Social Simulation Based on Cellular Automata: Modeling Language Shifts

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1. Introduction

Nowadays, language shifts (i.e., a community of speakers stops using their traditional language and speaks a new one in all communication settings) may produce a massive extinction of languages throughout the world. In this context, an important task for social sciences research should therefore be to achieve a deep comprehension of language shifts. However, modeling the social and behavioral variables that guide the social behavior of individuals and groups has traditionally been tricky in all the social sciences. In this situation, social simulation provides a tool for testing hypotheses and building models of social phenomena (see, for example, Gilbert, 1996; Gilbert & Toitzsch, 2005; and Goldspink, 2002), especially the techniques based on cellular automata theory (Hegselmann, 1996; Hegselman & Flache, 1998; Nowak & Lewenstein, 1996). According to this framewok, we introduce the properties of a cellular automaton that incorporates some assumptions from the Gaelic-Arvanitika model of language shifts (Sasse, 1992) and the findings on the dynamics of social impacts in the field of social psychology (Latané, 1981; Nowak et al. 1990). Thus, we define a cellular automaton and carry out a set of simulations in which it is used. We incorporate empirical data from recent sociolinguistic studies in Catalonia (a region in Southern Europe) to run the automaton under different scenarios. The results allow us to highlight some of the main factors involved in a language shift. Finally, we also discuss how the social simulation based on cellular automata theory approach proves to be a useful tool for understanding language shifts.

2. A sociolinguistic model of language shifts

Although there are languages spoken in the past that are not spoken today, e.g., Etruscan, Egyptian and Hittite, and people usually refer to them as dead languages, the death of a language is not only an ancient event. UNESCO (2003) estimated that, by the end of this century, more than 5,100 of the approximately 6,000 languages currently spoken around the world will have disappeared; i.e., approximatelly 90% of them. When a language dies, the community of people that speak that language lose a main element of their identity and their cultural framework is impoverished as a result. The most likely future of that

community is its assimilation into a larger cultural group. Hence, the death of a language implies an irreversible impoverishment of the world's cultural diversity. In summary, language death is a major cultural problem today because (a) the large number of languages affected by extinction includes several million people and (b) humankind's cultural wealth is reduced as a result of language extinction.

Why does a language die? Obviously a language dies if its speakers disappear, either due to an action such as direct genocide or genocide through the destruction of their habitat or economic resources. But usually a language dies because the speakers *decide* to abandon the traditional language and to adopt a new one in all communication settings (Mühlhäusler, 1996). Note that the key factor for declaring that a given language becomes extinct is usage, not the linguistic competence of the speakers. So, the next question is what factors impel a whole community of speakers to shift from one language to another? One premise is that such community must be fluent in at least two languages. Then, if there are two or more languages in a community, a hierarchical structure is frequently adopted, with one becoming the dominant language (DL) and the other the subordinate language (SL). Althouhg it is possible for both languages to coexist within such a hierarchy for long periods of time, historical events can disturb the equilibrium. In these cases, the speakers of the SL may notice that their language has lost value relative to the DL. They may then *decide* that it is no longer useful and stop speaking it in all domains of use. Hence, there are three phenomena involved in language death (Sasse, 1992): (a) the cultural, historical, sociological and/or economic factors which create pressure to abandon the language in the speakers' community (the so called *external setting*), (b) the domains of use and the attitudes towards the languages of the speakers (so called *speech behavior*) and (c) the linguistic impoverishment observed in the morphology, phonology, syntax, etc., of the SL (so called *structural consequences*).

Although these three phenomena are interrelated (the pressure on the community created by the external setting compels speakers to modify their speech behavior, which produces an impoverishment of the structure of the SL), in the present study we will focus on the speech behavior of the individuals. Given the fact that an important issue related to language death is the language policies designed to reverse the language shift of threatened languages (Fishman, 1991), it is very important to take steps in the external setting where the language shift process occurs, i.e., by implementing government initiatives to ensure that the use of the SL is not mitigated. However, deciding to shift language or not is an individual decision made by each SL speaker. Therefore, it is also necessary to focus on individual factors relating to speech behavior to better understand a language shift and to design policies addressed to reverse language shifts.

Based on studies of the death of two languages in Europe, namely a variety of Scottish Gaelic and an Albanian dialect spoken in Greece, Sasse (1992) introduced the Gaelic-Arvanitika model. This model stated that one of the main factors involved in maintaining a language across generations is transmission within the family. If the parents speak to their children in a language other than their own, the language shift process will be completed in approximately two generations (see Figure 1). Although the Gaelic-Arvanitika model is biased towards an European context, it points out some relevant features involved in language shifts. For example, the death of a language is not a slow process lasting several centuries, but a fast process that can take a few decades.

