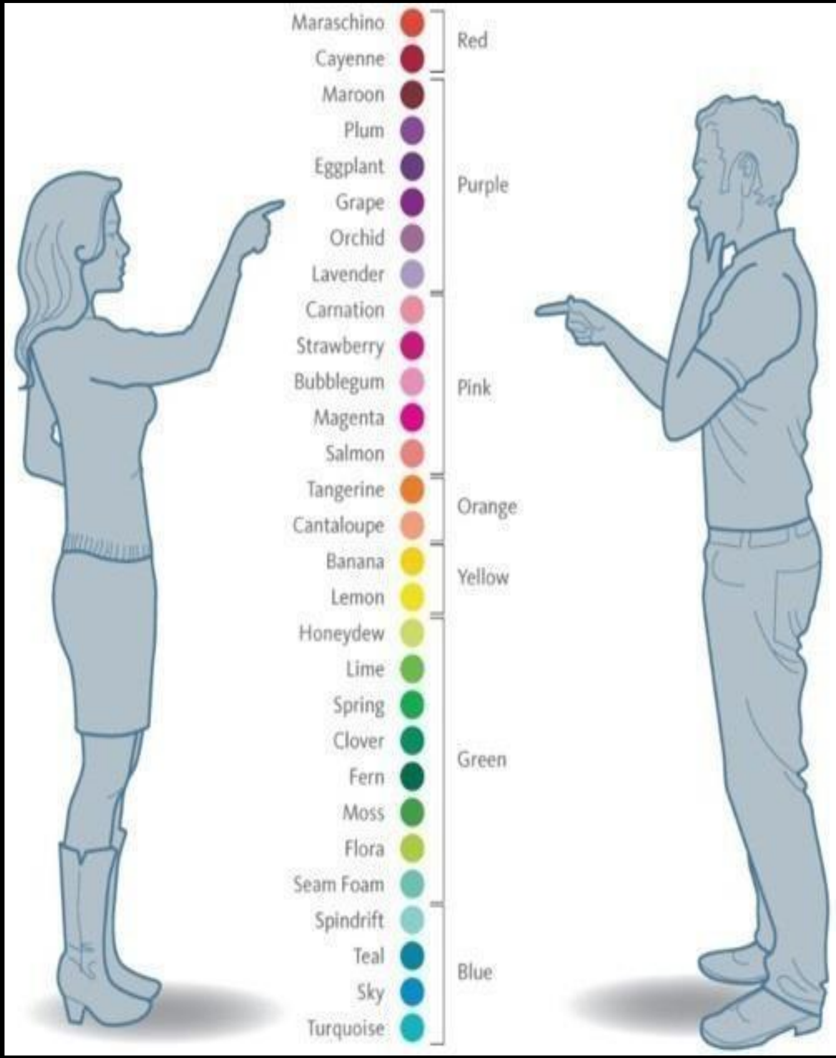
- Emergence of categorization from scratch without any pre-existing categorization in a group of individuals who interact in a pairwise way without any central coordination

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)]

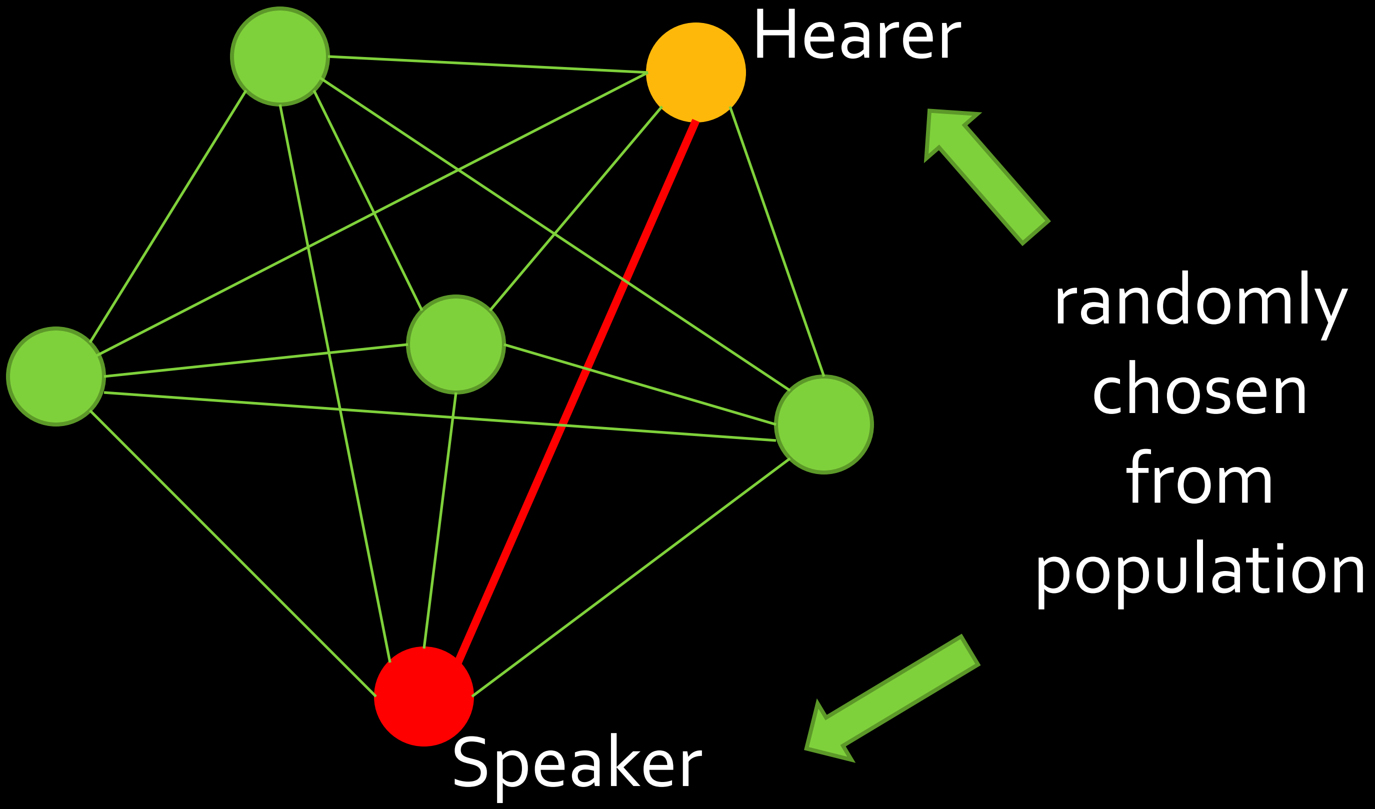


Motivation

- The World Color Survey(WCS)
  - ➢ color systems across language are not random
  - ➢ rather exhibit certain statistical regularities

