Dynamics of language competition: social consensus in complex networks

Xavi Castelló   Victor M. Eguíluz   Maxi San Miguel

X. Castelló, V. Eguíluz and M. San Miguel. *New Journal of Physics*, 8, 308 (2006)
\+ **Dietrich Stauffer,** *Physica A, **374**, 835-842 (2007)*
\+ **Lucía Loureiro Porto** *Advancing Social Simulation: The First World Congress. Takahashi, Shingo; Sallach, David; Rouchier, Juliette (Eds.) (2007)*
\+ **R. Toivonen, J. Saramäki, K. Kaski** *Europhysics Letters 79, 66066 (2007)*
\+ **R. Toivonen, J. Saramäki, K. Kaski** *Physical Review E 79, 016109 (1-8) (2009)*

IFISC

COLLECTIVE PHENOMENA: physics and social sciences

Statistical physics and Complex Systems

→ **novel approach to collective emergent phenomena in social systems**

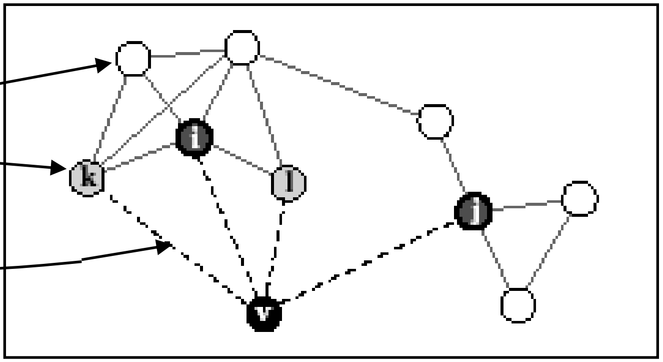
micro-Macro, non-linear interactions, non-equilibrium dynamics, coarsening, phase transitions, bifurcations

Complex networks

as *skeleton* of a complex system

Nodes (*individuals*)
Edges (*social links*)

■ Non-regular connectivity



Modelling in: biological, technical, **social**, …systems

Motivation: dynamics of language competition

►***Language competition***: dynamics of language use due to social interactions, modelled in a complex social network.

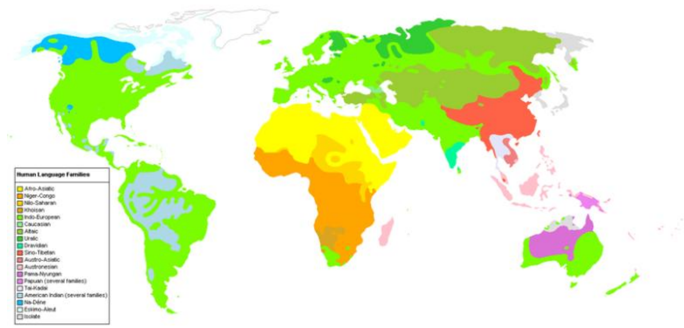
Languages in the world today

There exist around 6000 languages in the world.

- Over 50% of them are endangered (UNESCO).

4% of languages account for 96% of people.

- 25% of languages have less than 1000 speakers.



♦ D. Crystal. *Language Death* (Cambridge CUP 2000)

<u>INFORMATION on languages in the world</u>: ♦http://portal.unesco.org/culture
♦http://www.ethnologue.com/

Social networks in sociolinguistics

► L. Milroy *Language and social networks.* Oxford: Blackwell, 2nd ed (1987)

► Monographic issue on *role of social networks in language competition/shift* : K. De Bot and S. Stoessel, editors. *International Journal of the Sociology of Language*, volume 153 (2002)

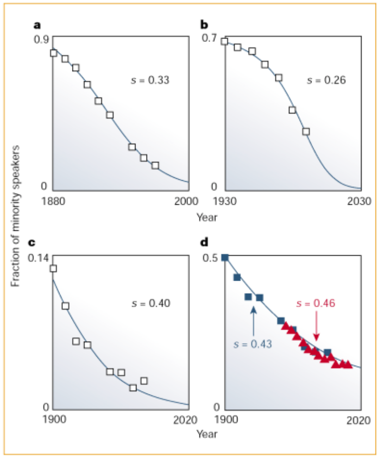
INTRODUCTION: "…while researchers agree intuitively that social networks should play a role in questions relating to language change, and several qualitative studies have shown what kind of role they play, there is very little, if any, quantitative support for a direct relation between social network characteristics and language use."

1st approach from complex systems

Abrams, Strogatz (2003). Nature **424**, 900.

"Question: Extinction of endangered languages"

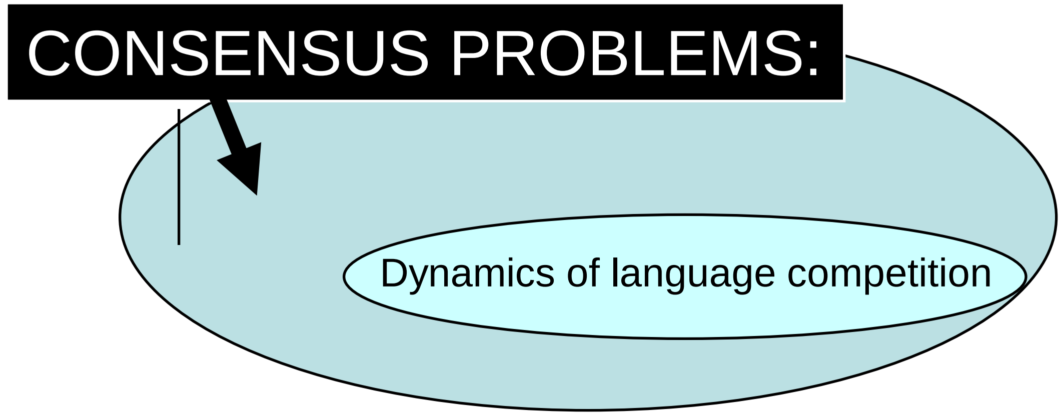
Figure 1 The dynamics of language death. Symbols show the proportions of speakers over time of: **a,** Scottish Gaelic in Sutherland, Scotland[9]; **b,** Quechua in Huanuco, Peru; **c,** Welsh in Monmouthshire, Wales[10]; **d,** Welsh in all of Wales, from historical data[10] (blue) and a single modern census[11] (red). Fitted curves show solutions of the model in equation (1), with parameters *c*, *s*, *a* and *x*(0) estimated by least absolute-values regression. Where possible, data were obtained from several population censuses collected over a long timespan; otherwise, a single recent census with age-structured data was used (although errors are introduced, the size of which are reflected in the differing fits in **d**). Using the fraction of Catholic masses offered in Quechua in Peru as an indicator, we reconstructed an approximate history of the language's decline.



NATURE | VOL 424 | 21 AUGUST 2003 | www.nature.com/nature

MODELS of CONSENSUS:

<u>Def.</u> Dynamics of a set of interacting agents that can choose among several **options** (*political vote, opinion, cultural features*,…) which can lead whether to a scenario of **consensus** of one of this opinions, whether to a state of **coexistence** of several options prevails.



Language competition → particular case of consensus model.

MODELS

- -VOTER MODEL
- -ISING MODEL (T=0) Glauber dynamics
- - SZNAJD MODEL
- -AXELROD MODEL
- -GRANOVETTER'S MODEL

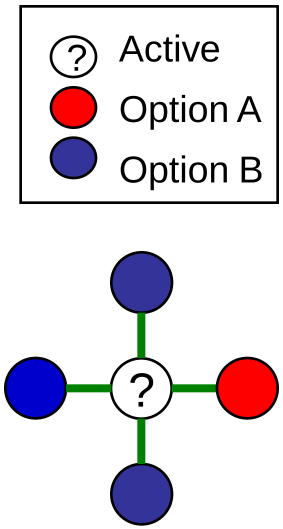
↔

MECHANISMS

- -Imitation
- -Following majority. Social pressure
- -Majority *CONVINCES*
- - Homophily
- - Threshold for social pressure

MODELS of CONSENSUS with *TWO OPTIONS* :

- Prototype models ***with excluding options***: - VOTER MODEL
  - SPIN FLIP KINETIC ISING MODEL T=0



$$p_{?\to B} = 3/4 \qquad p_{?\to A} = 1/4$$

Voter Model — **RANDOM IMITATION**

$$p_{?\to B} = 1 \qquad p_{?\to A} = 0$$

Spin Flip Kinetic Ising T=0 — **SOCIAL PRESSURE**

- New issue/class of models: ***AB agents with coexisting options***

Example: Bilingual agents in the dynamics of two competing languages

General: Coexistence of social norms at the individual level (linux or windows)

ORDERING DYNAMICS WITH TWO NON-EXCLUDING OPTIONS

♦ **GENERAL QUESTION:**

Which are possible **mechanisms to stabilize the coexistence** of two (equivalent) competing options (languages)? Which is the role of AB-agents (bilingual individuals) and social structure in this process?

♦ **PARTICULAR QUESTIONS:**

■ **Mechanisms of growth** of spatial domains (monolingual). Dynamics at the interfaces (linguistic borders). Metastable states

regular networks

■ Effect of the **degree of disorder** in the social network and **time scales for consensus**.

small world networks

■ Effects of social structure with **communities** in the dynamics *community-networks*

Agent-Based ABRAMS-STROGATZ model

Abrams, Strogatz (2003). Nature 424, 900.

N agents within a network: nodes → agents
links → social interaction

-States of the agents: -using language A: belonging to a monolingual community *A*.
-using language B: belonging to a monolingual community *B.*

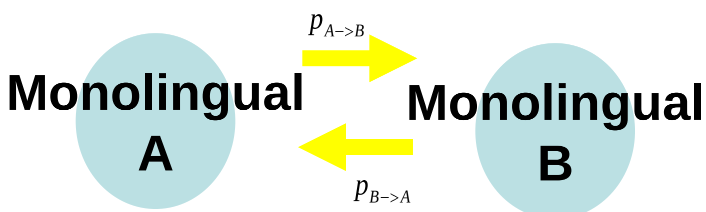
- Local density of speakers:

$$\sigma_{iA} = \frac{\#\,\text{neighbours in state A}}{k_i} \qquad \sigma_{iB} = \frac{\#\,\text{neighbours in state B}}{k_i}$$

- Dynamics of interaction: choose randomly an agent,

$$p_{A->B} = (1-s)\cdot(\sigma_B)^a$$

$$p_{B->A} = s(\sigma_A)^a$$

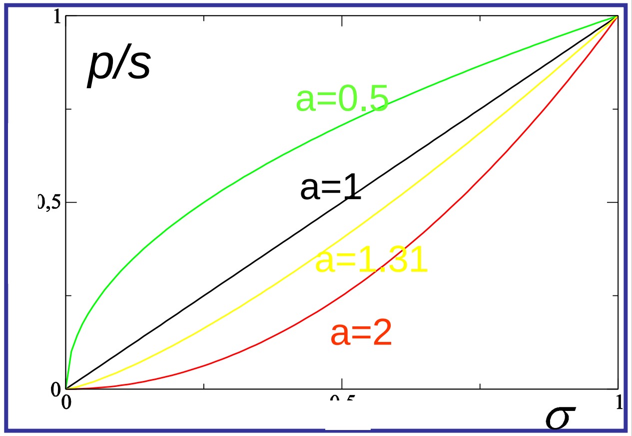


s: **prestige of language A (s$_B$=1-s)** <u>language property</u>

a: *volatility* (exponent) → determines the shape of $p_{A->B}$

<u>social dynamics property</u>

a>1: Dominance a<1: Coexistence



MINETT-WANG MODEL

-States of the agents: - using language A: belonging to a monolingual community *A*.
- using language B: belonging to a monolingual community *B*
- using both, A & B: belonging to the bilingual community *AB.*

- Dynamics of interaction: choose randomly an agent,

$$p_{A\to AB} = (1-s)\cdot(\sigma_B)^a$$

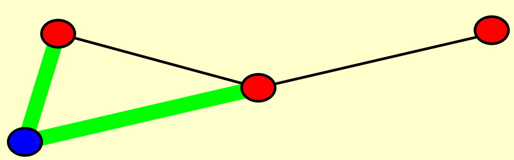
$$p_{B\to AB} = s\cdot(\sigma_A)^a$$

$$p_{AB\to A} = s\cdot(1-\sigma_B)^a$$

$$p_{AB\to B} = (1-s)\cdot(1-\sigma_A)^a$$

Wang, W. S-Y. and Minett, J. W, Trends in Ecology and Evolution,20(5) 263 (2005)

Order Parameter: Average interface density



$$\rho = \frac{\#\,\text{links joining agents in different state}}{\text{total}\,\#\,\text{of links}}$$

Interface: a link connecting nodes with different states.