Given the importance of attitudes towards the SL language in determining the speech behavior of the speakers, it is also necessary to take into account how individuals change their attitudes. In the field of social psychology, Latané (1981, 1996) explained how the opinions of
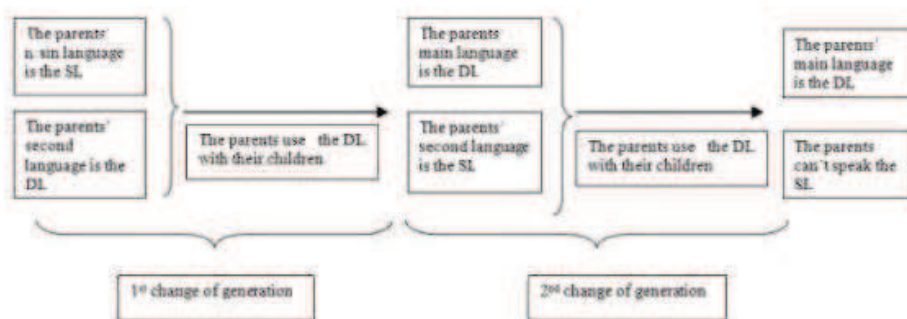
Fig. 1. Consequences of the interruption of language transmission in the family according to the Gaelic-Arvanitika model of language shifts: Given a dominant language and a subordinate language in a speaker community, the non-transmitted language (the SL) becomes extinct after two generations (from Beltran et al., 2009).

individuals change based on the social influence of the group they are in. According to Latané, the impact or social influence of a group over an individual is a product of three factors: (a) the strength over the individual, (b) the physical immediacy of group members and (c) the number of group members influencing the individual. The predictions of the theory and the dynamics of the social impact were studied exhaustively using both empirical research and simulation techniques (Latané et al., 1994, 1995; Latané & Wolf, 1981; Nowak et al., 1990). Similarly, we propose that an individual's speech behavior can be subjected to the same rules as social impact. We therefore hypothesize that a given individual will shift from the SL to the DL if he or she receives strong pressure from the individuals in the group and a considerable number of close neighbors maintain this pressure.

3. A language shift simulation based on cellular automata

3.1 A model of language shift based on cellular automata

There are currently many examples of potential language shifts around the world, so the social and cultural contexts where language shifts occur tend to vary. We developed a model involving a social context where two languages coexist and one is threatened with potential extinction. Our model states that the individuals will change their speech behavior in regard to the SL if they are weakly engaged with it and/or a considerable number of their neighbors maintain a different speech behavior. We can summarize the main features of speech behavior in our model as follows:

- It is a local behavior in time and space, because the decision to shift languages affects one individual at a given time.
- It is an autonomous behavior, because the external setting puts pressure on each individual to make the decision to shift languages, but this shift occurs without an explicit consensus with the members of the speaker community.
- It is mass behavior, because a great number of individuals make the decision to stop using their usual language and use the DL.
- It is parallel behavior, because the individuals make the decision to stop using their usual language and use the DL at approximately the same time.

All these properties produce a self-organized emergent social phenomenon because there is no centralized unit guiding the process and the overall result, i.e., the extinction of a

language, is not explicit in individual behavior. Note that the external setting that triggers a shift from a SL to a DL is usually a process guided by the group of DL speakers, which puts pressure on the speakers of the SL, but the language shift itself is an autonomous individual *decision* made by the speakers of the SL.

The behavior of the cellular automata exhibits properties of localism, parallelism, emergence, etc., as occurs empirically during a language shift. Thus, the transition rules of a given cellular automaton are frequently simple, but it is only possible to know the state of the cells in a given future time *t+k* by running the automaton from *t=0* to *t= k*. Similarly, it is possible to assume that the language shift is regulated by a set of simple rules at the local level (the speech behavior of individuals) which produces global behavior at the social level (the extinction of a language). If it is possible to define the transition rules that describe the main features of a language shift, running the automaton will make it possible to predict the future of a SL given different scenarios in the present.

According to our model, depending on the attitude towards the SL (i.e., the strength or weakness of individuals' engagement with the SL), the social pressure favoring the use of the DL and the number of neighbors engaged with the DL, the speech behavior of each person can be categorized in one of three main states. Each state number indicates the level of engagement with the SL, from zero (0) to maximum strength (2):

a. State 0: The person only speaks the DL.
b. State 1: The person usually speaks the DL, but also speaks the SL, depending on the communication setting. The person transmits the DL to his or her children.
c. State 2: The person usually speaks the SL, but also speaks the DL, depending on the communication setting. The person transmits the SL to his or her children.

Because of the hierarchical structure of the two languages, everyone usually knows the DL, but only a percentage of people know the SL. So a percentage of people are monolingual in the DL, but there are no monolinguals in the SL. To include the information about the speech behavior of individuals provided by the Gaelic-Arvanitika model, the definitions of states 1 and 2 include transmission of the DL or the SL to the next generation. Obviously, the speakers in state 0 transmit the DL to their children. The bilinguals transmit their preferred language to the next generation (the state-1 bilinguals transmit the DL and the state-2 bilinguals transmit the SL).

The speaker community of our model lives in a discrete two-dimensional torus-shaped world. The world contains 105x64 cells, with each cell containing an individual. In general, a simulation based on cellular automata makes use of an unlimited world (i.e., a torus) rather than a limited world (e.g., a square), because in a limited world the cells near the edge have incomplete neighborhoods. Moreover, a torus space in a language-shift simulation also shows that all individuals interact with each other without restriction. The amount data provided by the 6,720 cells makes it possible to do both statistical descriptions and visual analysis on the computer screen. At each unit of time, a cell can only be classified in one of the three possible language states (0, 1 or 2), indicating the individual's strength in the use of the SL. Our cellular automaton does not include the *birth* or *death* of cells, but each cell inherits the transmitted language when the generation is renewed.