- CG is able to reproduce qualitatively and quantitatively the empirical data gathered in the WCS

The CG Model



Hearer

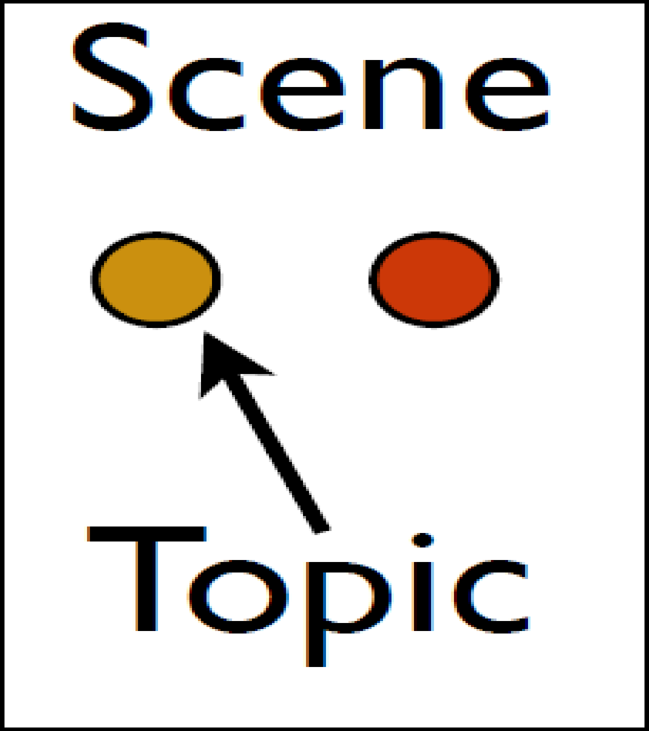
randomly chosen from population

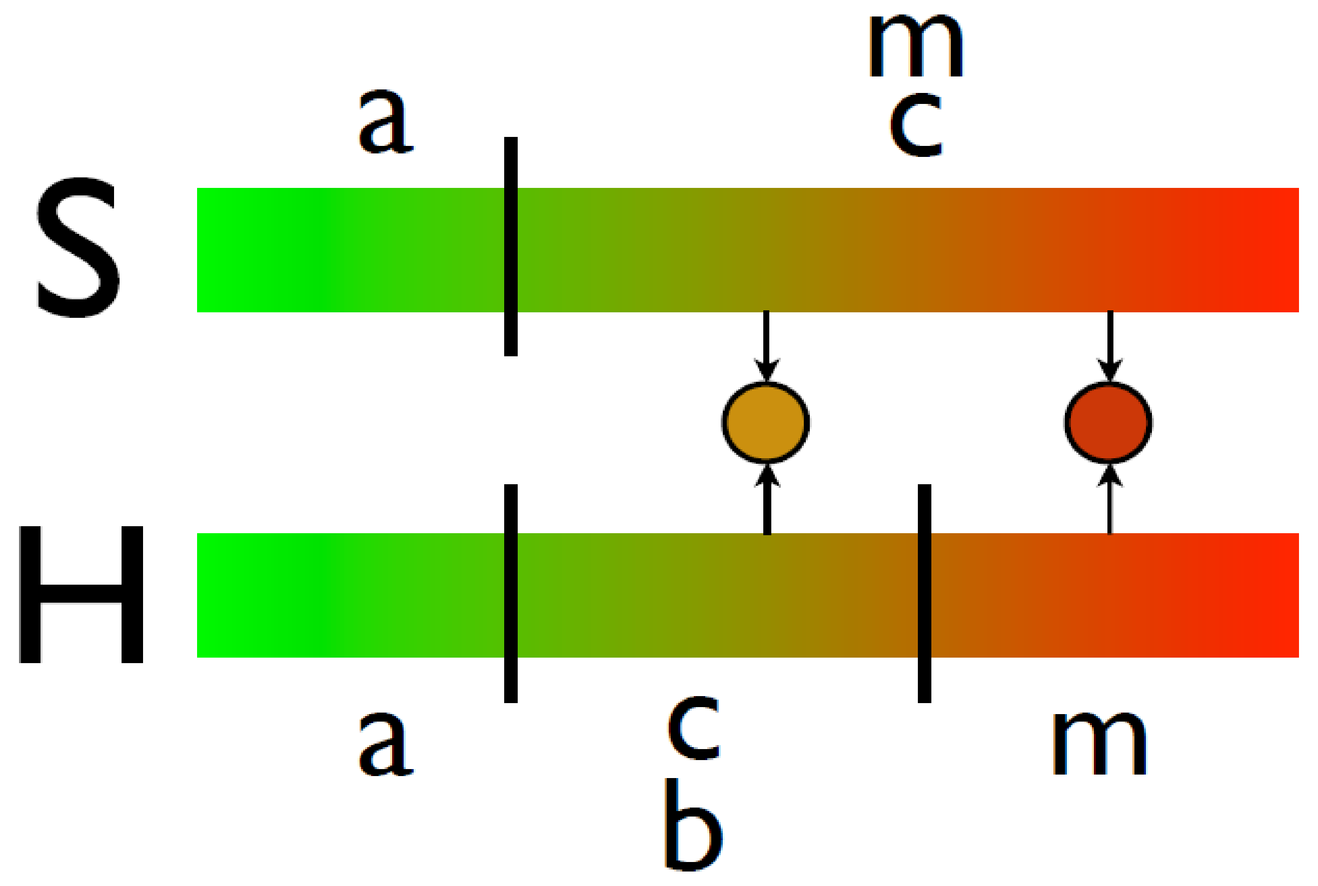
Speaker

The CG Model

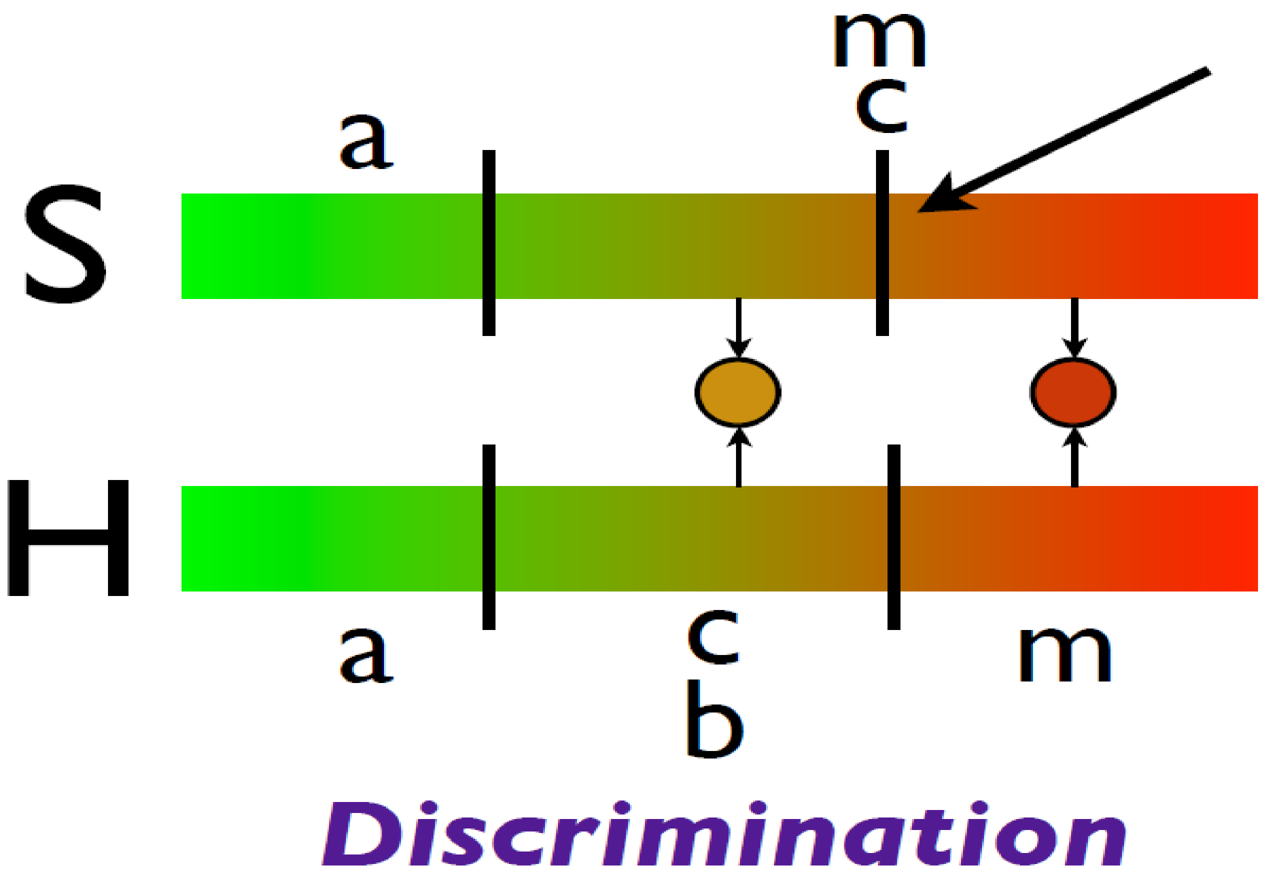
- Both the speaker and hearer are presented with a scene of M >= 2 stimuli (objects)