ρ=0 in absorbing/ordered state

MEAN-FIELD analysis of Agent-Based ABRAMS-STROGATZ model

D. Abrams, S. Strogatz. Nature 424 (2003) 900

General case

$$\frac{d\sigma_A}{dt} = (1-\sigma_A)\sigma_A(\sigma_A^{a-1}s-(1-\sigma_A)^{a-1}(1-s))$$

$$\sigma_B(t) = 1-\sigma_A(t)$$

Fixed points :

	DOMINANCE $a>1$	**COEXISTENCE** $a<1$
$(\sigma_A,\sigma_B)=(1,0)$ $=(0,1)$	stable	unstable
(σ_A^*,σ_B^*)	► unstable	► stable

s>0.5 → state A favoured
s<0.5 → state B favoured

a=1: Marginal case

$$\frac{d\sigma_A}{dt} = (1-\sigma_A)\sigma_A(2s-1)$$

Logistic-Verhulst equation

VOTER MODEL ((a=1,s=1/2))

$$\begin{cases} \dfrac{d\sigma_A}{dt} = 0 \\ \sigma_B(t) = 1-\sigma_A(t) \end{cases}$$

Any proportion of A-agents is a marginally stable solution
IMP! Magnetization is conserved

MEAN-FIELD analysis of MINETT-WANG model

General case

$$\frac{d\sigma_A}{dt} = (1-\sigma_A-\sigma_B)(1-\sigma_B)^a s - \sigma_A \sigma_B{}^a (1-s)$$

$$\frac{d\sigma_B}{dt} = (1-\sigma_A-\sigma_B)(1-\sigma_A)^a (1-s) - \sigma_B \sigma_A{}^a s$$

$$\sigma_{AB}(t) = 1-\sigma_A(t)-\sigma_B(t)$$

Fixed points:	**DOMINANCE** $a \geq 0.63$	**COEXISTENCE** $a < 0.63$
$(\sigma_A, \sigma_B, \sigma_{AB}) = (1,0,0)$ $= (0,1,0)$	stable	unstable
$(\sigma_A{}^* \neq 0, \sigma_B{}^* \neq 0, \sigma_{AB}{}^* \neq 0)$	▶ unstable	▶ stable

s>0.5 → state A is favoured
s<0.5 → state B is favoured

AB-model (a=1, s=1/2)

$$\begin{cases} \dfrac{d\sigma_A}{dt} = \dfrac{1}{2}\left[-\sigma_A + (\sigma_B)^2 - 2\sigma_B \right. \\ \dfrac{d\sigma_B}{dt} = \dfrac{1}{2}\left[-\sigma_B + (\sigma_A)^2 - 2\sigma_A \right. \\ \sigma_{AB}(t) = 1-\sigma_A(t)-\sigma_B(t) \end{cases}$$

Fixed points:

Two stable points, corresponding to total dominance of one of the states:

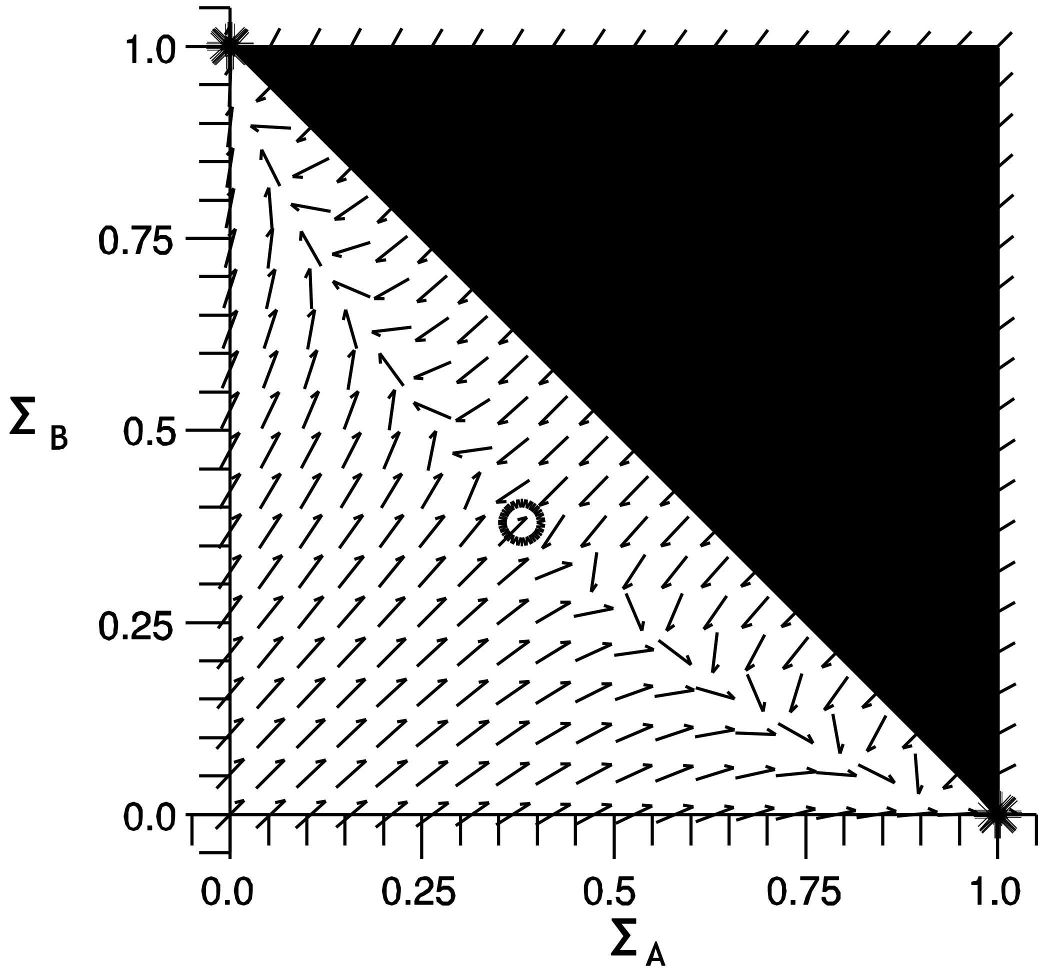
$$(\sigma_A, \sigma_B, \sigma_{AB}) = (1,0,0)$$
$$= (0,1,0)$$

▶ Unstable coexistence

$$(\sigma_A{}^*, \sigma_B{}^*, \sigma_{AB}{}^*) \cong (0.4, 0.4, 0.2)$$

Phase portrait:

AB-model
(a=1, s=1/2)

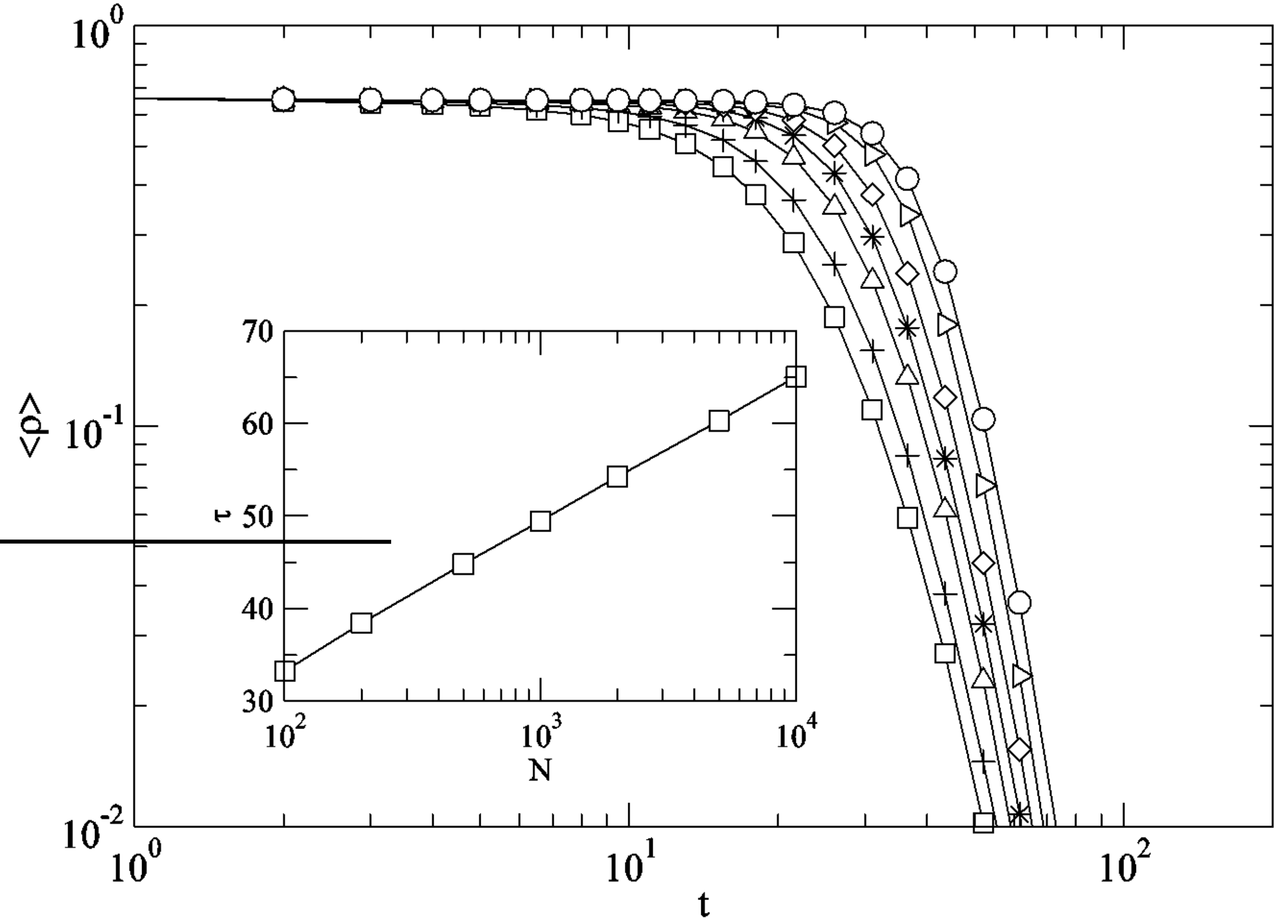


AB-model (a=1, s=1/2). **Fully connected networks**

Finite system size:

N=100,…,10000

$$\tau \propto \ln N$$



RESULTS 1:

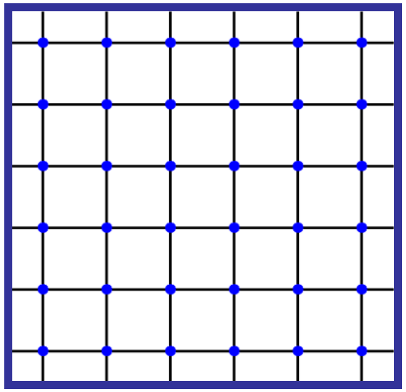
Voter model VS AB-model in regular networks

→ **Castelló et al.** *New Journal of Physics*, 8, 308 (2006)

\+ **Dietrich Stauffer,** *Physica A*, ***374***, *835-842 (2007)*

RESULTS. Regular network

SEE APPLET!
http://www.ifisc.uib-csic.es/research/complex/APPLET_LANGDYN.html



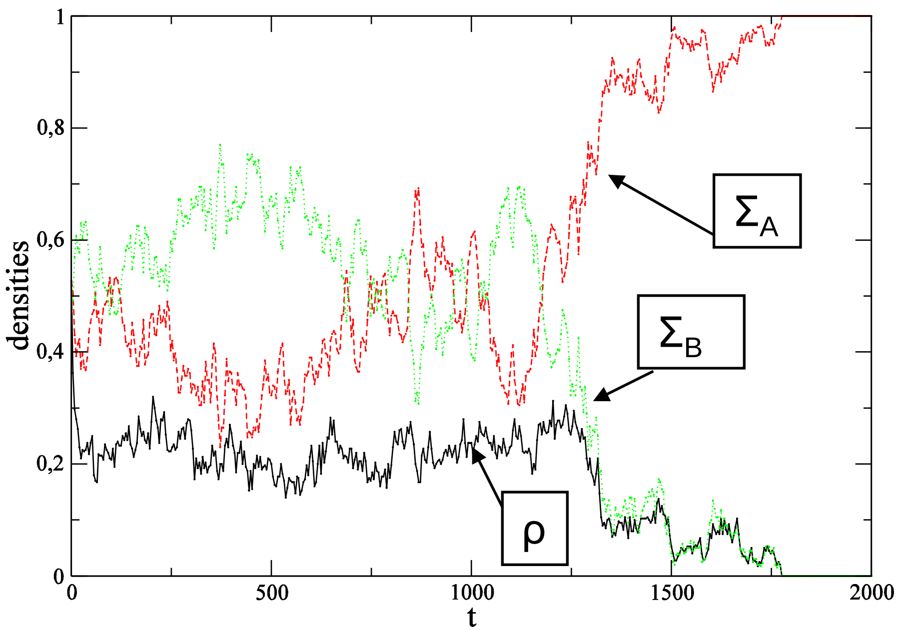
In both models → Final scenario of **CONSENSUS**

But… differences in the transient towards consensus:

VOTER MODEL	AB-MODEL
▶ Domains grow slowly	▶ Single-option domains grow **FASTER**
▶ No formation of localized domains	Formation of "localized" single-option domains ▶ AB-agents → do not form AB-domains → at the **interfaces**
Noisy interface dynamics	**Curvature driven dynamics**

LOCAL EFFECTS: Typical realization in a 2-d regular lattice:

VOTER MODEL

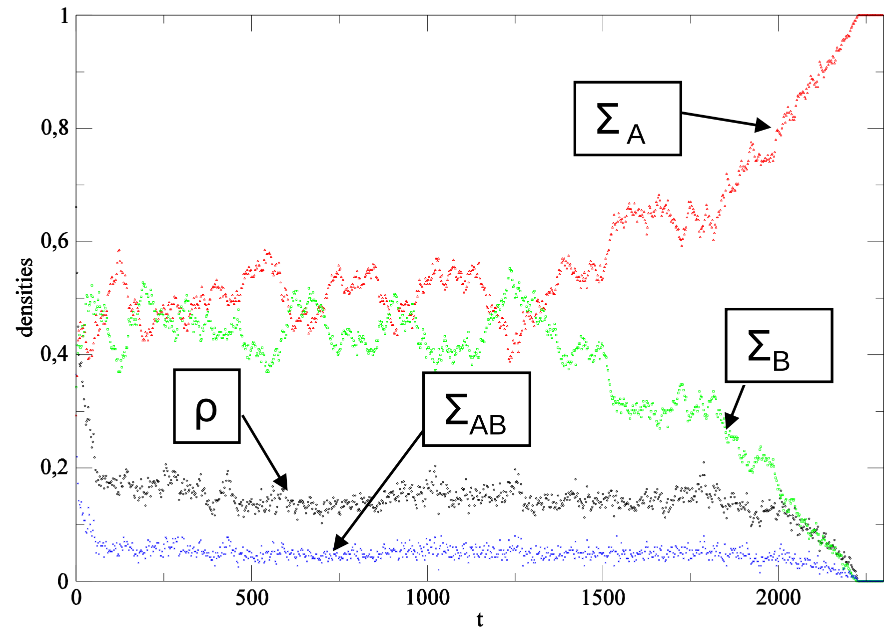


$N = 400$

Extinction of one single option community

- ρ initial decay
- ρ vanishes together with the extinct state

AB-MODEL



$N = 400$

Extinction of one option + AB-agents

- ρ **stronger** initial decay

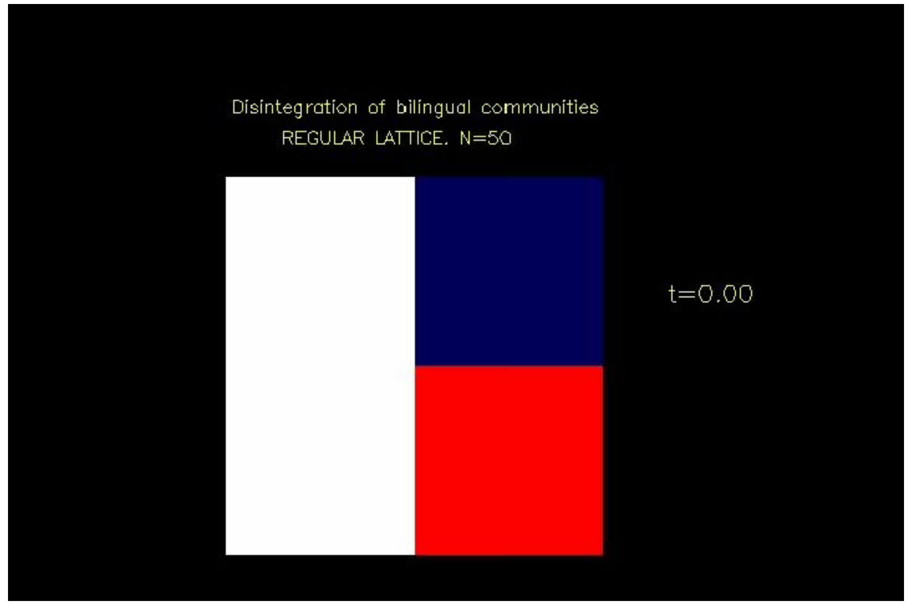
-AB-agents density follows the evolution of ρ

Disintegration of AB-domains

SEE APPLET!
http://www.ifisc.uib-csic.es/research/complex/APPLET_LANGDYN.html

AB- MODEL

- State A
- State B
- AB-state



$N = 50^2$

► Disintegration of **AB-domains**

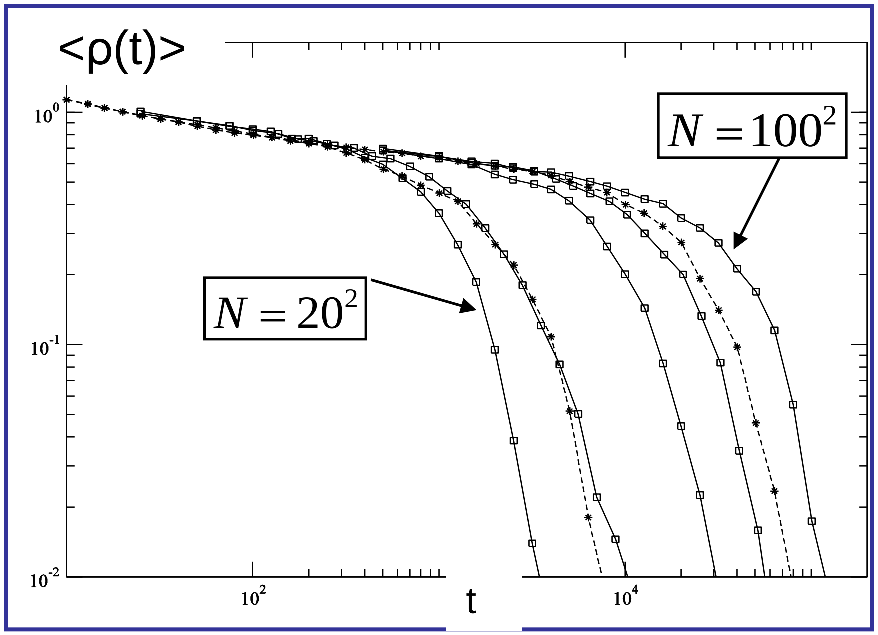
Within the assumptions of our model:
Societies with possibility of ***sharing two options at the individual level***

$\Downarrow$

tend to end up splitting into single-option communities, even if the options are ideally socially equivalent.

LOCAL EFFECTS: domain growth

VOTER MODEL

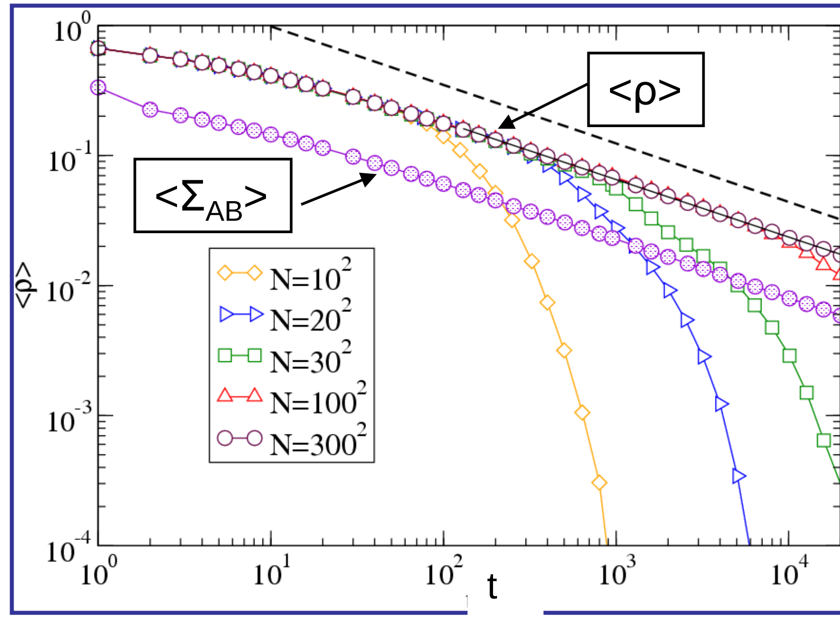


$$< \rho > \propto t^{-0.11}$$

compatible with ρ~1/ln(t) coarsening (VOTER MODEL)

Domain growth: $l(t) \propto t^{0.11}$

AB-MODEL



$$< \rho > \propto t^{-0.45}$$

$$< \Sigma_{AB} > \propto t^{-0.45}$$

- <ρ> and Σ_{AB} related
- compatible with curvature driven growth (SFKI)

Domain growth: $l(t) \propto t^{0.45}$

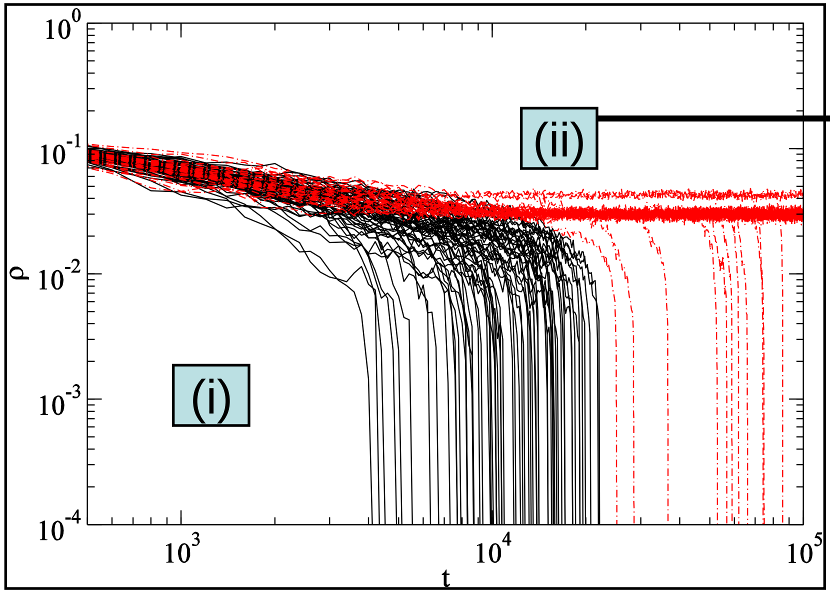
DYNAMICAL METASTABLE STATES:

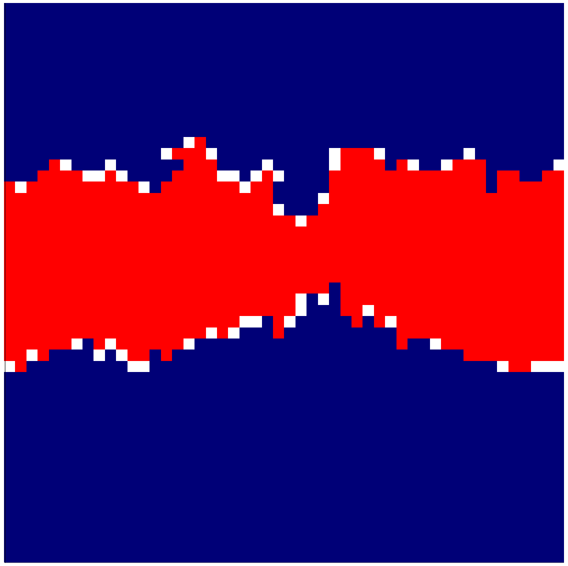
On a closer inspection …

TWO TYPES OF REALIZATIONS

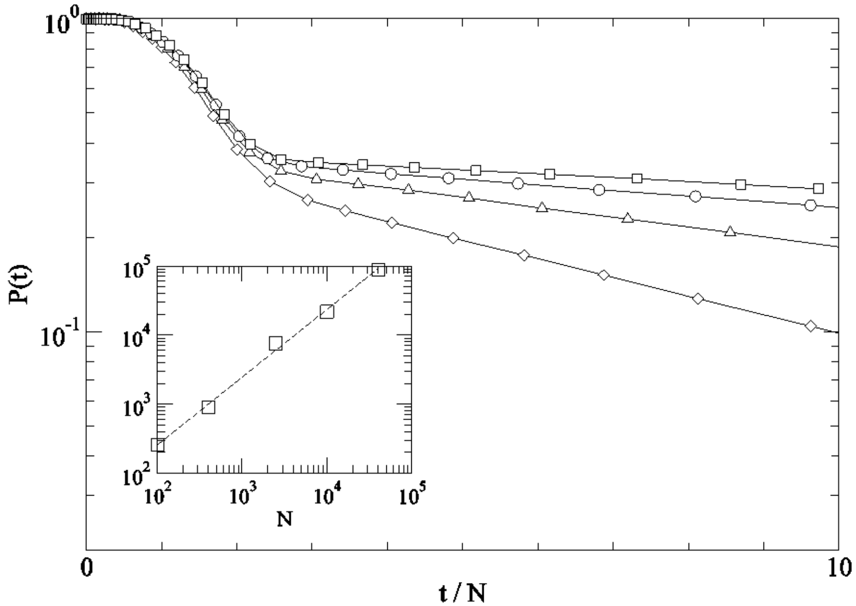
p=2/3 i) coarsening stage + finite size fluctuation towards consensus

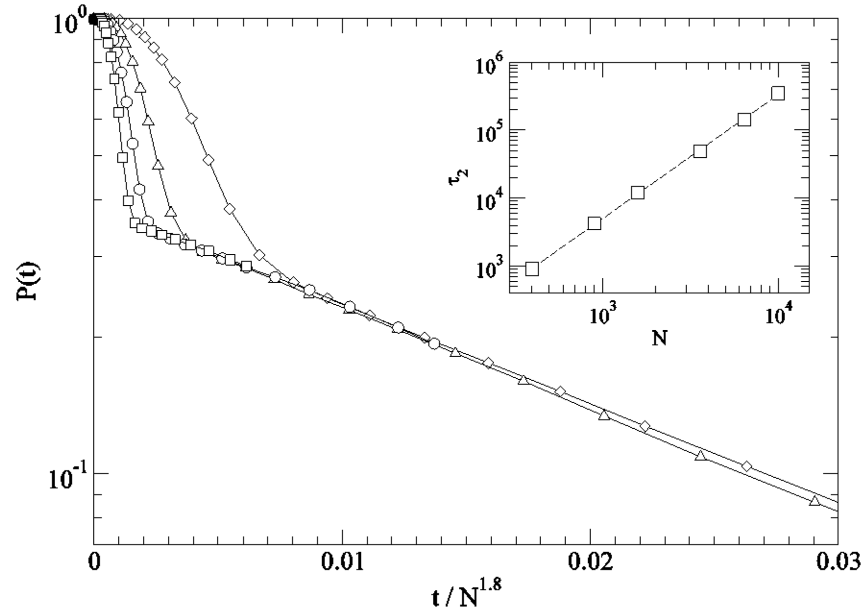
p=1/3 ■ ii) coarsening + **long-lived metastable state** *(ρ≈cte)*+finite size fluctuation towards consensus





DYNAMICAL METASTABLE STATES: P(t) fraction alive runs





(i) Average time to reach consensus $\tau \propto N$

characteristic of curvature driven coarsening (Ising model)