A factor in determining the use of a given language is the number of interactions where it is possible to use that language. This includes *the submission rule*, a typical behavior of state-2 speakers, who tend to use the DL automatically when they address a DL speaker, even if the DL speaker is competent in the SL (for a complete explanation of the submission rule, mathematical modeling and language shift effects, see Melià, 2004). Thus, the number of

neighbors in each linguistic state also determines a given individual's use of the DL or the SL. In our model each cell has eight adjacent neighbors on the side and at the vertex (a Moore neighborhood with a radius of 1), and the sum of neighbor values indicates the social pressure on the individual to use the DL or the SL (a value between 0, if all cells in the neighborhood are classified in state 0, and 18, if all cells are classified in state 2). A low sum value means an individual has few opportunities to interact with his/her neighbors using the SL, but if the sum value increases, the individual's opportunities to interact using the SL also increase.

The transition rule determines the future state in time *t+1* of a given cell, which has a given state in time *t*. The new state of a cell depends on whether or not the sum of the neighborhood values, including the cell target, surpasses a previously defined threshold. There are three thresholds:

a. S_a: a sum value below the threshold produces a sharp transition, i.e., state 2 changes sharply to state 0.
b. S_b: a sum value below the threshold produces a transition from a higher-value state to a lower-value state, but a sum value above the threshold produces a transition from a lower-value state to a higher-value state.
c. S_c: a sum value above the threshold produces a transition from a lower-value state to a higher-value state.

		To state:		
		0	1	2
From state:	0	$\Sigma \leq S_b$	$\Sigma > S_b$	----
	1	$\Sigma < S_b$	$S_b \leq \Sigma \leq S_c$	$\Sigma > S_c$
	2	$\Sigma \leq S_a$	$S_a < \Sigma < S_b$	$\Sigma \geq S_b$

Table 1. The transition rule of the cellular automaton that simulates language shifts. Note that the transition from state 0 to state 2 is difficult to observe empirically, because it involves a monolingual speaker becoming bilingual with a preference for the SL.

The threshold values ($S_a < S_b < S_c$) indicate the individual's level of engagement with the SL. When there is a greater level of engagement, the individual needs a lower threshold value to move up to a higher-value state. So the individual increases his/her usage and transmission of the SL eventually increases with only a minimal number of current neighbors using the SL. Conversely, when there is a lower level of engagement, the individual needs a higher threshold value to move up to a higher-value state. So the individual decreases his/her usage and transmission of the SL eventually decreases if there is not a large number of current neighbors using the SL. The transition rule and an example are described in detail in Table 1 and Figure 2.

Our cellular automaton's universe, the states and the transition rule to simulate a language shift were implemented on a Microsoft® Excel spreadsheet. We defined three spreadsheets in an Excel book. One spreadsheet allowed the user to define the number of cells classified in each state at *t=0*, the threshold values (S_a, S_b and S_c) and the number of simulations, given an initial number of states and threshold values. The number of cells classified in each state was determined by indicating the probability of each cell falling into one of the three states at *t=0*. Another spreadsheet showed the cells and their states at each time unit. The state of the cell was indicated by a color: white for state 0, orange for state 1 and green for state 2. This spreadsheet also displayed the frequency of the states at each time unit. Finally, a third
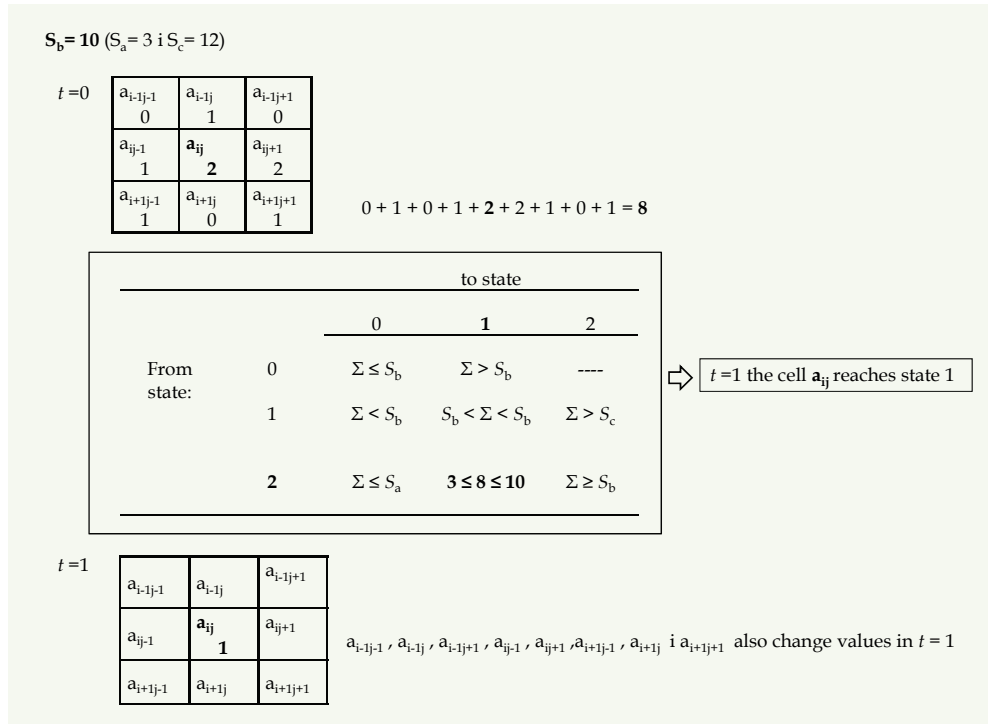
S_b = 10 (S_a = 3 i S_c = 12)

t =0

a_{i-1j-1} 0	a_{i-1j} 1	a_{i-1j+1} 0
a_{ij-1} 1	**a_{ij}** **2**	a_{ij+1} 2
a_{i+1j-1} 1	a_{i+1j} 0	a_{i+1j+1} 1