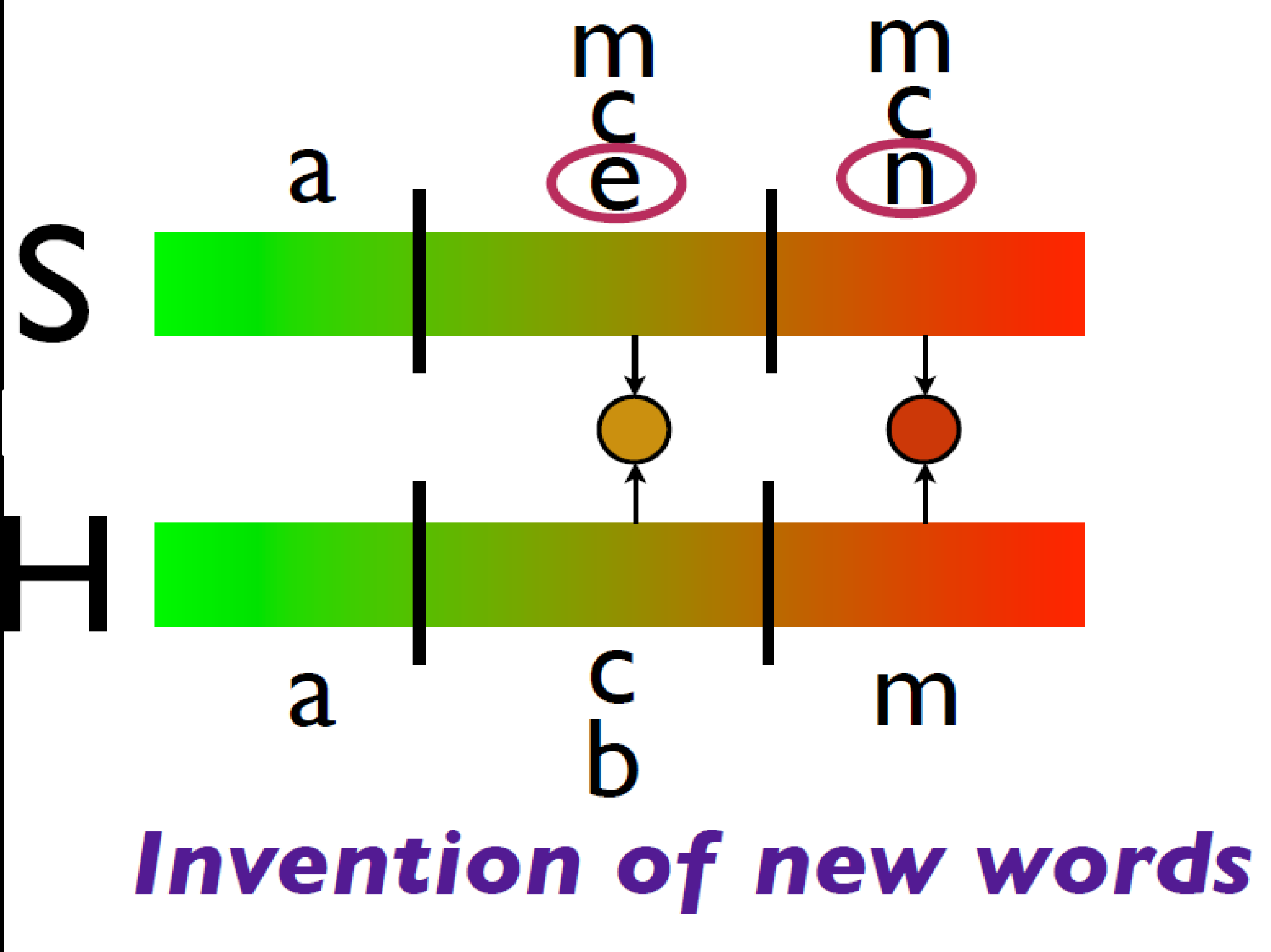
- no two stimuli appearing in the same scene can be at a distance closer than d_{min}
  - the only parameter of the model encoding the finite resolution power of any perception


Scene
Topic


m
a
c
S
H
a
c
m
b

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

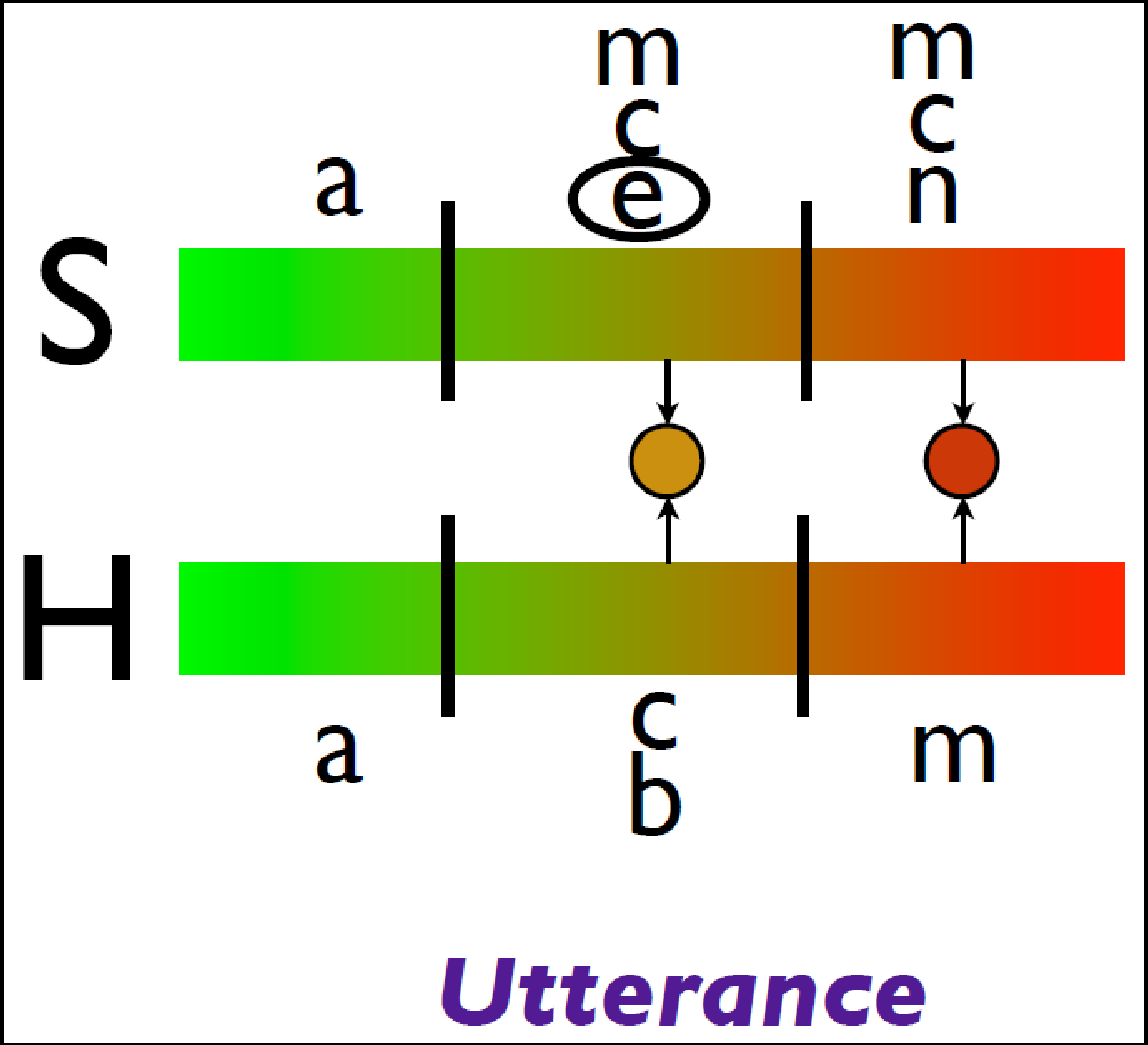




Invention of new words

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

- 2 possibilities:
  - ➢ chooses the last winning word
  - ➢ Otherwise, choose the newly created one