(ii) Distribution of survival times:

$$P(t) \sim e^{-\alpha(N)t} \longrightarrow \tau \propto N^{1.8}$$

These states dominate the global scaling for large systems

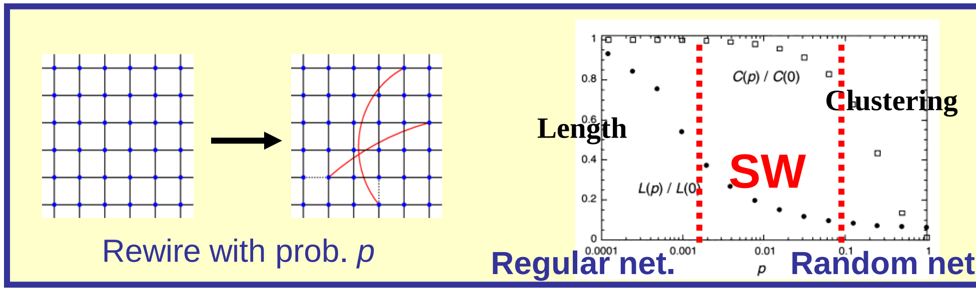
$$\tau_{AB} / \tau_{voter} \propto N^{0.8} / \ln N$$

RESULTS 2:

Voter model VS AB-model in small world networks

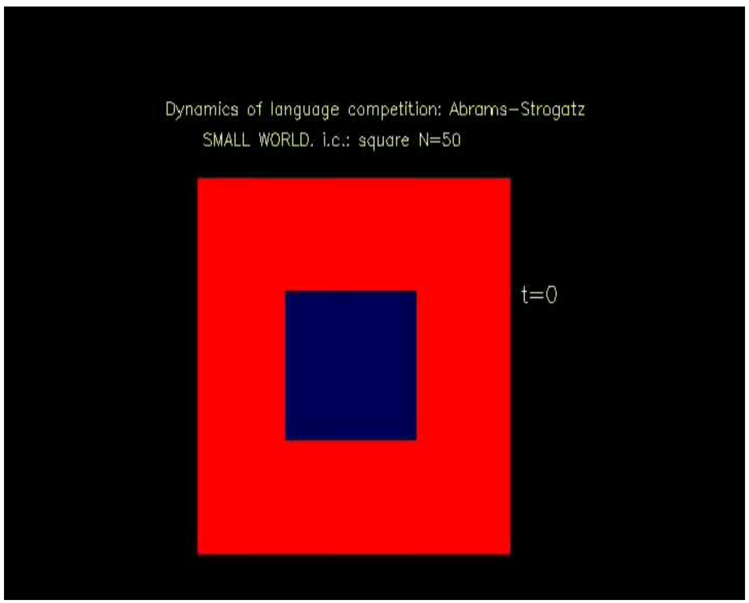
➡ **Castelló et al.** *New Journal of Physics*, 8, 308 (2006)

Social Structure: Small World Network

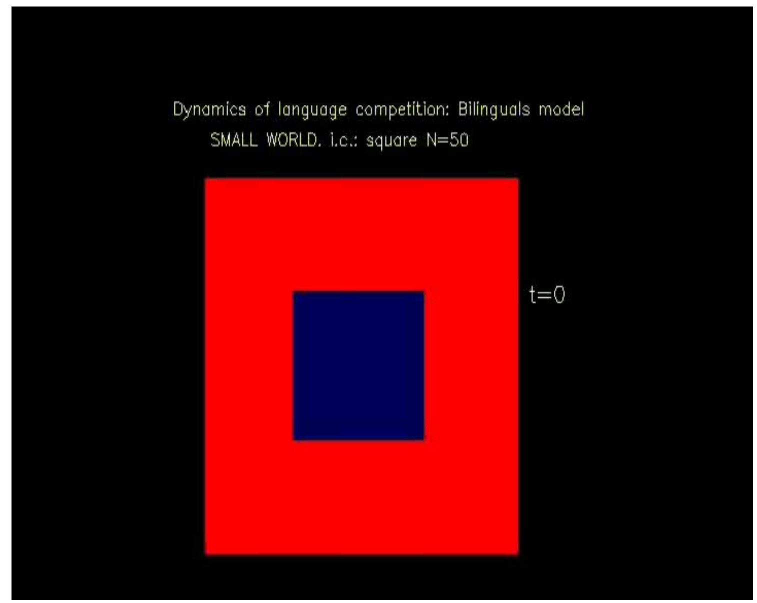


- State A
- State B
- AB-agents

VOTER MODEL



AB-MODEL



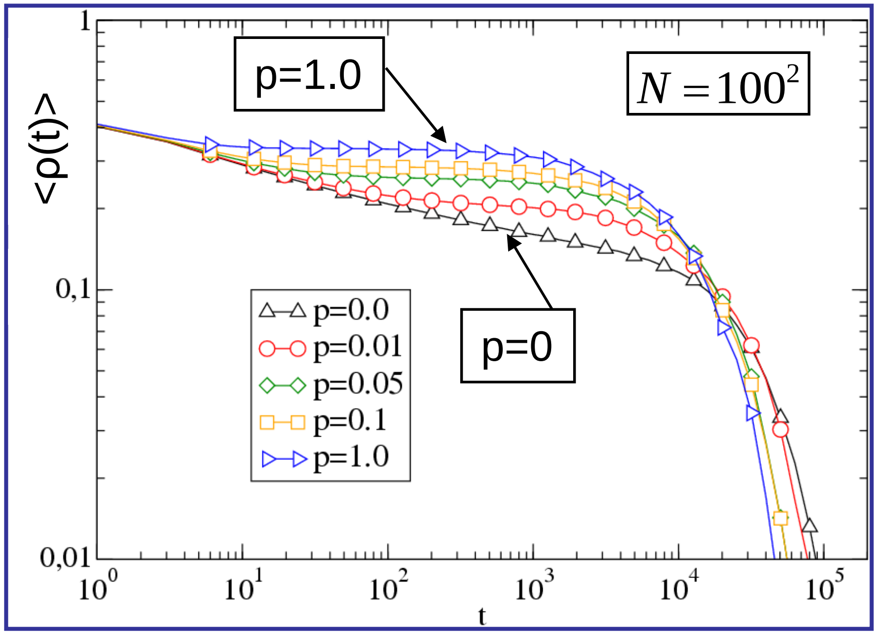
$p = 0.1 \quad N = 50^2$

AB-agents + Small World produce faster path to consesus

Social Structure: Small World network

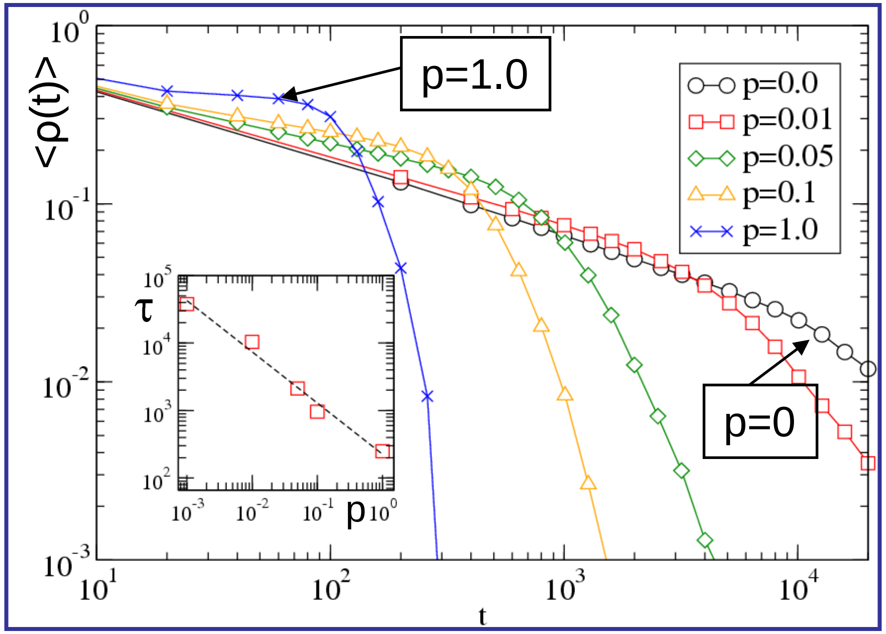
τ : average time to reach an absorbing state

VOTER MODEL



- Coarsening stopped: ***Metastable states***
- Minor effect of *p* $\tau \approx cte$

AB-MODEL

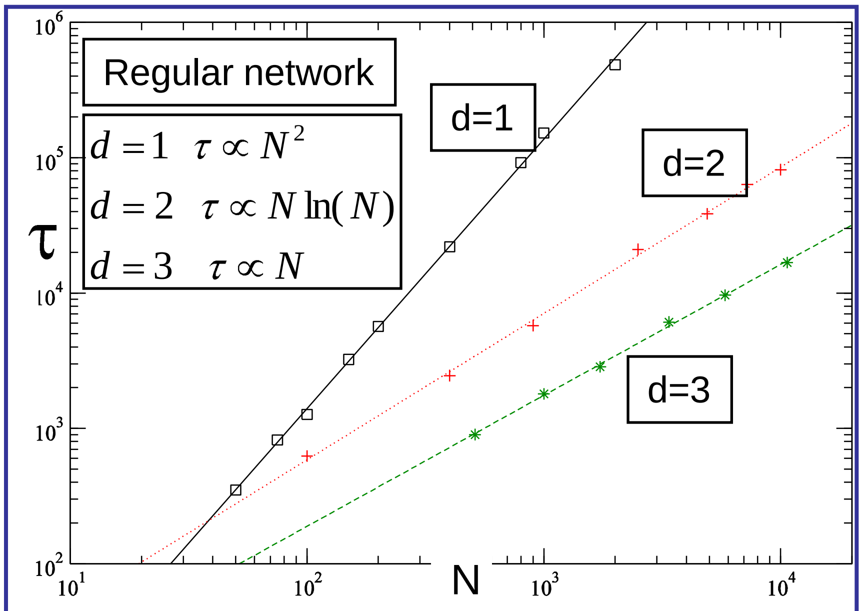


- Slower coarsening when increasing *p*.
- Strong effect of p. $\tau \propto p^{-0.74}$

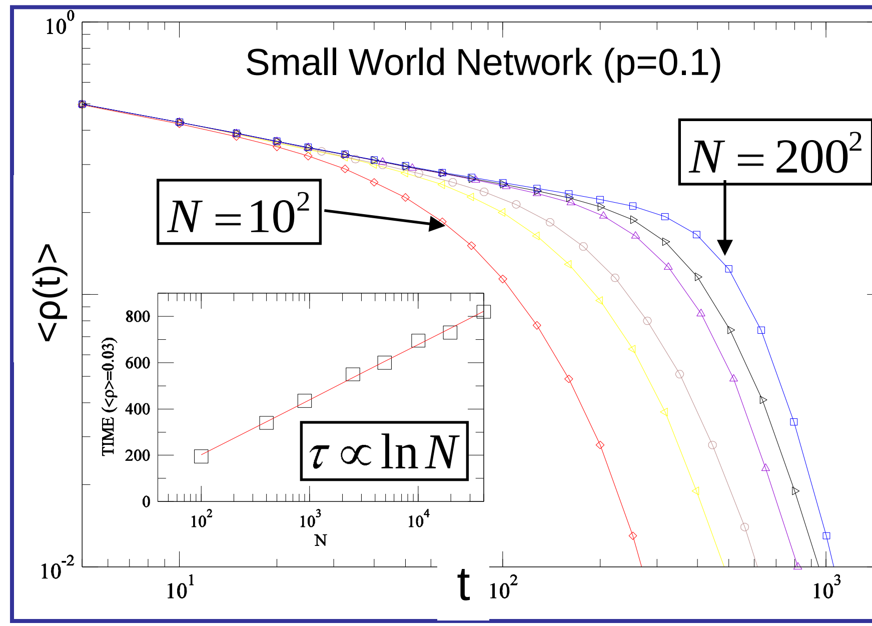
For fixed *p*: AB-agents produce: faster growth of single-option domains also a faster extinction of one of them $\tau_{AB} / \tau_{voter} \propto \ln N / N$

Time to consensus: dependence on system size.

VOTER MODEL



AB- MODEL



- Small World net: $\tau \propto N$ (voter model)

In a **smW network** bilingual agents cause a faster extinction: $\tau_{AB} / \tau_{voter} \propto \ln N / N$

Characteristic times to consensus. Summary

	VOTER MODEL	AB-MODEL
Regular d-dimensional networks	$d=1 \quad \tau \propto N^2$ $d=2 \quad \tau \propto N\ln(N)$ $d=3 \quad \tau \propto N$	$\tau \propto N^{1.8}$ (2 dim. Regular Net) $\tau_{AB}/\tau_{voter} \propto N^{0.8}/\ln N$
Small World network	$\tau(p) \approx cte$ $\tau \propto N$	$\tau(p) \propto p^{-0.74}$ $\tau \propto \ln N$ **(also in FC Nets)** $\tau_{AB}/\tau_{voter} \propto \ln N / N$ **AB agents foster consensus**

CONCLUSIONS I

AB-model (extension of the *voter model*): **AB-agents** is **NOT** effective mechanism in stabilizing the coexistence of two competing options. **Consensus ALWAYS** reached.

Role of AB-agents: **-** ***AB-agents*** **→** at the *interfaces*

- no formation of AB-domains

-dynamical metastable states (stripe-like configurations)

<u>Noisy interface dynamics → Curvature driven</u>

Role of Small World social structure (large systems): consensus **earlier** when AB-agents are *present*!!!