$0 + 1 + 0 + 1 + \mathbf{2} + 2 + 1 + 0 + 1 = \mathbf{8}$

		to state		
		0	**1**	2
From state:	0	$\Sigma \leq S_b$	$\Sigma > S_b$	----
	1	$\Sigma < S_b$	$S_b < \Sigma < S_b$	$\Sigma > S_c$
	2	$\Sigma \leq S_a$	$\mathbf{3 \leq 8 \leq 10}$	$\Sigma \geq S_b$

⟹ t =1 the cell $\mathbf{a_{ij}}$ reaches state 1

t =1

a_{i-1j-1}	a_{i-1j}	a_{i-1j+1}
a_{ij-1}	**a_{ij}** **1**	a_{ij+1}
a_{i+1j-1}	a_{i+1j}	a_{i+1j+1}

a_{i-1j-1} , a_{i-1j} , a_{i-1j+1} , a_{ij-1} , a_{ij+1} , a_{i+1j-1} , a_{i+1j} i a_{i+1j+1} also change values in t = 1

Fig. 2. An example of the transition rule in the cellular automaton that simulates language shifts. Given the thresholds equal to S_a = 3, S_b = 10 and S_c = 12, and the sum of the Moore neighborhood of radius 1 of the target cell equals eight, if the target cell is in state 2 at t=0, the transition rule states that the cell target will be in state 1 at t=0 (the value of the sum of the neighborhood is between 3 and 10, the values of the thresholds S_b and S_c, respectively).

spreadsheet summarized the frequency of states for each simulation at each time unit until the automaton stabilized. Although the automaton runs automatically when the number of simulations is defined and the data are displayed on the spreadsheet where the frequency of states was indicated, the automaton can also be run step by step and display the evolution over time of the states on the spreadsheet that shows the cells and their states by color. (The Excel macros used to define the automaton and the main instructions to run it can be downloaded from www.ub.edu/gcai. Go to *download* in the main menu)

3.2 Testing the model: the example of Catalan

The availability of empirical data from recent language surveys on the use of Catalan prompted us to choose Catalan as an empirical example with which to evaluate our model. Catalan is a Romance language currently spoken by approximately ten million people along the Mediterranean coast from near Southern Spain to the South of France, the Balearic Islands and the town of Alghero in Sardinia (see Figure 3). This area is currently divided politically into four countries: Andorra, France, Italy and Spain, each of which grants a different official status to Catalan. Thus, Andorra recognizes Catalan as its single official

language, Spain recognizes Catalan as a joint official language in the regions where Catalan is spoken, and France and Italy do not grant Catalan any official status. Hence, the knowledge and use of Catalan varies accros the area where it is spoken and interacts with differents languages, such as French, Italian and Spanish.

In previous studies we tested the cellular automaton using some data from a language survey on knowledge and use of Catalan in Valencia, a region of Spain where Catalan is spoken (Ninyoles, 2005). The results of the simulations showed the automaton's extreme sensitivity to variations in threshold S_b compared with variations in thresholds S_a and S_c. Moreover, our simulations showed that, given the initial size of the current speech behavior of the individuals indicated by the cellular automaton states, the value of threshold S_b became critical in explaining the dynamics observed in the simulation. Thus, the results of our previous research stated that given a linguistic setting with an initial size of the current speech behavior of the individuals (Catalan and Spanish speakers in our research), the individual's social support for the SL, i.e., Catalan, becomes critical when determining the individual's speech behavior with regard to the SL (Beltran et al., 2009, 2010).
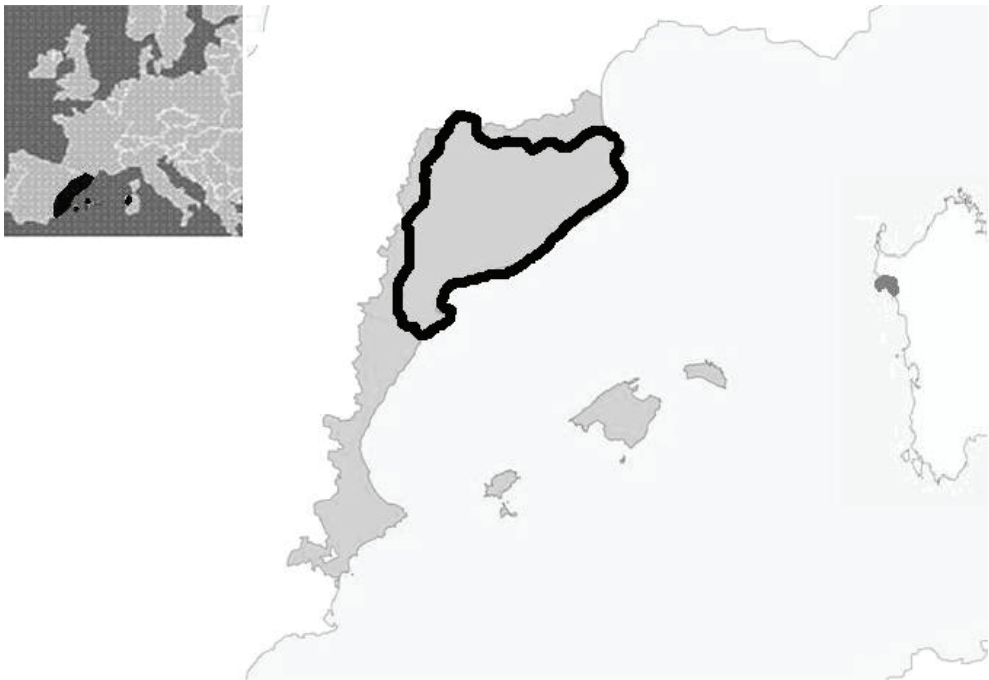