m
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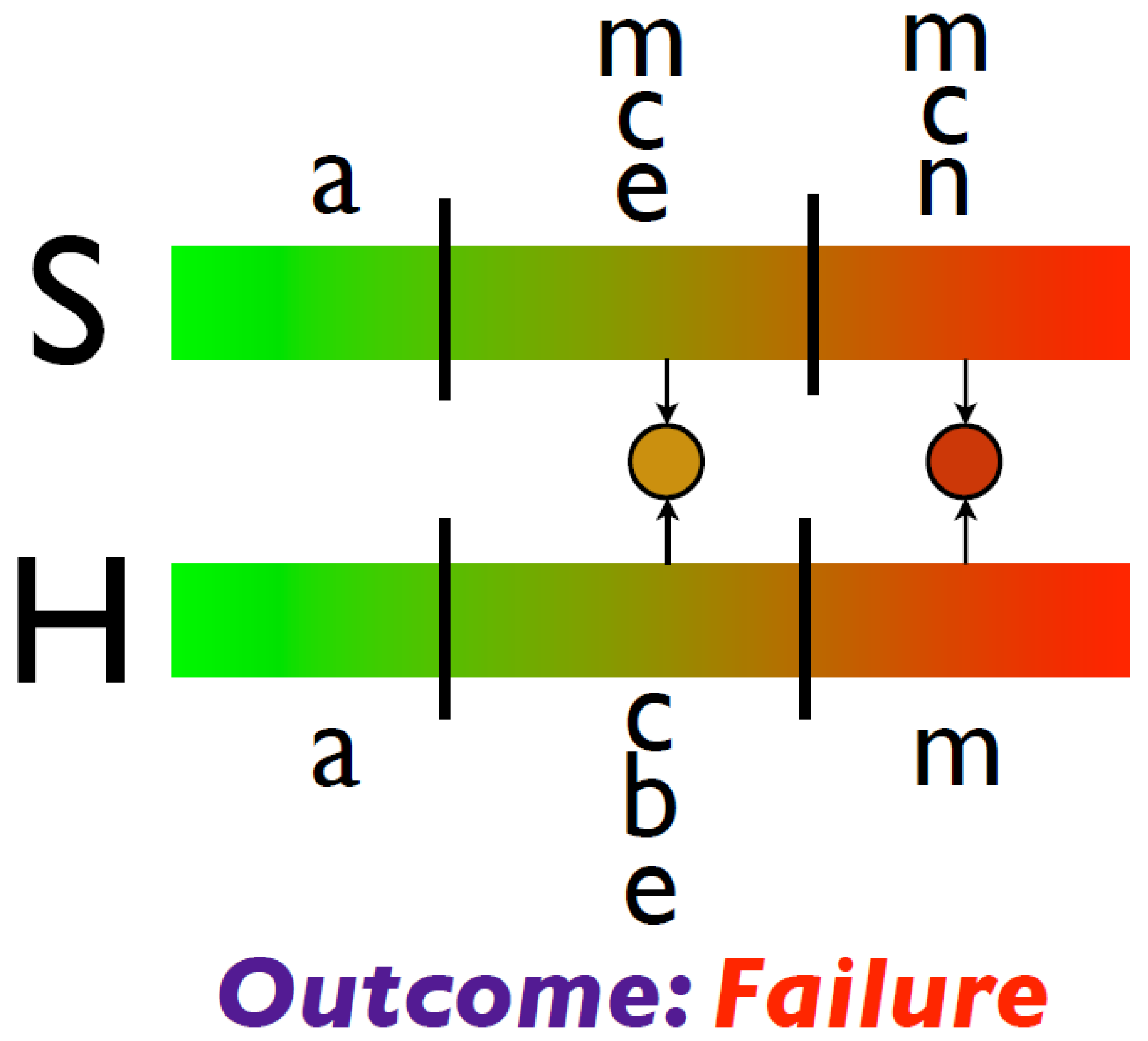
Utterance