LANGUAGE COMPETITION*. Within the assumptions and limited framework of current models:*

bilingualism is **NOT** an effective mechanism in stabilizing the coexistence of two competing languages, and extinction is accelerated when a **small world social structure** is considered

RESULTS 3(a)

Voter model VS AB-model in community networks

Castelló, X.;Toivonen, R.; Eguíluz, V. M.; Saramäki,J.; Kaski, K.; San Miguel,M.
Europhysics Letters 79, 66066 (2007)

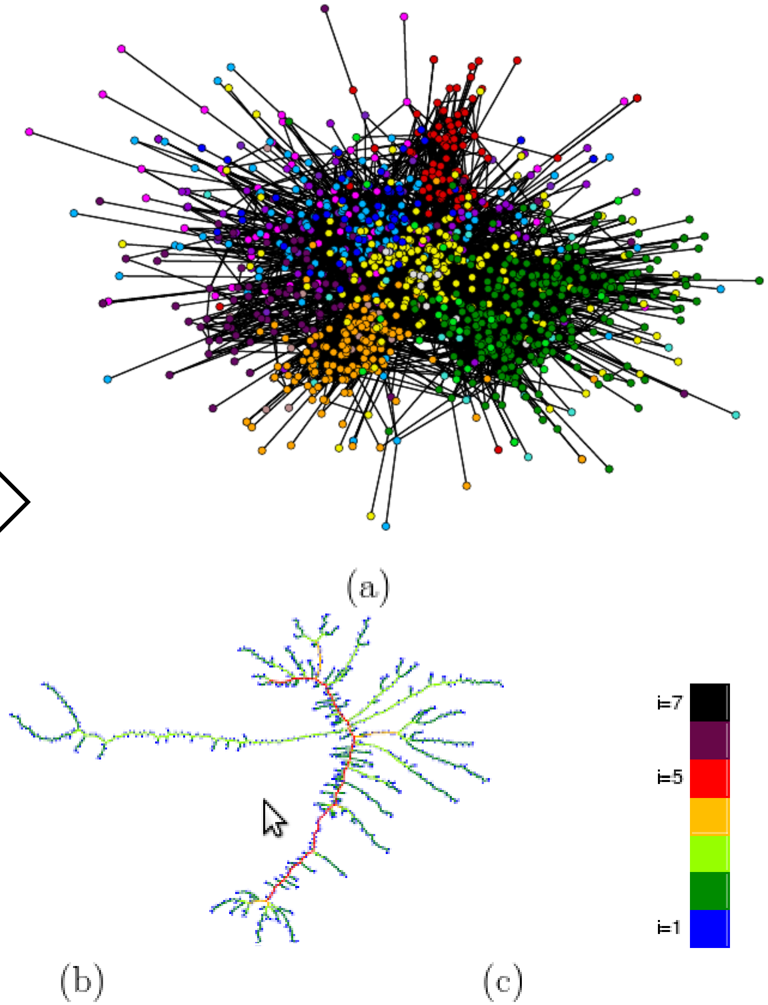
NETWORKS WITH COMMUNITY STRUCTURE

Definition of ***community***: set of nodes more interconnected with one another, than with the rest of the network

EXAMPLE

E-mail network of Universitat Rovira i Virgili (Tarragona)

R. Guimerà, L. Danon, A. Díaz-Guilera, F. Giralt and A. Arenas, Journal of Economic Behaviour and Organization , 61(4), 653-667 , (2006)



Detection algorithm used:

→ removal of high betweeness links

Newman M E J and Girvan M, Phys. Rev. E 69 026113 (2004)

DYNAMICAL EFFECTS

Impact on the dynamics already found in:

- synchronization

A. Arenas, A. Díaz-Guilera, and C. J. Pérez-Vicente, Phys. Rev. Lett. 96, 114102 (2006)

- information transfer

J.-P. Onnela, J. Saramäki, J. Hyvönen, G. Szabó, D. Lazer, K. Kaski, J. Kertész, and A.-L. Barabási, PNAS. (USA) 104, 7332 (2007)

- emergence of cooperation

S. Lozano, A. Arenas, and A. Sánchez, PLoS ONE 3, e1892 (2008)

MODEL NETWORK:

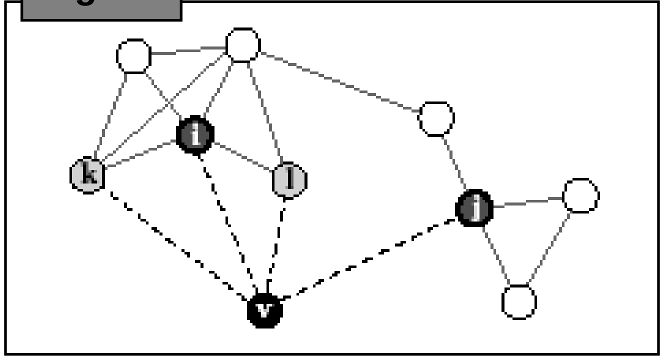
→ mimics features found in real social networks

- i) Communities
- ii) Hubs
- iii) Assortativity
- iv) High clustering

Algorithm:

- i) Start with seed network of N_0 nodes.
- ii) Add a new node *v*.
- iii) Pick on average $m_r \geq 1$ random vertices as initial contacts. *(I,j in figure)*
- iv) Pick on average $m_s \geq 0$ random neighbours of each initial contact as second contacts. *(l, k* in figure*)*

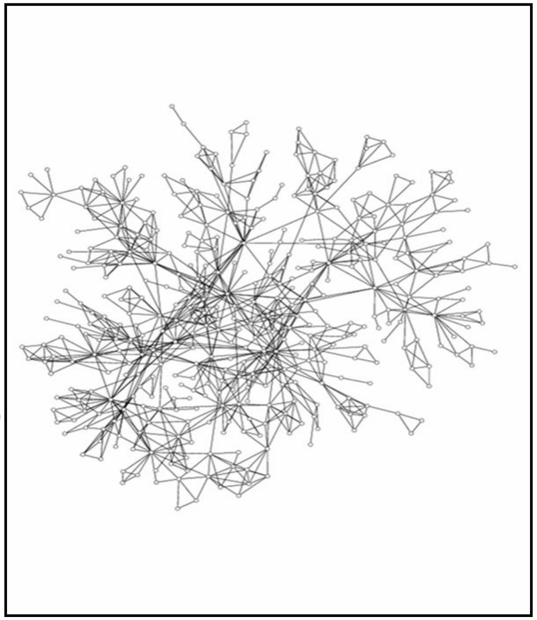
Figure:



Standard parameters:

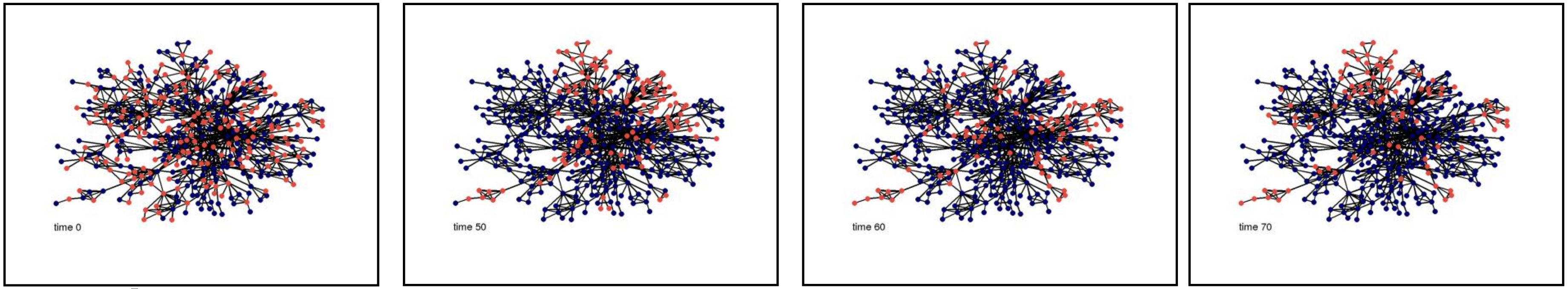
1st contacts: $p_1=0.95$; $p_2=0.05$

- 2nd contacts from U(0,3)



R. Toivonen, J.-P. Onnela, J. Saramäki, J. Hyvönen, K. Kaski, *Physica A*, Volume 371, Issue 2, 15 Nov 2006, Pages 851-860

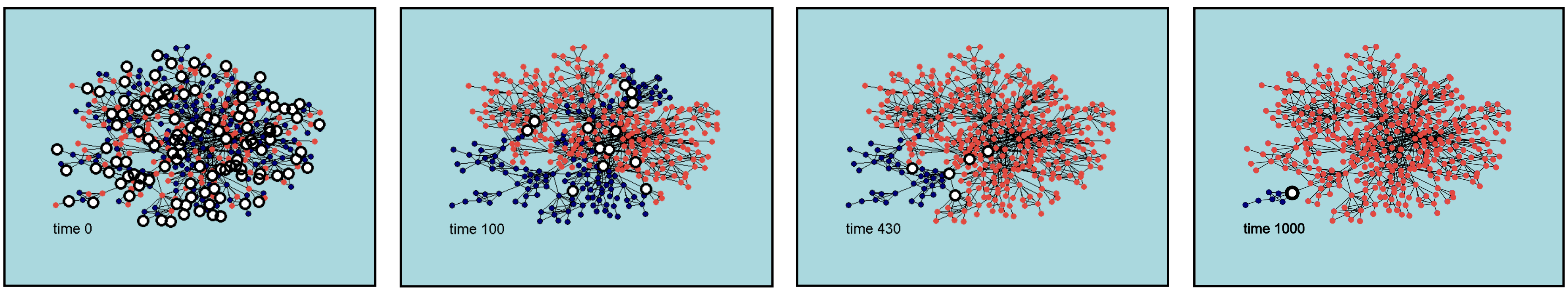
VOTER MODEL → Minority option **does not get localized** in the network!



→ Minor effect of community structure.

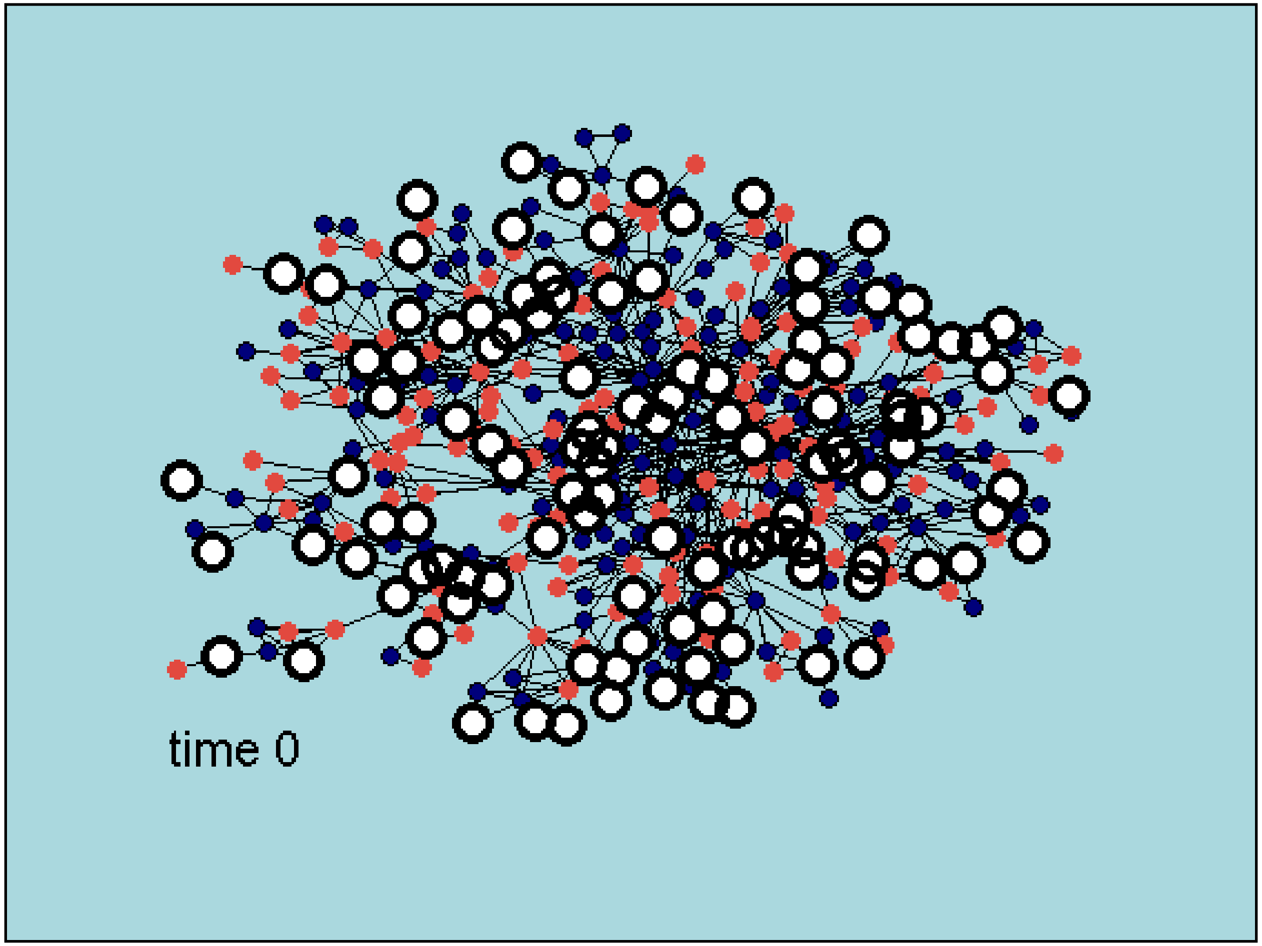
- State A
- State B
- AB-agents

AB-MODEL → Single-option domains **correlated with the communities!**

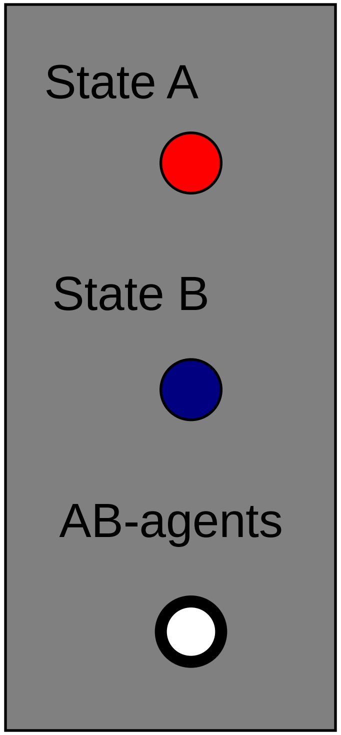


→ **IMPORTANT** effect of community structure.