Fig. 3. Complete linguistic area where Catalan is spoken (grey area). The outlined area in black indicates Catalonia, the zona where we obtained the data from the linguistic survey used in this research study (Idescat, 2008). The map in the top-left corner shows the location of the whole linguistic area of Catalan in Europe.

In this study we used empirical data from a recent language survey carried out by the *Secretaria General de Política Lingüística* (Secretariat General for Language Policy) (Idescat, 2008) of the autonomous government of Catalonia, another region of Spain where Catalan is

spoken. The data from the survey were collected in 2008 from a sample of 7,140 people aged 15 and over on the use of Catalan with reference to different variables such as age, gender, educational level, place of residence, etc. We obtained data from the survey in a number of different social contexts and we systematically tested the effective use of Catalan in four social contexts: at home, with friends, in traditional stores and at large shopping malls. (These survey data are summarized in Table 2)

The percentages for the use of Catalan obtained in the survey gave us the number of cells containing each state at the beginning of the simulation ($t=0$). Thus, "Always Spanish" and "More Spanish than Catalan" were assigned to state 0; "Equal Catalan and Spanish" was assigned to state 1; and "More Catalan than Spanish" and "Always Catalan" were assigned to state 2. The percentage of states at $t=0$ obtained after the conversion is shown in Table 3.

	Always Catalan	More Catalan than Spanish	Equal Catalan Spanish	More Spanish than Catalan	Always Spanish	Other language / Did not answer
Social context						
Home	31.6	3.6	8.3	6.0	42.6	7.9
Friends	22.5	10.8	16.8	9.0	33.9	7.1
Traditional stores	28.7	11.0	14.9	7.5	36.0	1.9
Large shopping malls	23.9	9.9	15.5	9.5	39.4	1.8

Table 2. Percentage of Catalan use in four social contexts. Data were obtained in 2008 from a sample of 7,140 people aged 15 years and over (Idescat, 2008).

State of the automaton	Home	Friends	Traditional stores	Large shopping malls
State 2	35.2	33.3	39.7	33.8
State 1	14.3	25.8	22.4	25.0
State 0	42.6	33.9	36.0	39.4

Table 3. Percentage of the states at $t=0$ after conversion to the automaton states based on the linguistic survey data on Catalan use in four social contexts (Idescat, 2008).

Given the initial values, the variation in the threshold values gave us different scenarios of possible social support for the individuals using Catalan. Thresholds S_a and S_c were set at 3 and 15, respectively. As stated above, the results of previous simulations showed the automaton's extreme sensitivity to variations in threshold S_b compared with variations in thresholds S_a and S_c. The values of thresholds S_a and S_c were therefore kept constant in all simulations and threshold S_b was varied across seven values (4 to 10) in the four social contexts. The factorial combination of the four social contexts (at home, with friends, at traditional stores and at large shopping malls) and the seven thresholds S_b (4 to 10) produced twenty-eight different simulation conditions. We carried out 200 simulations for