m
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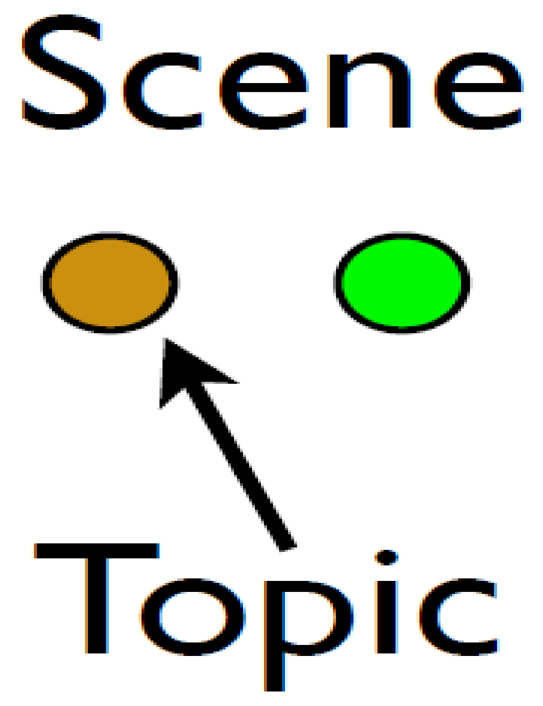
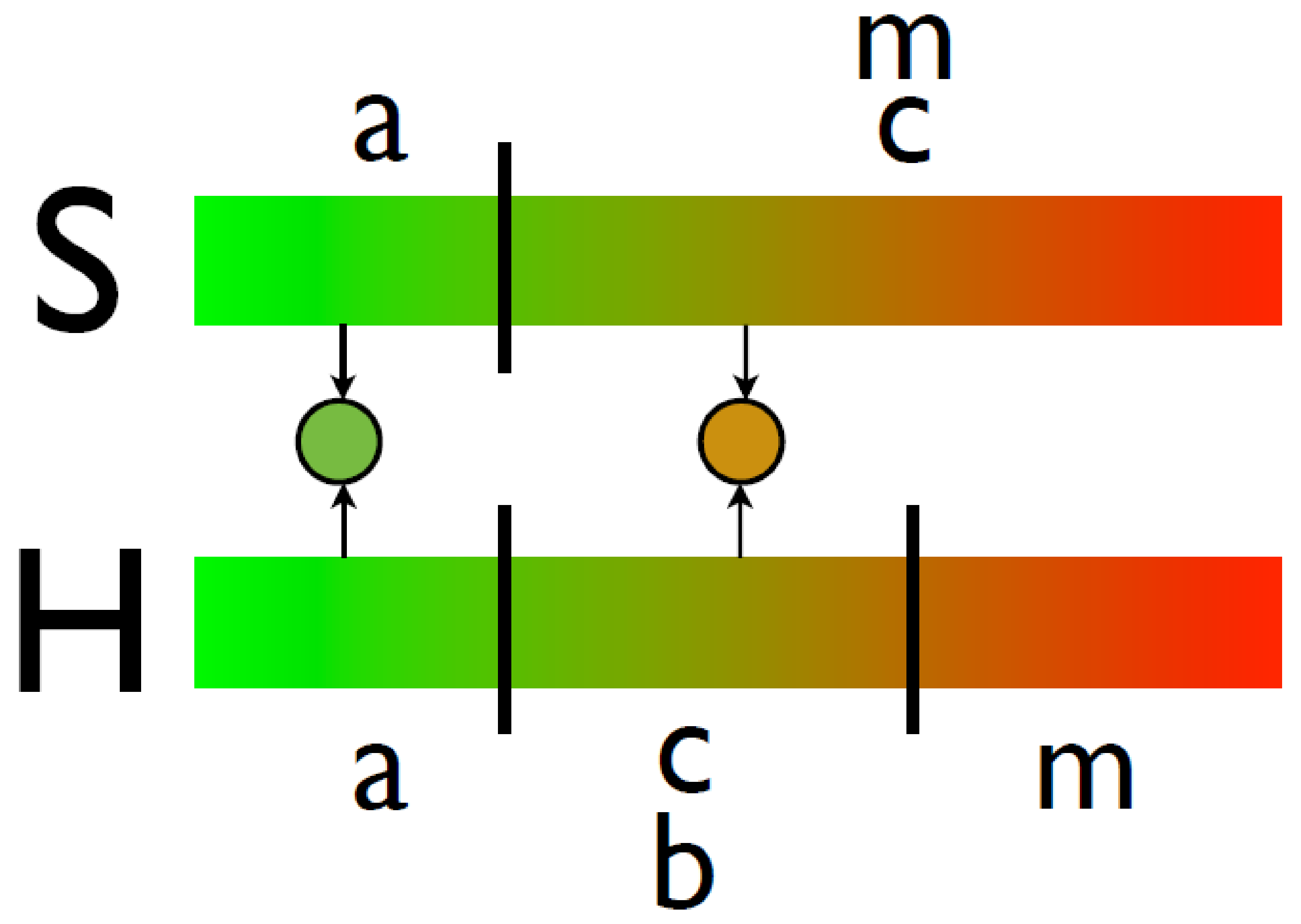
e
m
Outcome: Failure


