Cultural Route to the Emergence of Linguistic Categories

- Motivations and theoretical challenges
- A very short review of the *Naming Game*
- The *Category Game*
- Discussion and conclusions

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A physicist approach..

Statistical mechanics and complex system science:

emergence
self-organization

Study of language:

Language as an evolving set of conventions socially (i.e. globally) accepted by a group: a complex adaptive system [1].

Semiotic dynamics

View of language as an evolving and self-organizing system and focus on culture

Motivations

- The Web allows for global monitoring of human communication
- Many social, biological and technological systems are made of communicating entities
- Understand how global behaviors emerge out of local interactions

our strategy

- Definition of simple models (of increasing complexity)
- Quantitative analysis
- Analytical approaches (whenever possible)
- Connection with real world systems and experiments
The “Talking Heads” experiment

- Artificial robotic agents
- Hidden internal states
- Agents are not given any prior lexicon
- Open ended population and set of meanings

**Language Games**: Naming, Single property Guessing, Multiple property guessing, etc...

The Naming Game

(categories coming soon..)

with A. Barrat, E. Caglioti,
L. Dall’Asta, G. Gosti, V. Loreto,
M. Felici and L. Steels
Theoretical challenges

• What are the minimal requirements for a shared vocabulary to emerge?
• What are the global dynamics that lead to convergence?
• Which features lead to *efficiency*?
• Which is the role of the system size?
• Which is the role of topology?
The Naming Game

- Population of N agents
- Each agent is characterized by its *inventory* (or lexicon) i.e. a list of name-object associations
- Agents want to build a shared lexicon
- Homonymy is discarded $\rightarrow$ one single object
- Peer to peer *negotiation*. At each time step two agents (speaker and hearer) are selected

The microscopic interaction rules depend on the particular model and yield to different collective behaviors
Microscopic Rules

**Failure:** the hearer does not know the uttered word; after the interaction he records it

\[
(w_1^i, w_2^i, \ldots, w_{n_i}^i) \rightarrow (w_1^i, w_2^i, \ldots, w_{n_i}^i, w_{n_i+1}^i)
\]

**Success:** the hearer knows the uttered word; after the interaction both agents lexicons contain *only* the winning word

\[
(w_1^i, w_2^i, \ldots, w_{n_i}^i) \rightarrow (w_1^{winner})
\]

Microscopic Rules

Failure

Speaker | Hearer
---|---
ATSALLAD AKNORAB AVLA | TARRAB AVLA OTEROL

Success

Speaker | Hearer
---|---
ATSALLAD AKNORAB AVLA | TARRAB AVLA OTEROL

AVLA | AVLA

negotiation + memory + dynamic inventories
The communication system is efficient.
Detailed analysis

✓ Convergence dynamics
✓ Scaling properties
✓ Role of the topology
✓ Microscopic activity patterns
✓ Generalization of the model (consensus-polarization phase transition)
✓ Role of homonymy
✓ Etc..

$N_w^{\text{max}} \sim N^{1.5}$
$t_{\text{max}} \sim N^{1.5}$
$t_{\text{conv}} \sim N^{1.5}$
The Category Game

with V. Loreto and A. Puglisi

PNAS (in press)
pre-print: arXiv:physics/0703164v1
Theoretical challenges

- How does a population of agents establish and share an effective set of categories? [1]

- Is a macroscopic stationary state always reached starting from very simple microscopic dynamical rules?

- Quantitatively: which is the role of the
  - system size?
  - complexity of the environment?
  - resolution power of the agents ($d_{min}$)?

- The Big Question: categorizing a continuum perceptual space?

Linguistic categories

Most natural examples of linguistic categories are “common names”, i.e. words that indicate many different things.

Thus, linguistic categories

- allow to quickly point out something without giving too many details (lossy compression)
- are well calibrated to avoid confusion, i.e. to discriminate something among different things
- in brief: must be not too large nor too small
The Category Game

• Population of $N$ agents

• Individual: set of (perceptual) categories + inventories for them, i.e. a list of name-category associations

• Language-mediated, peer to peer negotiation. At each time step two agents (sp + hea) are selected and presented a scene with different objects (say: colors or real numbers)

• a topic is chosen, the speaker must indicate it through a word

• the hearer must guess which is the topic listening to that word

• discrimination of the topic is implicitly required

• based on success/failure: categories, words and their associations are updated

See also: L. Steels & T. Belpaeme, BBS 28, 469 (2005)
A simple scheme

**INDIVIDUALS:** a simple low-dimensional input channel, such as the complete 3d color channel or just the 1d **hue channel**, temperature sensor, altimeter, etc.

![Real values on the interval [0, 1]](image)

**CATEGORIES (perceptual):** subsets of the interval
(many ways of defining the subset, not crucial)

**SYNONYMY:** many words -> one category

**HOMONYMY:** one word -> many categories
Rules (1/3)

• each agent has a set of non-overlapping categories [subsets of \((0,1)\)], defined by boundaries; categories fully cover the interval; at the beginning only the category \((0,1)\) exists

• each category comes with an inventory of words; at the beginning a brand new word is associated to each category

• the scene: \(M\) real numbers in \((0,1)\) at a minimal distance \(d_{\text{min}}\) (resolution power, Just Noticeable Difference or Difference Limen)

• one of the objects is the topic, known by the speaker only
Rules (2/3)

- the **speaker** discriminates the topic: this may require the creation of new boundaries; each new category inherits the words of the old category, plus a brand new one.