each condition. The states were randomly seeded at *t=0* in all simulations, given that Catalan and Spanish speakers in Catalonia were very mixed. Random seeding therefore indicated the spatial distribution of the different kinds of speakers in our empirical example.
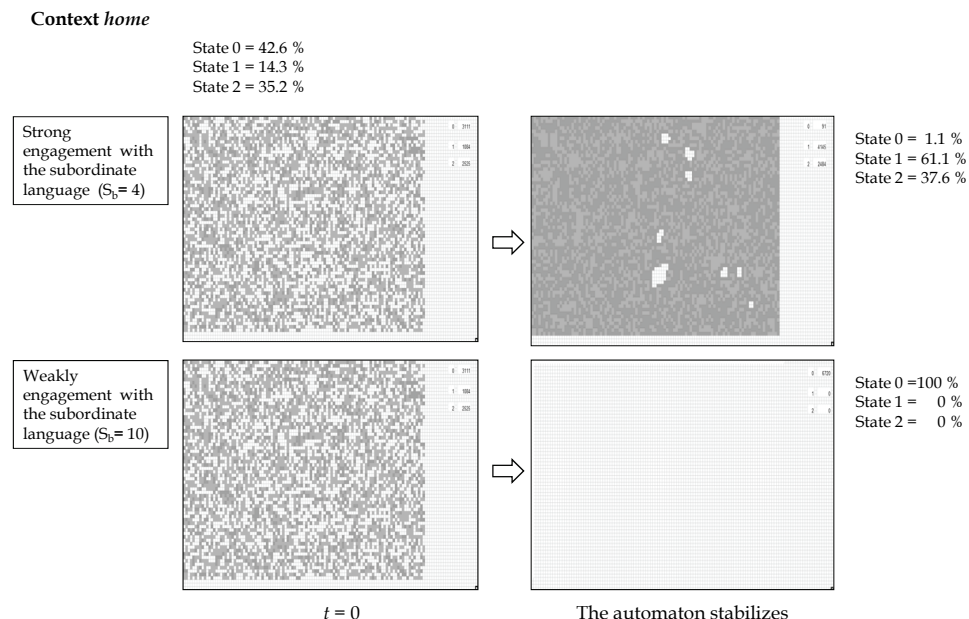
Context *home*

State 0 = 42.6 %
State 1 = 14.3 %
State 2 = 35.2 %

Strong engagement with the subordinate language (S_b= 4)

State 0 = 1.1 %
State 1 = 61.1 %
State 2 = 37.6 %

Weakly engagement with the subordinate language (S_b= 10)

State 0 =100 %
State 1 =   0 %
State 2 =   0 %

t = 0   The automaton stabilizes

Fig. 4. An example of the dynamics of the cellular automaton that simulates language shifts. The initial values of the cellular automaton (*t=0*) were the percentage of states of the use of Catalan at home according to the linguistic survey (Idescat, 2008). The dark grey cells indicate state 2, the light grey cells indicate state 1 and the white cells indicate state 0 (on the Excel spreadsheet the states were represented by white, orange and green, respectively). Strong engagement of individuals with the subordinate language (threshold S_b= 4) allows the subordinate language to survive, because, when the cellular automaton stabilizes, there are bilinguals that use the subordinate language in states 1 and 2; but weak engagement (threshold S_b= 10) produces the extinction of the subordinate language, because, when the automaton stabilizes, all individuals become monolinguals in the dominant language (state 0).