Scene
Topic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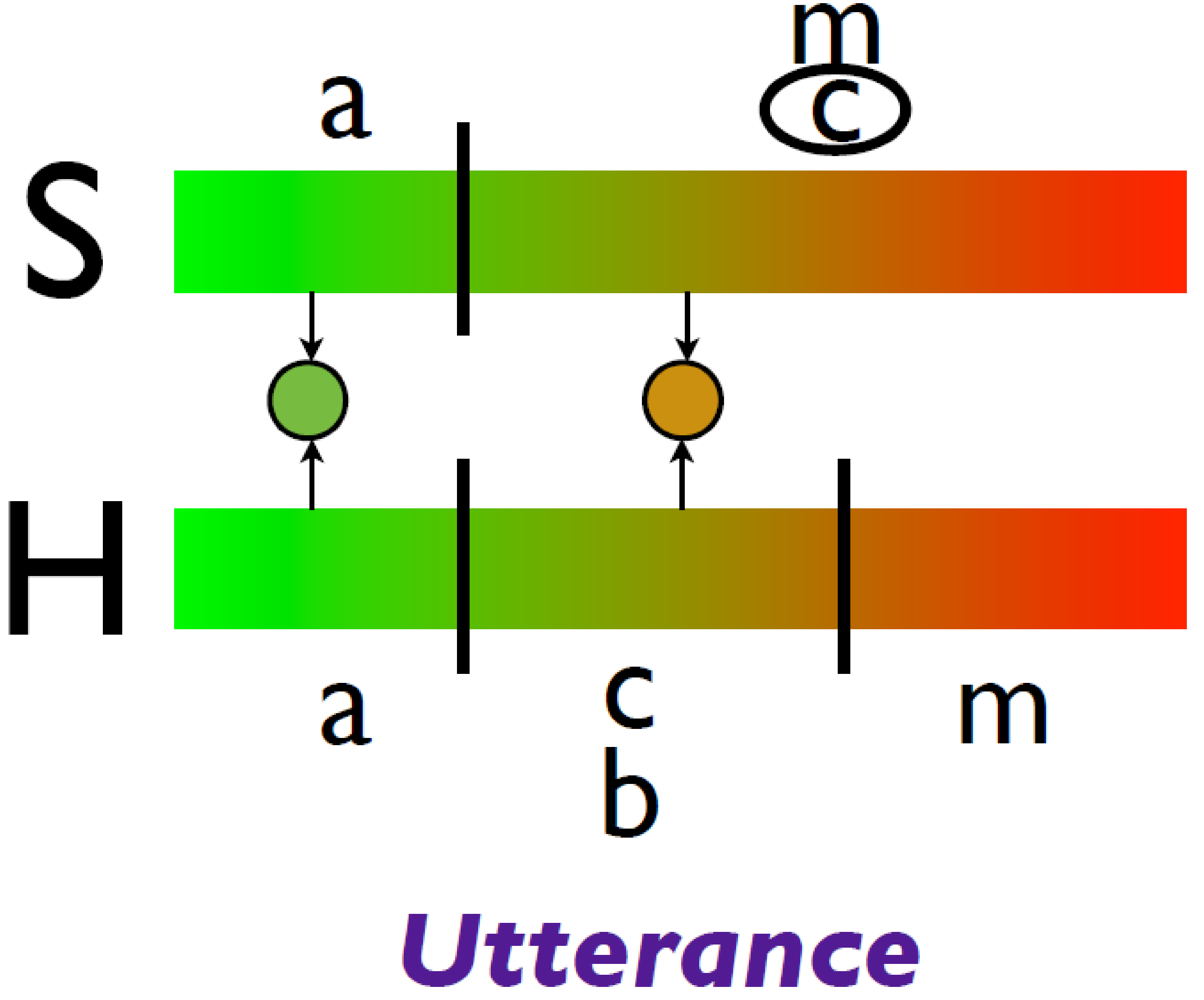
m