AB-model in CommNet: time evolution



Legend



Analysis of the distribution of "alive" runs, P(t)

$$P(t) = 1 - \int_0^t p(t')dt'$$

p(t): probability distribution of life times

VOTER MODEL

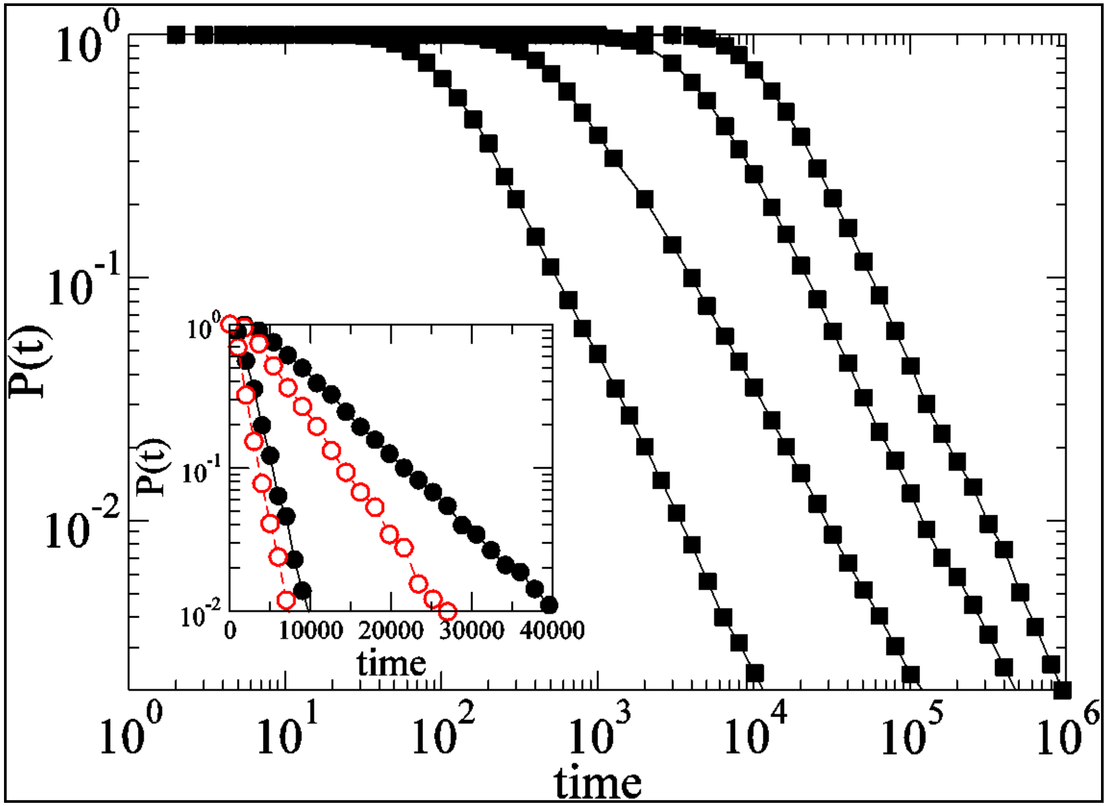
Exponential decay for the distribution of "alive" runs (*inset*)

AB-MODEL

Power law decay for the distribution of "alive" runs

$$P(t) \propto t^{-\alpha}, \alpha \approx 1{,}3$$

<τ> does not define a characteristic time scale!
► alive runs at any time scale



N=100, 400, 2500, 10000

Closer inspection: analysis of single runs in the AB-model

CLASSES OF REALIZATIONS:

(i)

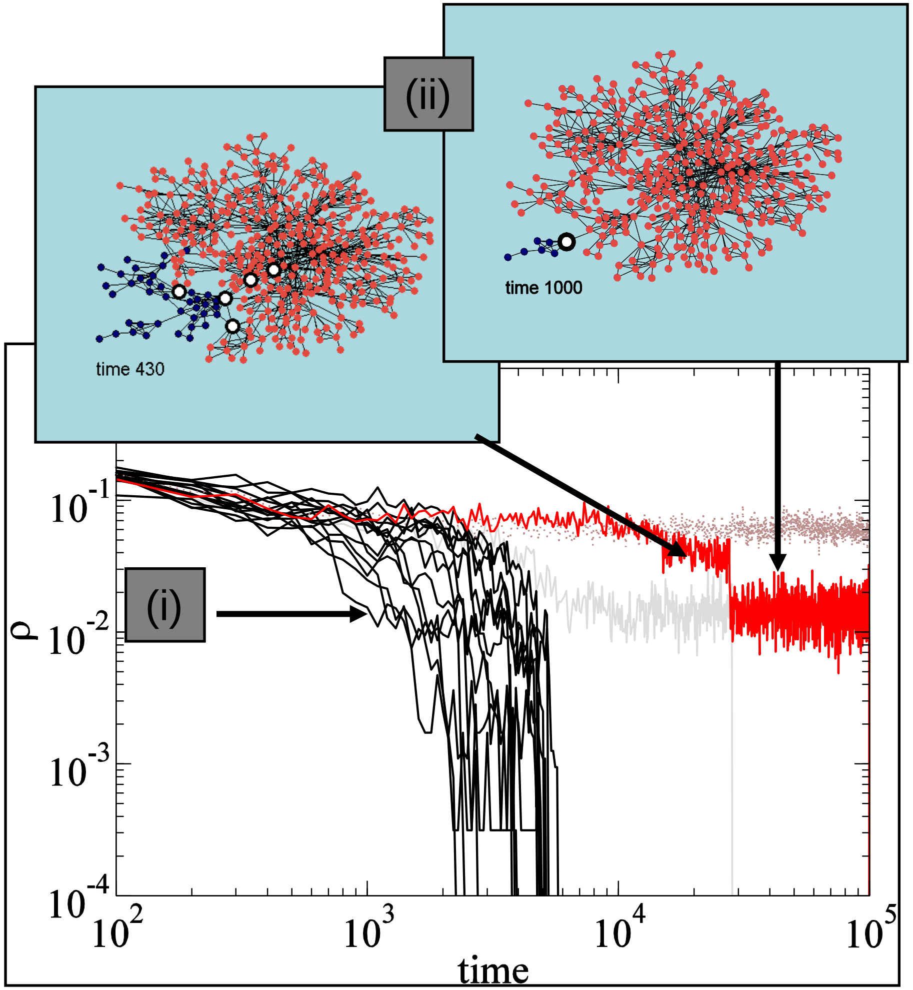
Ordering stage + extinction

(ii)

Ordering + fall into long-lived
trapped metastable states

NO characteristic
time scale
scenario of coexistence at any time scale

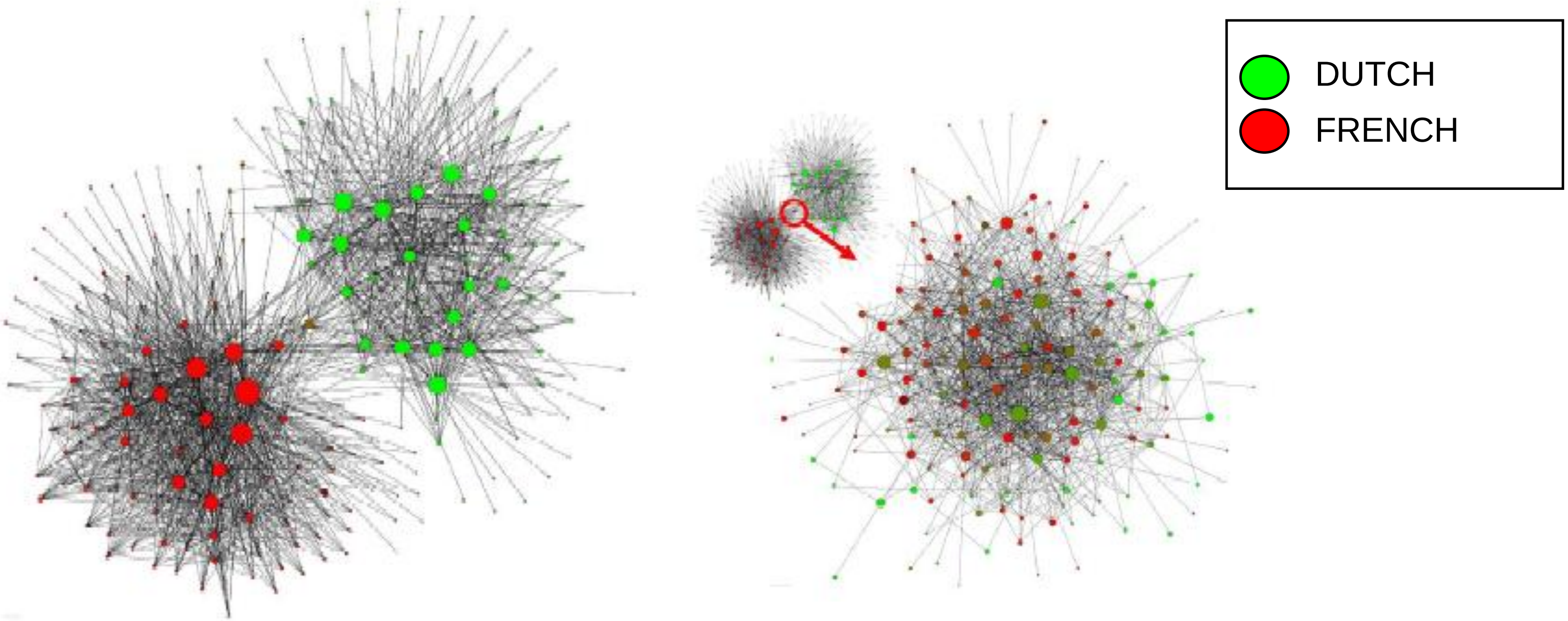
Hierarchical levels



DATA on LANGUAGE USE

analysis of a Belgian mobile phone network of 2.6 million customers

V. D. Blondel, J.-L. Guillaume, R. Lambiotte, E. Lefebvre arXiv:0803.0476v1 [physics.soc-ph] (March 2008)



RESULTS 3(b)

AB-model in *clique-like* community networks

Toivonen, R.; Castelló, X.; Eguíluz, V. M.; Saramäki, J.; Kaski, K; San Miguel,M.
Physical Review E 79, 016109 (1-8) (2009)

MECHANISMS AT WORK AT MESOSCALE LEVEL

Which are the minimal (sufficient) ingredients for the existence of a PL distribution for P(t) such that a characterstic time scale does not exist in the dynamics??

IDEA: build up a simple "controllable" community structure

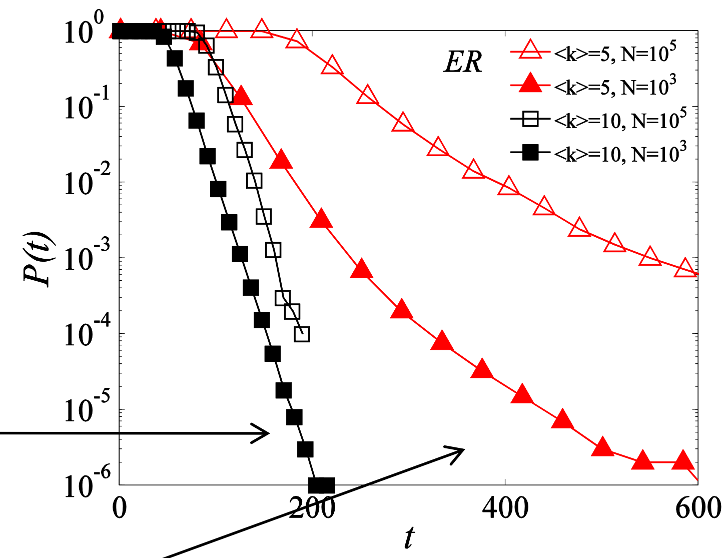
→ complex networks with **cliques** as *super-nodes*
(clique: set of nodes which are all interconnected)

Topologies studied:

► a) Erdös Renyi random networks (*no communities*)

► b) Clique-community networks

a) Erdös-Rényi networks



- <u>Networks with *large* <*k*>:</u>

P(t) shows exponential decay (<k>=10)

$$P(t) \propto e^{-t/\tau}$$

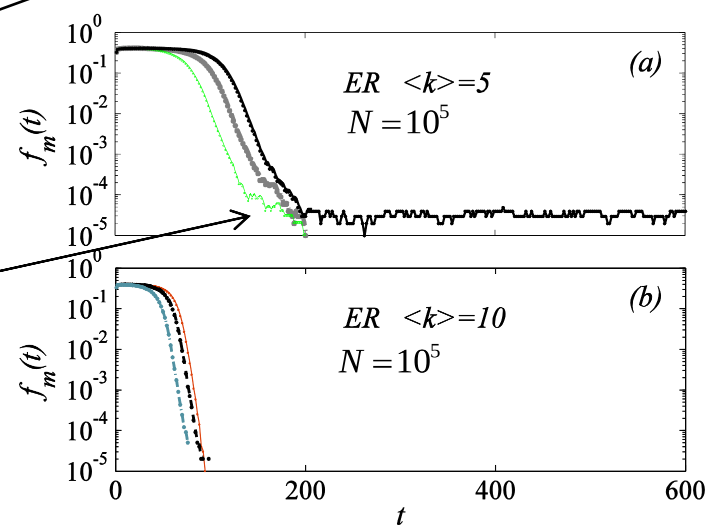
- <u>Networks with *small*<*k*>:</u>

P(t) shows broader than exponential tails for “small *k*” (<k>=5)

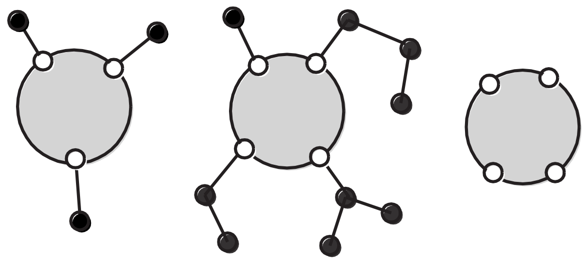
↓

metastable states

f_m : fraction of nodes in the minority state



What happens for small <k>?