![Diagram showing color categories]

- the **speaker** says the “last-winning” word associated with the discriminating category, or the newly created one if this is the first game played with that category.

- the **hearer** looks at her inventory for that word: a **set of candidate categories** (containing at least one object and that word) is obtained.
Rules (3/3)

• if the **set is empty**, the game is a failure; the speaker points at the topic and the *hearer* **discriminates** it and **adds** the speaker’s word to the correct category

• if the **set is not empty**, the *hearer* chooses at random the category and the object in it, and finally **makes** her guess **manifest**

• if the **guess is correct**, both individuals **reduce** the inventory associated to the winning category to the **winning word** only, which is assigned the status of “last-winning” word

• **otherwise**, the topic is unveiled, the *hearer** discriminates** the scene and (if not present) the uttered word is **added** to the discriminating hearer’s category
Time evolution

- Initially, most games are unsuccessful
- After $\sim 10^3 xN$ games a **sharp transition**: the success rate becomes very high ($\sim 90\%$ or higher)
1. Naming Game + free categories

- For each category: typical NG synonymy curve
- Number of categories grows as $t^{1/2}$, free discrimination: probability of a new category $1/n_{cat}$
- The growth of category number slows down when $n_{cat} \sim 1/d_{min}$; category number cannot grow above $2/d_{min}$
2. Full communicative success

- Success is high (\(\sim\)90%)
- Synonymy is eliminated
- Categories are still evolving (slow refinement)
- Categories are poorly aligned (!)

Pb: How can the success rate be so high?

\[ o_{ij} = \frac{2 \sum_{c_i}^{j} (l_{c_i})^2}{\sum_{c_i}^{j} (l_{c_i})^2 + \sum_{c_j}^{j} (l_{c_j})^2} \]
The definition of an overlap functional is not trivial since the number of categories is not constant. Luckily, we do not need sophisticated measures.

\[ O = \frac{2}{N(N-1)} \sum_{i<j} o_{ij} \]

\[ o_{ij} = \frac{2 \sum c_i^j (l_{c_i^j})^2}{\sum c_i (l_{c_i})^2 + \sum c_j (l_{c_j})^2} \]

The overlap functional is defined as:

\[ l_{c_i} = \sum l_{c_i} \quad l_{c_i}^2 \geq \sum l_{c_i}^2 \]

\[ c_i = U c_i^j \]
Emergence of homonymy

As synonymy disappears, homonymy is growing

Number of categories associated to the same (unique) word
The word-contagion effect

Homonymy growth is due to an intra-category word-contagion
Emergence of Linguistic Categories

adjacent categories identified by the same word can be considered a single linguistic category

Linguistic categories:
• emerge as connected sets
• their number is much lower and becomes stable
• their alignment is much higher (hence the success!)
Role of the parameters

The number of linguistic categories:

• slightly increases with N and
• most importantly, saturates for small $d_{min}$
Role of the environment 1

Inputs uniformly distributed in (0,1)

\[ N = 100 \]

\[ d_{\text{min}} = 0.01 \]
Role of the environment 2

$N=100, \ d_{\text{min}}=0.01$
Role of the environment 3

N = 100
$d_{\text{min}} = 0.01$
“Genetic” biases

$d_{min}$ is a “genetic” trait of the individuals

In principle it can vary:
1. On the [0,1] axis (different resolution power for different stimuli)
2. From individual to individual (population heterogeneity) \[1\]

Here we focus on 1.


Also with T. Gong, presently at “La Sapienza” University.
Non-uniform $d_{min}$

three regions: smaller $d_{min}$ for larger numbers

agents using the same word

perceptual space
Non-uniform $d_{\min}$

Continuous $d_{\min}$

Agents using the same word

Perceptual space

Perceptual space
Non-uniform $d_{min}$

"Human" $d_{min}$

From Long et al. 2006.

Non-uniform $d_{\text{min}}$
The next step (a roadmap..)

- Linguistic categories work better thanks to compositionality.
- If a category is not sufficient to discriminate our topic, we can add further specifications.
- We ignored this possibility, but this more advanced issue should be taken into account in the next step.

A possible path could be continuing in the same spirit.

**CG agent**: made of NG agents (perc. categories). Decides which NG agent must play and in case can create new NG agents.

**NEXT agent**: made of CG agents (channels), Decides which CG agent must play (or which combination) and in case can create new CG agents.
Conclusions

- The Category Game is simple, can incorporate empirical results, could produce checkable predictions (in progress..)

- **Quantitative approach** and **new discoveries** (continuum, role of $d_{\text{min}}$, $N$, environment, perceptual biases, etc..)

- The systematic appearance of homonymy defines linguistic categories as an emerging layer on top of perceptual categories

- Linguistic categories are much more aligned in the population
Conclusions

• The success rate obviously decreases (slowly) with the number of objects in a scene. In human language we have compositionality

• The number of linguistic categories is kept low by the necessity of alignment, i.e. of comprehension among individuals

• Just to mention: Some anomic aphasics, despite normal color vision, are unable to name color categories (try with few or many)\(^1\), but do not exhibit general categorization problems\(^2,3\). A possible explanation is that they are unable to produce the necessary\(^4\) non-perceptual discontinuity (e.g. verbal) in the perceptual continuum\(^4,5\).

References can be found here

http://andrea.baronchelli.googlepages.com/home

Thank you!