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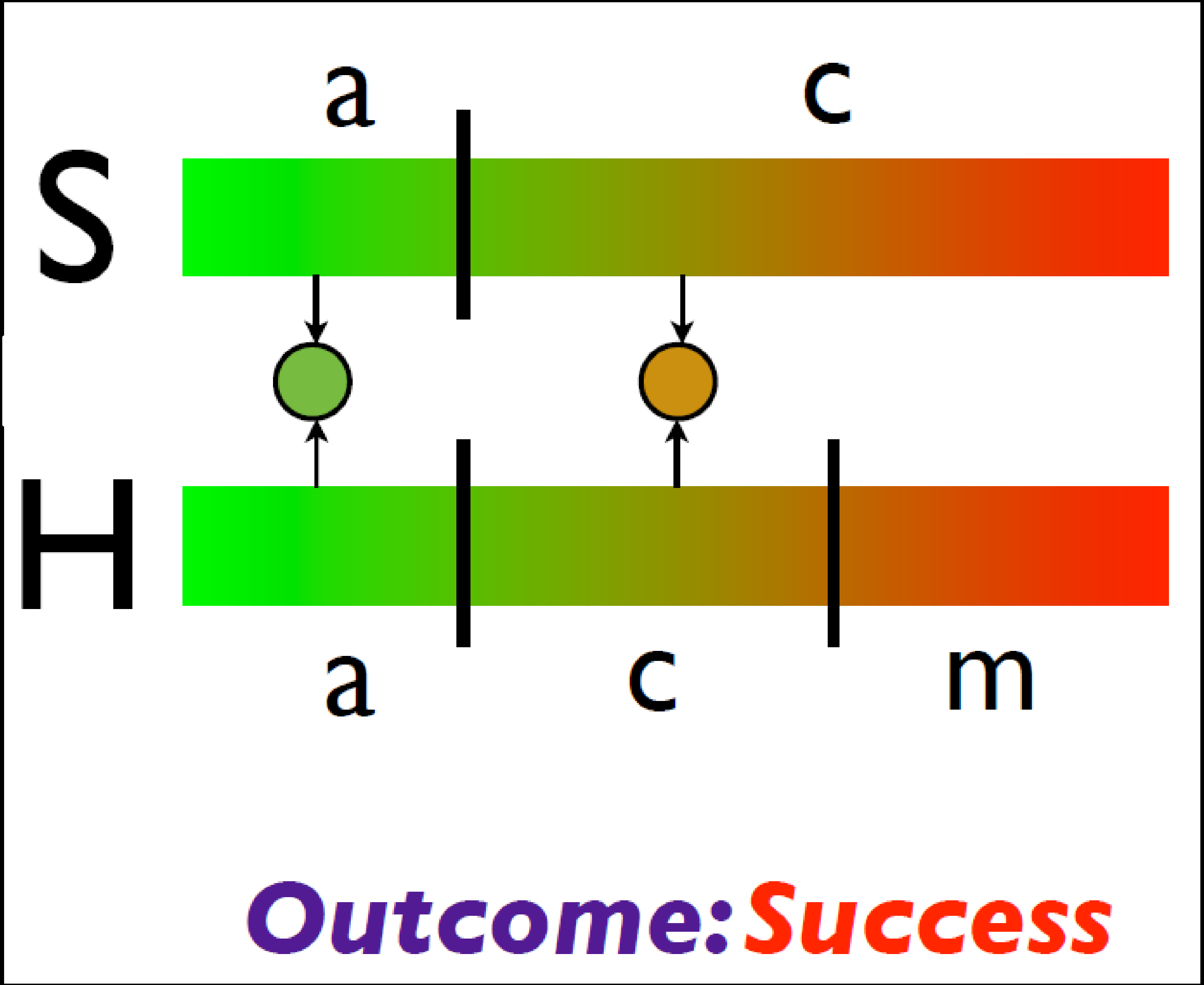
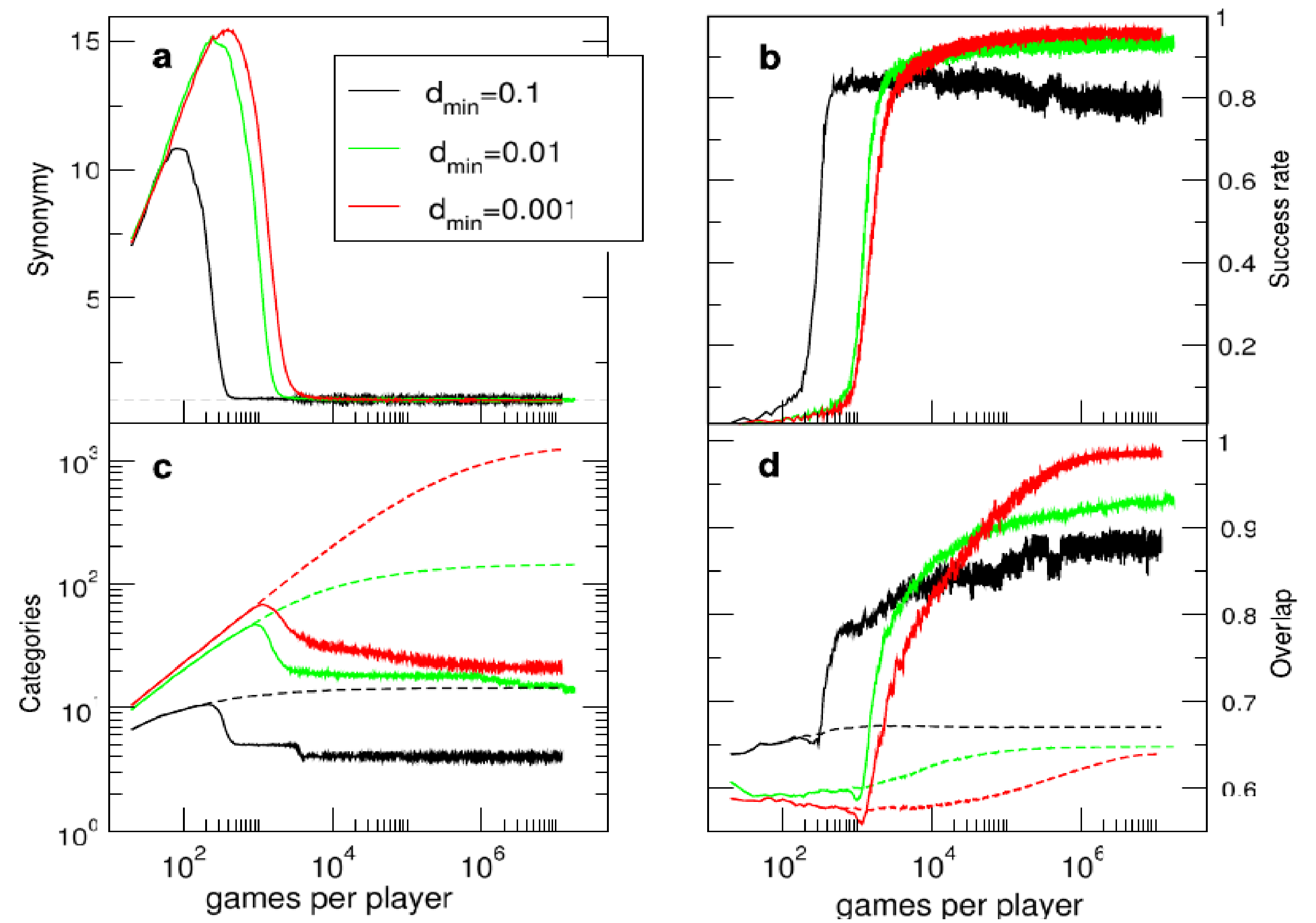
Utterance