<k>=10 <k>=5 2-core of <k>=5

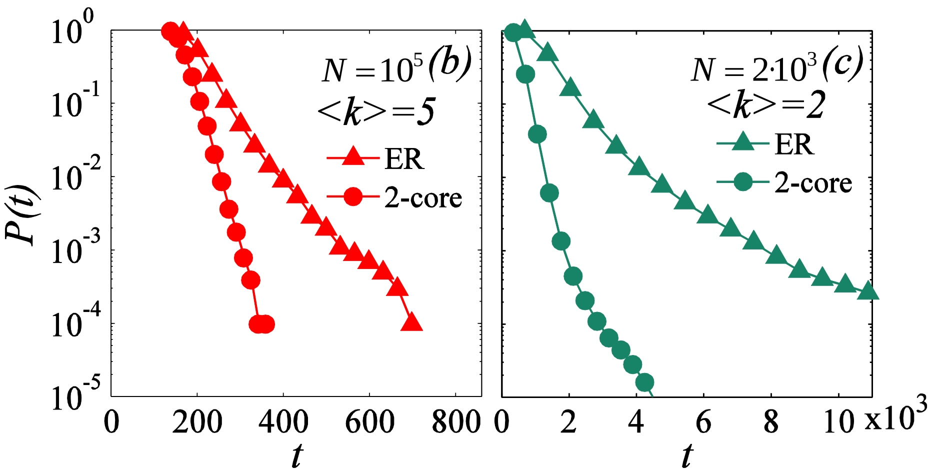
<u>The role of *branches*:</u>

Get the *2-core of the network*

(remove nodes *i* with $k_i = 1$ until all nodes have $k_i \geq 2$)

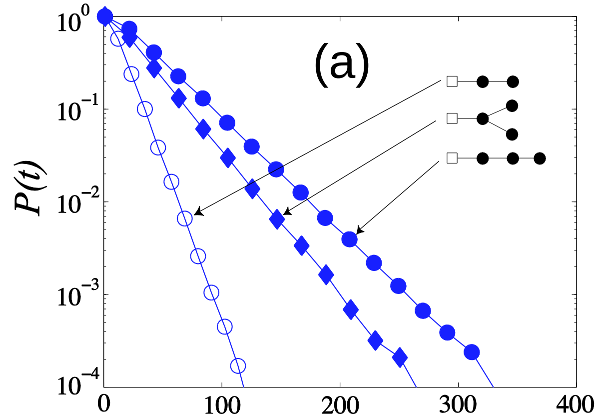
►*Except for very sparse networks (<k>=2), an exponential tail is recovered.*

► *Branches are responsible for the longest-lived metastable states.*



Dynamical robustness

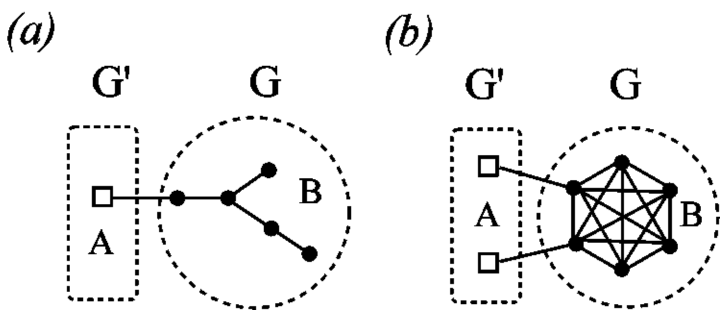
(for a given topological structure *G in a given dynamics)*



The resistance of *G* against consenting to outside preasure applied to G by its neighbours *G'*

Characterized by a survival time τ

$$P(t) \propto e^{-t/\tau}$$

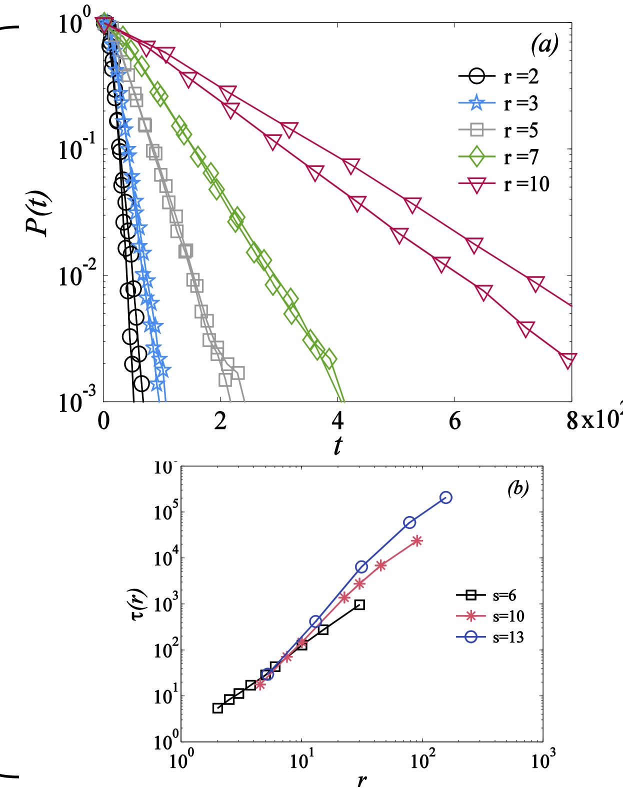


Dynamical robustness for a *clique* (size: *s*) (characterized by the topological measure, *r*)

$$r \equiv \frac{k_{n_{in}}}{< k_{n_{out}} >} = \frac{s(s-1)}{k_{c_{out}}}$$

s ↑ → **r** ↑

K



b) Clique-community networks

random networks (degree $k_{c,out}$) with **cliques** as *super-nodes*

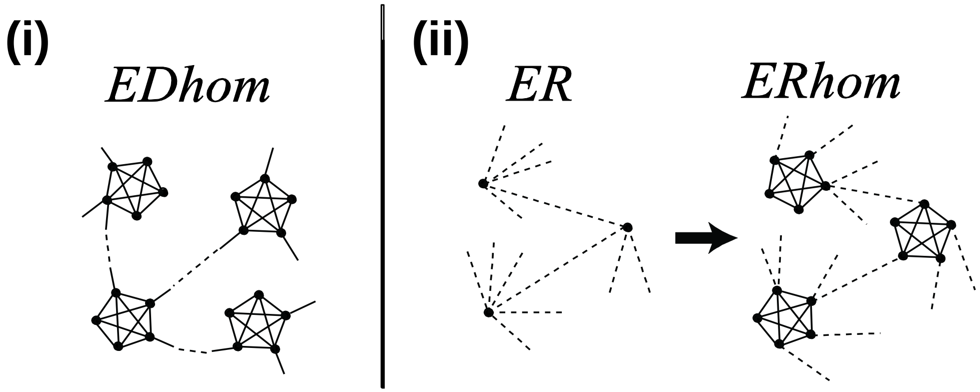
► Equally sized cliques (s: clique size): $p(s)=\delta(s-s')$

i) Equal out-degree random network $p(k_{c_{out}})=\delta(k_{c_{out}}-\langle k_{c_{out}}\rangle)$ (**EDhom nets**)

ii) Erdös-Rényi networks (**ERhom nets**)

► Exponential distribution of clique sizes $p(s)\propto e^{-(s-s_{\min})/\mu}$ $\longrightarrow$ heterogeneous cliques

iii) Equal out-degree random network $p(k_{c_{out}})=\delta(k_{c_{out}}-\langle k_{c_{out}}\rangle)$ (**EDexp nets**)



i) EDhom Nets

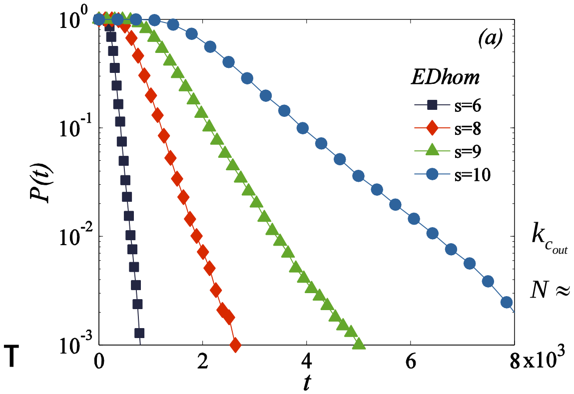
$$p(s) = \delta(s - s')$$

$$p(k_{c_{out}}) = \delta(k_{c\,out} - \langle k_{c_{out}} \rangle)$$

homogeneous dynamical robustness of cliques

$$P(t) \propto e^{-t/\tau}$$

Well defined characteristic time, τ



$k_{c_{out}} = 10$

$N \approx 10^3$

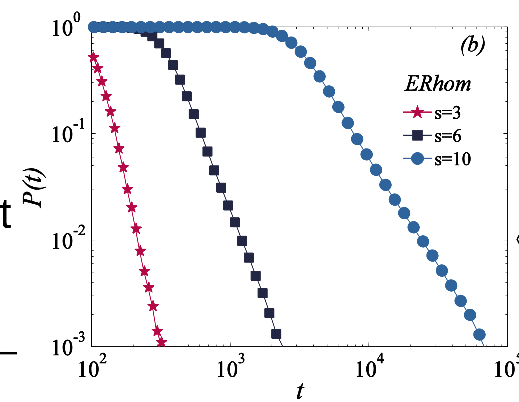
ii) ERhom Nets

$$p(s) = \delta(s - s')$$

$$p(k_{c_{out}}) = e^{-\langle k_{c_{out}} \rangle} \frac{\langle k_{c_{out}} \rangle^{k_{c_{out}}}}{k_{c_{out}}!}$$

small differences in dynamical robustness of cliques

P(t) broader than exponential, but with well defined characteristic time, τ



$\langle k_{c_{out}} \rangle = 10$

$N \approx 10^3$

iii) EDexp Nets

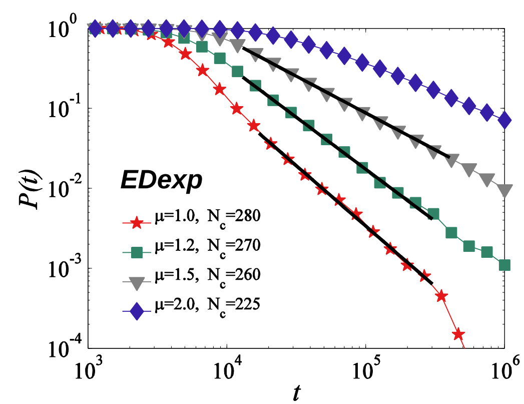
$$p(s) \propto e^{-(s - s_{\min})/\mu}, \; s_{\min} = 3$$

$$p(k_{c_{out}}) = \delta(k_{c\,out} - \langle k_{c_{out}} \rangle)$$

$$P(t) \propto t^{-\eta}, \; 1 < \eta < 2$$

Dynamical robustness heterogeneity

→ NO characteristic time!!

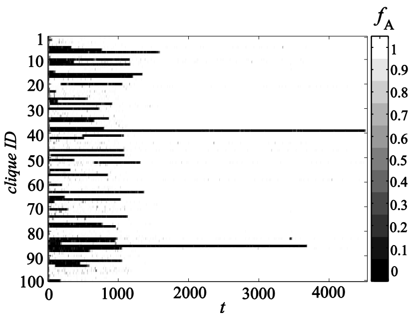


$k_{c_{out}} = 3$

$N \approx 10^3$

SUFFICIENT MECHANISM dynamical robustness heterogeneity at mesoscale level

Metastable states

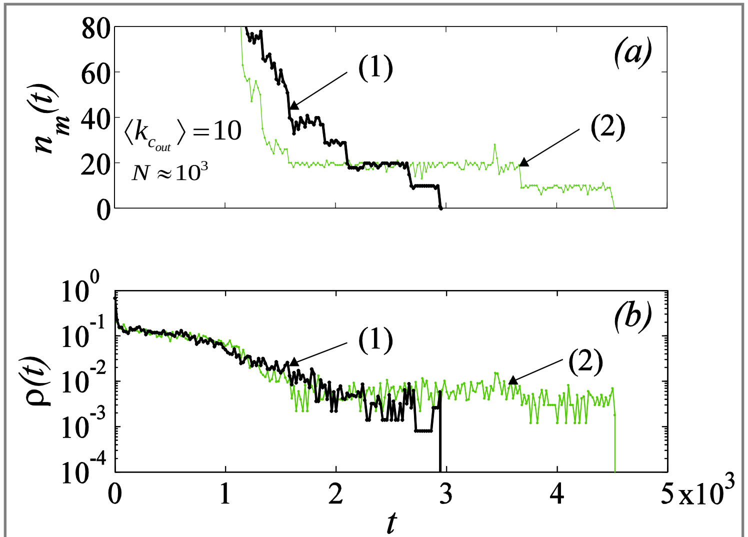


■ ERHom (*s=10*)

n_m: number of agents in the minority state
ρ: interface density

- Cliques **rarely convert** to the minority state

- *Role of branches* : cliques that remain in the minority state have a relatively small number of out-links (hence are slightly more dynamically robust).