We carried out the simulations for each condition and recorded the frequency of each state when the cellular automaton stabilized. The criterion of stabilization was three sequential iterations without changes in any state of all the cells of the automaton. The mean percentage of the 200 simulations was obtained for each state in each condition. The results coincide with the results obtained from previous simulations (see Beltran et al., 2010) and showed that below a given S_b threshold, state 0 disappeared and the SL survived, but above a certain S_b threshold, states 1 and 2 disappeared and the SL consequently became extinct (see Figure 5). In summary, the results suggested that, given the values of the states at *t* = 0 and a value of threshold S_b, we can determine whether the SL will survive or become extinct.
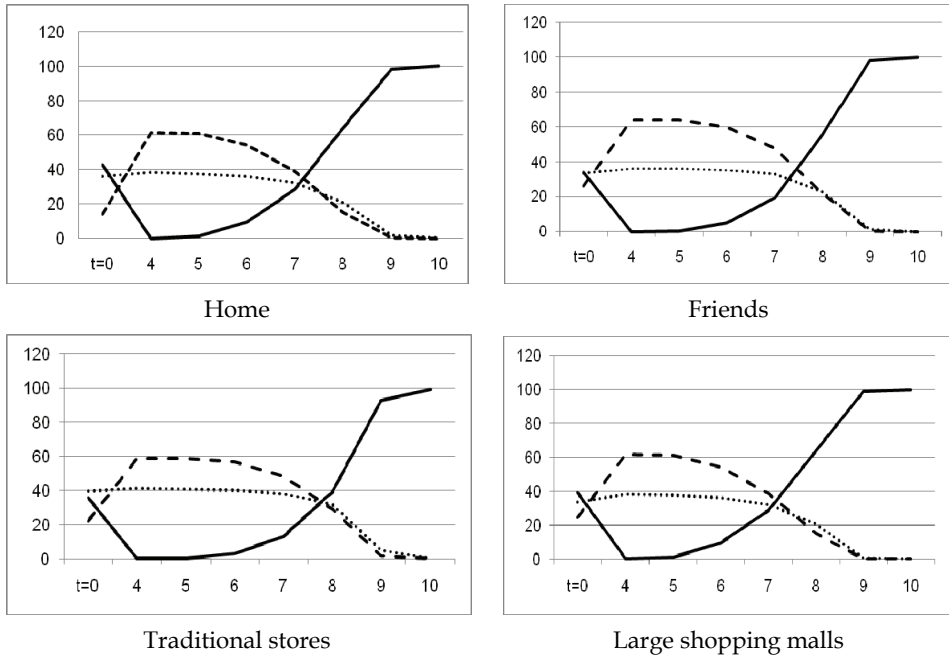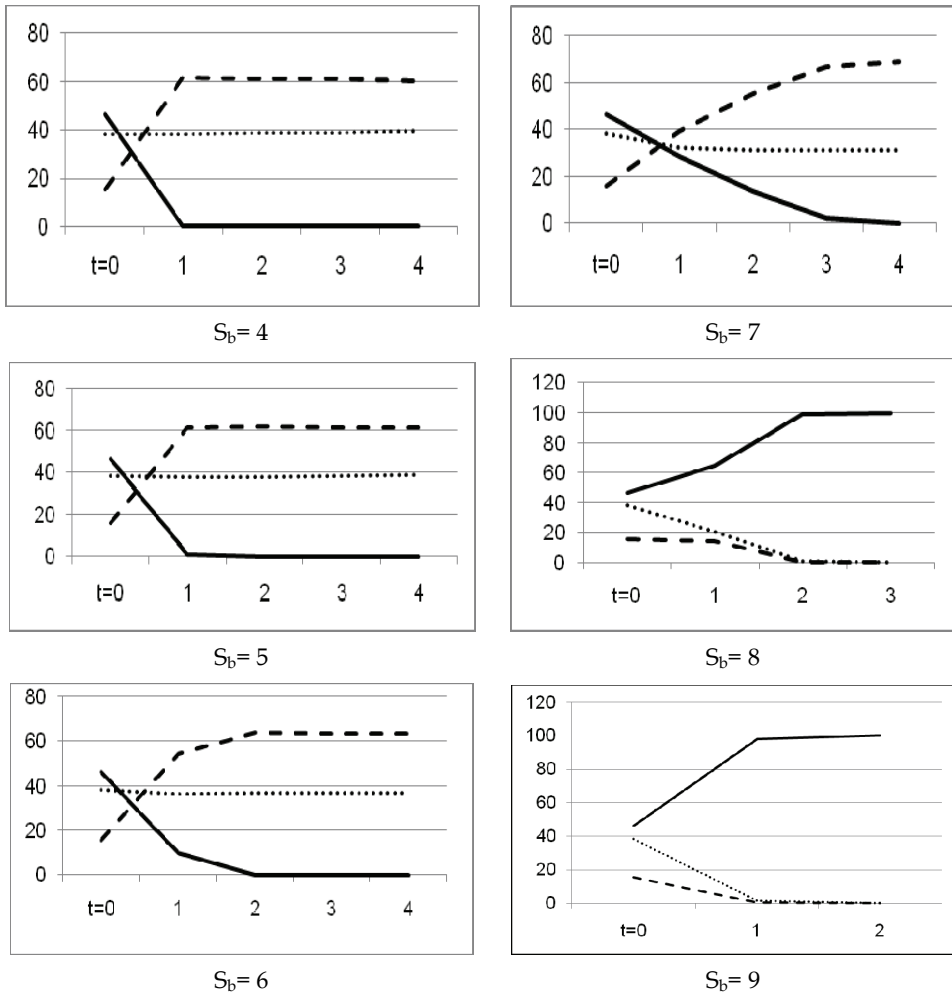
Fig. 5. Mean percentages of states 0 (solid), 1 (dashed) and 2 (dotted) for the values of threshold S_b when the automaton stabilized (values of S_b= 4 to 10) for each social context. The percentage of initial values (*t=0*) is also shown.

Moreover, as pointed out above, the Gaelic-Arvanitika model states that the language shift happens over a short period of time, namely two generations. We performed a second set of simulations to test that statement by determining whether the cellular automaton could forecast the progress or reversal of the language shift across generations. The procedure to simulate a change of a generation was as follows: We ran a given simulation and the data recorded after stabilization of the automaton were used as the initial values (*t=0*) of a new simulation, and so on. So each simulation run in the automaton indicates a change produced in a generation. As in the first set of simulations, the percentages for the use of Catalan obtained in the linguistic survey gave us the number of cells containing each state at the beginning of the simulation (*t=0*) (Idescat, 2008). In this second set of simulations, we chose only the context *home*, because the Gaelic-Arvanitika model stated that the key factor for the survival of a language is transmission in the family across generations.

Thresholds S_a and S_c were set at 3 and 15, respectively, and threshold S_b was varied across six values (4 to 9). According to the procedure mentioned above, the results of a given simulation furnish the initial values of a new simulation. This procedure was carried out four times for each value of threshold S_b and 15 simulations were performed for each value of S_b. The frequency of each state was recorded when the cellular automaton stabilized at the end of each simulation and the mean percentage of each state was obtained from the records of the 15 simulations. Thus, for each generation the mean percentage of each state was obtained under the six values of threshold S_b.

The results indicated that the percentage of the states showed a clear trend in the earlier generations (see Figure 6). Also, the results agreed with those obtained in the first set of simulations, i.e., the results showed that, below a given S_b threshold, state 0 disappeared and the SL survived S_b (values 4 to 7), but above a certain S_b threshold, states 1 and 2 disappeared and the SL consequently became extinct (values 8 and 9). An important finding was that in the cases where the SL became extinct, this extinction was reached quickly (in one or two generations) as the Gaelic-Arvanitika model predicts.

Fig. 6. Mean percentages of states 0 (solid), 1 (dashed) and 2 (dotted) for the values of threshold S_b when the automaton stabilized (values of S_b= 4 to 9) for the social context *home*. The x-axis indicates the generations of speakers. The percentage of initial values (*t=0*) is also shown. (Note that for the values S_b= 8 and S_b= 9, state 2 quickly reaches value 0).