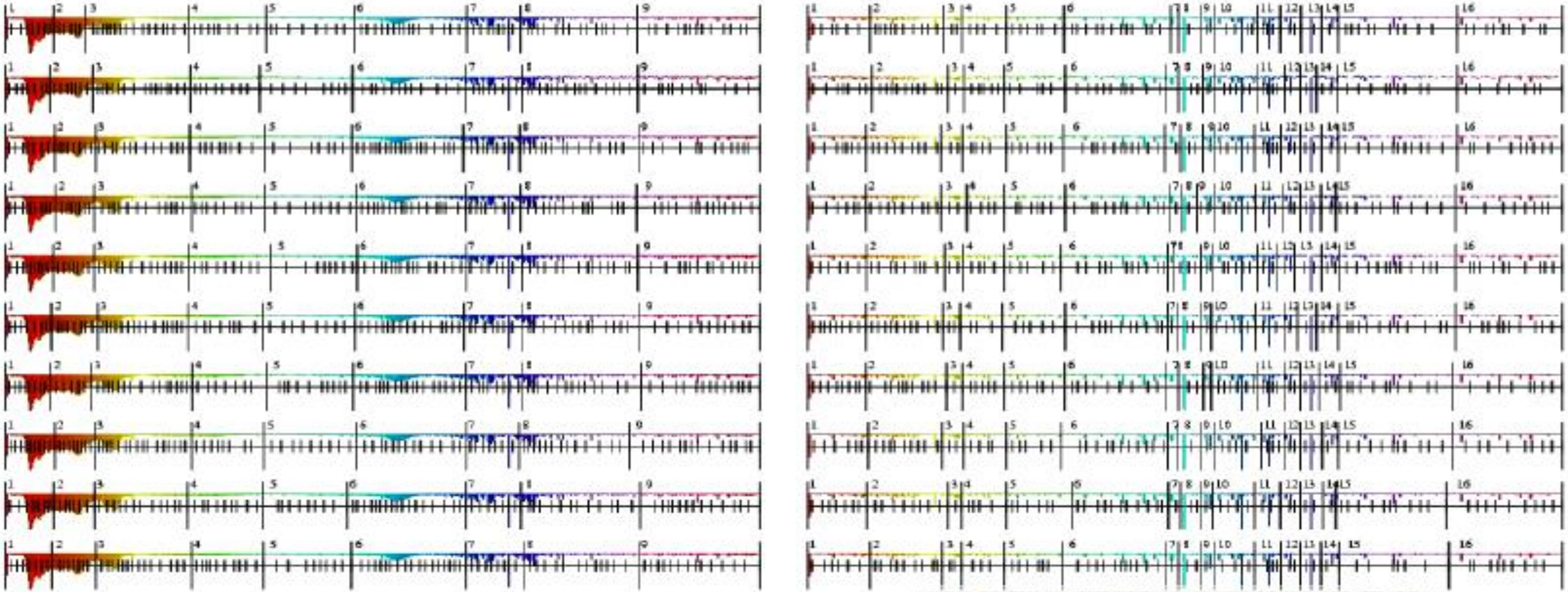

a
c
S
H
a
c
m
Outcome: Success



---- perceptual category

—— linguistic category

Categories and pressure of environment



Thank You

Any Questions ?