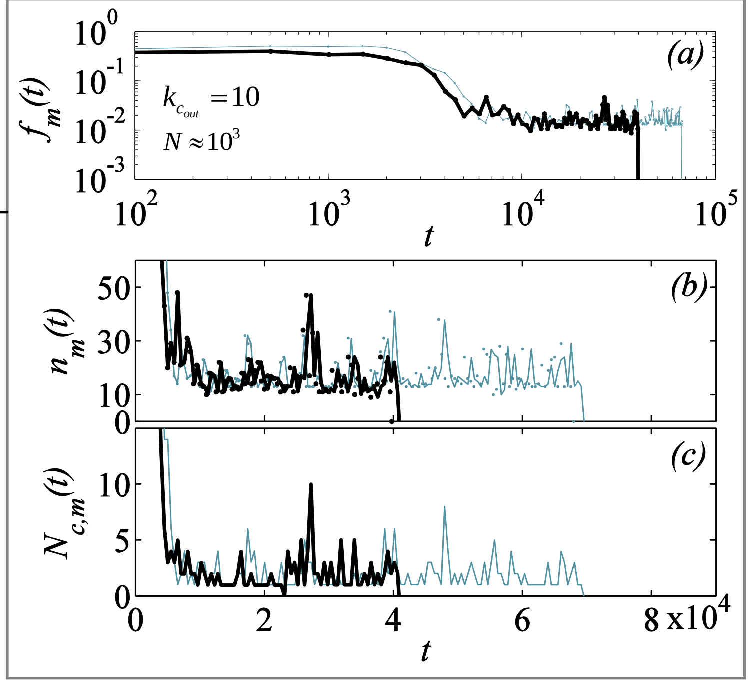


■ EDexp

f_m: fraction of agents in the minority state
$N_{c,m}$: number of cliques in which more than 90% were in the minority state

<u>*Buffering effect*</u>: a relatively big cluster converts its less dynamically robust neighbouring cliques

→ $N_{c,m}$ **fluctuating** around 1



CONCLUSIONS II

Final scenario (Voter Model & AB-model) ➡ **CONSENSUS** in *A* or *B* option **(***absorbing states***)**

Important: **TRANSITION** towards **consensus** ⟶ depends on **NETWORK STRUCTURE**

Role of Community Structure in the ordering dynamics:

● Voter Model : not significantly sensitive to mesoscale structure

● AB-model: **LONG** extinction times. NO characteristic time scale..!!
- we find scenario of coexistence of the options at any time scale
- single-option domains correlated with community structure!! (+hierarchical levels)

→ *Sufficient mechanism* **: dynamical robustness heterogeneity at the mesoscale level**

Within the assumptions and limited framework of current models for socially equivalent languages:

Language coexistence is favoured by social structures with **heterogeneous mesoscale structure** when **bilingual agents** are considered in the modelling (effect of *curvature driven dynamics*)

→ contrary to *smW*, they favour minority language to be resilient in dynamically robust communities

Other works

Consider languages within a **viability/resilience problem**.

effects on the tuning of prestige (s) → actions of the government

Bernard, Chapel, Castelló et al. et al. (2008) preprint

Explore the whole **parameter space** (a,s): transitions from scenarios of coexistence → dominance

→ **MW-model** has a *generalized voter model transition* shifted compared to **AS-model**

work in progress... with F. Vázquez

Link dynamics: language modelled as a property of the interaction (LINK) rather than of the agent (NODE)

bilingual agents emerge naturally + dynamics in the associated line graph

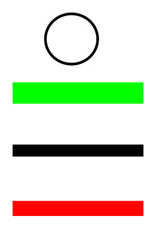
work in progress... with V. Eguíluz & M. San Miguel

Explore new dynamics allowing for the **emergence of a NEW language** due to language contact (preliminary results using the Naming Game framework)

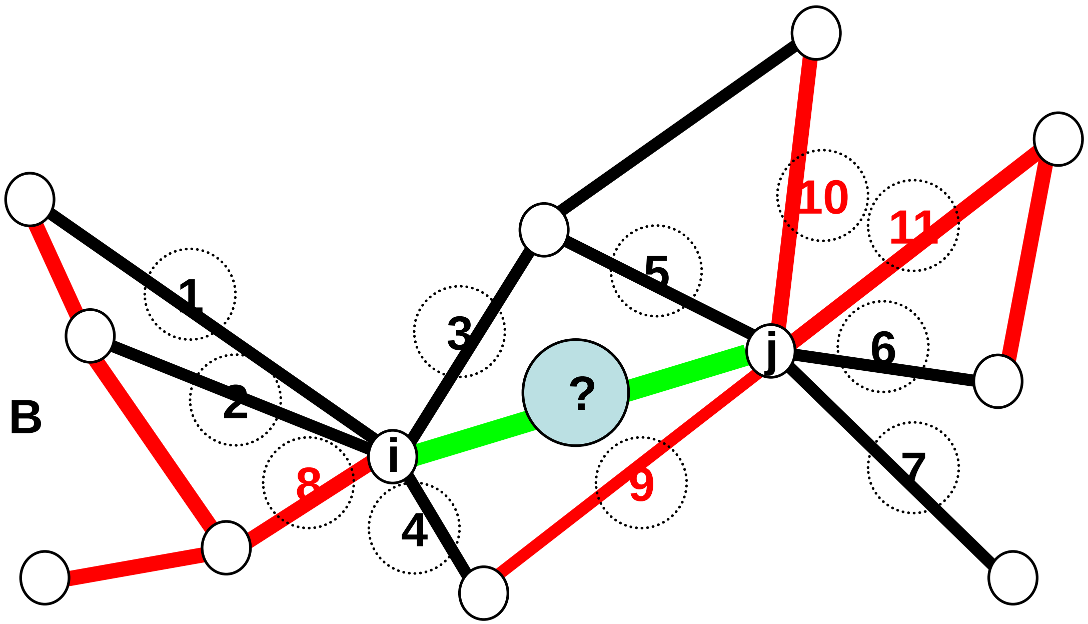
→ towards *creolization*

Castelló, Baronchelli, Loreto (2009) preprint
+ work in progress ...

LINK Dynamics: Language is a link, not an agent property



σ_m proportion of m-links of contacts from i and j. m=A, B



$$p_{?\to B} = \sigma_B = 4/11$$

$$p_{?\to A} = \sigma_A = 7/11$$

a=1, s=0.5

Types of agents

Monolingual A ***100% A-links***

Monolingual B ***100% B-links***

Bilingual agent ***q % A-links*** ***100-q % B-links***

→ ***different degrees of bilingualism***

Bilinguals: Agents vs. Link Dynamics

- Monolingual A
- ¾ links A
- 2 links A, 2 links B
- ¾ links B
- Monolingual B

Regular network, marginal volatility (a=1), no prestige (s=0.5)

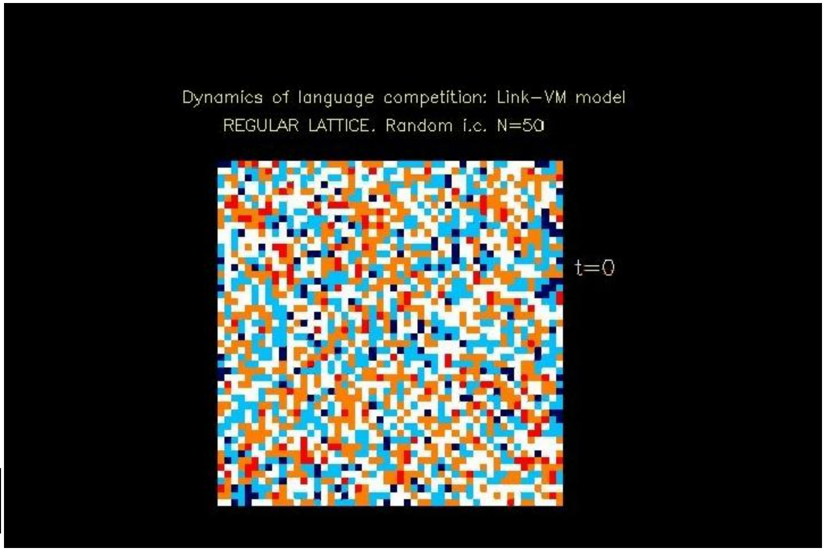
Agent-based model

SEE APPLET!

http://www.ifisc.uib-csic.es/research/complex/APPLET_LANGDYN.html

$N = 50^2$

Link-based model



Coarsening: Growth of monolingual spatial domains. No bilingual domains

Bilinguals *are* the interfaces (linguistic borders)
► Dynamics: Curvature driven
FASTER growth of the monolinguistic domains.

Broad linguistic borders
► Dynamics: Interfacial noise
SLOWER growth of the monolinguistic domains.

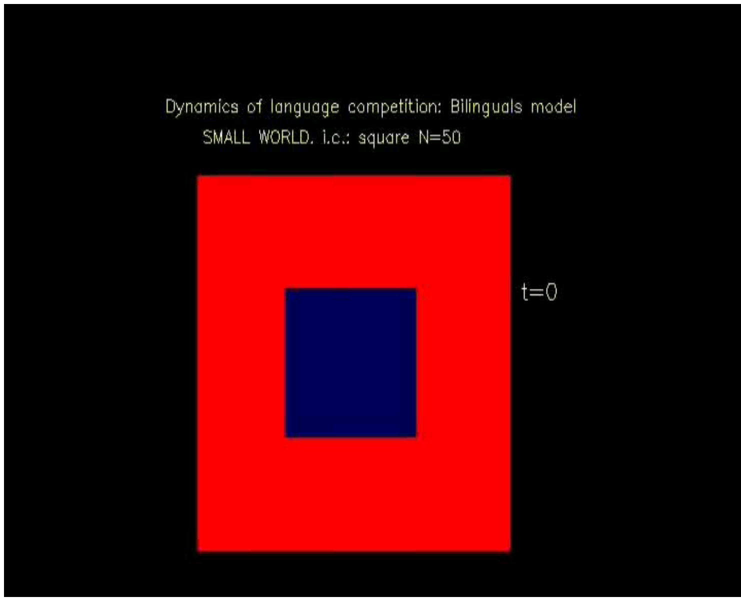
Bilinguals: Agents vs. Link Dynamics

Monolingual A
Links A > 60%
40%< Links A< 60%
Links B > 60%
Monolingual B

Small World Network

marginal volatility (a=1)
no prestige (s=0.5)

Agent-based model

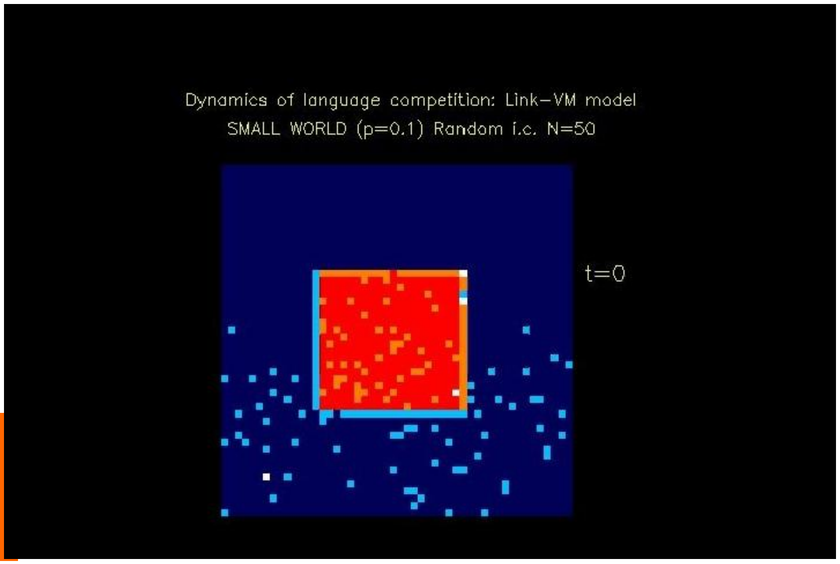


- ***Fast extinction of one monolingual community***

$p = 0.1$

$N = 50^2$

Link-based model



- ***Long lived metastable states of language coexistence***
- ***Large fraction of bilingual agents in state of coexistence ~ 40%***

THANK YOU FOR YOUR ATTENTION!

List of publications:

X. Castelló, V. Eguíluz and M. San Miguel. *New Journal of Physics*, 8, 308 (2006)

+ **Dietrich Stauffer,** *Physica A, **374**, 835-842 (2007)*
+ **Lucía Loureiro Porto** *Advancing Social Simulation: The First World Congress. Takahashi, Shingo; Sallach, David; Rouchier, Juliette (Eds.) (2007)*
+ **R. Toivonen, J. Saramäki, K. Kaski** *Europhysics Letters 79, 66066 (2007)*
+ **R. Toivonen, J. Saramäki, K. Kaski** *Physical Review E 79, 016109 (1-8) (2009)*