The results of the two sets of simulations confirmed the importance of attitudes regarding the SL to determine individual speech behavior. If individuals are weakly engaged with the SL (according to our model a higher value of threshold S_b is required to use and eventually increase the use of the SL), the SL will disappear. However, if individuals are strongly engaged with the SL (according to our model a lower value of threshold S_b is required to use and eventually increase the use of the SL), the SL will survive. In this case, we also observed that the percentages of state 2 remained approximately constant, while the percentages of state 1 increased and those of state 0 decreased (Figures 5 and 6). Hence, the SL survived because the state-2 speakers continued speaking the SL, i.e., they did not become state-0 speakers, and the state-0 speakers used the SL because they became state-1 speakers, i.e., the monolinguals in the DL become bilinguals.

The results of the second set of simulations confirmed the results obtained in the first set, because values 4 to 7 of threshold S_b produced the extinction of state 0 (the monolinguals became state-1 bilinguals) and values 8 and 9 of threshold S_b produced the extinction of states 1 and 2 (all the bilinguals became monolinguals in the DL). That result remained constant across generations. Furthermore, the results of the second set of simulations confirmed a main prediction of the Gaelic-Arvanitika model, because the threatened language disappeared in few generations when transmission in the family failed (the extinction of states 1 and 2 occurred in only two generations).

4. Conclusion

As in our previous studies (Beltran et al., 2009, 2010), the results of the simulations using the empirical data of linguistic surveys showed the importance of the initial values of the speakers of the SL and their engagement with the SL (the percentage of initial states and value of the threshold S_b in our model) to the future of a SL when it coexisted with a DL. According our model, when high S_b values were set, states 1 and 2 completely disappeared, so the SL died out. However, when lower values were set, state 0 disappeared and the SL survived because all the individuals became bilinguals. The results also coincided in all social contexts tested by the simulations (at home, with friends, at traditional stores and at large shopping malls), because the values of the states were similar in the four contexts.

The results also agreed with the Gaelic-Arvanitika model. As stated above, a strong engagement of individuals with the SL produced the reversion of the language shift because all the monolinguals in the DL became bilinguals. Moreover, transmission of the SL to subsequent generations increased because the number of bilingual people who transmitted the SL grew. But weak engagement of individuals with the SL produced the extinction of the SL in only two generations, i.e., the results support the prediction of the Gaelic-Arvanitika model, which anticipated a quick language shift.

The results of our simulations provided some answers about the future of Catalan. Using the results of a language survey carried out in Catalonia on the effective use of Catalan to determine the initial size of the states (Idescat, 2008), the simulations confirmed that, given an initial size of the states, the value of threshold S_b (the engagement of individuals with the use of the SL) determined whether Catalan died out or not. Strong engagement of individuals (a low S_b value) with Catalan led many of the non-Catalan speakers to become bilingual (changing from state 0 to state 1). Thus, Catalan survived. Given the fact that an important issue related to language death is designing language policies to reverse language shifts, our results suggest that, together with government initiatives favoring the use of

Catalan, it will be necessary to implement language initiatives that favor speech behavior. Specifically, given the fact that the individual's engagement with the SL becomes critical in determining his or her speech behavior with regard to the SL, language initiatives should be aimed at convincing people to use Catalan even if there are few neighboring Catalan speakers. Moreover, these linguistic policies should be implemented as soon as possible, because the possible shift from the SL to the DL, from Catalan to Spanish in our example, is a rapid process.

As stated in the introduction, language extinction is a widespread social phenomenon that requires close attention from social scientists. Although future research should be improved in different ways (for example, the automaton should be applied to different examples of possible language shifts around the world), modeling the linguistic behavior of individuals by means of a cellular automaton has proven to be a useful tool for understanding language shift processes. Also, the study of language shifts based on a cellular automata approach can be a way to predict the future of threatened languages and, consequently, to design language policies to reverse the language shift process. Social simulation using cellular automata can therefore give us a new and promising framework for future theoretical and empirical development of language shift studies.

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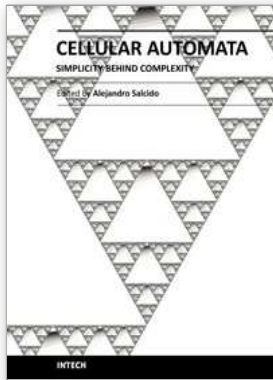
Cellular Automata - Simplicity Behind Complexity

Edited by Dr. Alejandro Salcido

ISBN 978-953-307-230-2

Hard cover, 566 pages

Publisher InTech

Published online 11, April, 2011

Published in print edition April, 2011

Cellular automata make up a class of completely discrete dynamical systems, which have became a core subject in the sciences of complexity due to their conceptual simplicity, easiness of implementation for computer simulation, and their ability to exhibit a wide variety of amazingly complex behavior. The feature of simplicity behind complexity of cellular automata has attracted the researchers' attention from a wide range of divergent fields of study of science, which extend from the exact disciplines of mathematical physics up to the social ones, and beyond. Numerous complex systems containing many discrete elements with local interactions have been and are being conveniently modelled as cellular automata. In this book, the versatility of cellular automata as models for a wide diversity of complex systems is underlined through the study of a number of outstanding problems using these innovative techniques for modelling and simulation.

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