

## Evolutionary Perspectives on Diachronic Syntax

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The main purpose of this chapter is to argue the merits of 'population thinking' in gaining insight into linguistic and, in particular, syntactic change. Population-level thinking and modelling can shed new light on many issues in the study of language acquisition and language change, and leads directly to a precise and useful characterization of E-language, something which is lacking in current generative linguistics. Moreover, this way of thinking is fully compatible with the major insights of the latter, and integrates them into a framework in which language variation and change are inherent and inevitable, rather than peripheral and/or accidental, properties of language. I will argue that (E-)languages are best modelled as particular kinds of *dynamical systems*; namely, *complex adaptive systems* (where these terms are used in technical senses made precise below).

The chapter both introduces some relevant ideas and techniques from modern evolutionary theory, and from the mathematical and computational study of dynamical systems, and also offers a critique and review of some recent work on syntactic change in this emerging framework, arguing that a useful population model needs to support overlapping generations of language users and learners and to allow quite detailed modelling of differing demographic scenarios. I utilize simple linguistic scenarios based on constituent order changes to illustrate the ideas and techniques clearly. I abstract away from the sociolinguistic detail of the actuation and diffusion of changes, and also from much of the linguistic detail of attested changes. However, the chapter also contains extensive references both to further background material and to more specific and detailed work within the general framework exemplified here.<sup>1</sup>

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<sup>1</sup> McMahon (1994: ch. 12) is a brief account of the chequered history of evolutionary ideas and terminology in linguistic theory. Keller (1994) provides a detailed critique of Müller and Schleicher's theories of language and goes on to argue for a similar view of (E-)language to that taken here. My fundamental argument is that, despite this chequered history, it is worth a second try as the neo-Darwinian synthesis and subsequent analytic and algorithmic thinking about evolution and dynamical systems makes available a panoply of new perspectives and techniques that were not available to

## 4.1. THE BASIC MODEL

A formal model achieves greatest generality, and thus validity, by making as few assumptions as necessary and by omitting as much extraneous detail as possible. It is a matter of judgement, of course, deciding what is extraneous and what essential. Chomsky (1965) defined grammatical competence in terms of the language of (i.e. stringset generated by) an ideal speaker-hearer at a single instant in time, abstracting away from working memory limitations, errors of performance, and so forth. The generative research programme has been very successful, but one legacy of the idealization to a single speaker at a single instant has been the side-lining of variation and change. My model will embody similar assumptions: language users will, in essence, be Chomskyan ideal speaker-hearers (and learners), their linguistic interactions will be very simplified, and so forth. An assumption I will make here, in common with most work in diachronic generative syntax, is that language acquisition is the fundamental factor in significant syntactic change, and that there is a critical period for, at least, syntactic acquisition, after which no major change to the acquired adult grammar takes place (e.g. Lightfoot 1979, 1999).

## 4.1.1. A language agent

We want to model language users and learners in a manner which abstracts away from many details potentially relevant to their behaviour, but which preserves what we think is essential for a model of language learning and use. A language agent can learn, produce, and interpret a language, defined as a well-formed set of strings with associated logical forms, by acquiring and using a generative grammar according to precisely specified procedures.<sup>2</sup> We can think of language agents as embodying a model of the language acquisition device (i.e. a universal grammar, *UG*, a parsing procedure, *P*, and a grammar learning procedure, *LP*) with the addition of a simple generating procedure, *G*.

I will define *UG* to be the space of classical Categorial Grammar (i.e. AB CG, e.g. Wood 1993: 7–14) with atomic categories S, N, and NP, other (complex) categories formed by left-associative combination of categories with slash or backslash (e.g. SNP, 'English intransitive verb'; (SNP)/NP, 'English transitive verb'), and the two directional variants of function-argument application defined below (where X and Y are variables over distinct tokens of (sub)categories and X' and Y' denote the semantic values of these (sub)categories):

nineteenth-century or even nineteen-sixties linguists. For accessible introductions to this new intellectual landscape see e.g. Cziko (1995), Dennett (1995), Kauffman (1993), Peak and Frame (1994), Sigmund (1993).

<sup>2</sup> I borrow the term 'agent(s)' from computer science for this idealization to emphasize both their autonomy and their artificiality, and because they are going to form part of a decentralized, distributed system.

Forward Application (FA):

$$X/Y \Rightarrow X \quad \lambda Y' [X' (Y')] (Y') \Rightarrow X' (Y')$$

Backward Application (BA):

$$Y X \backslash Y \Rightarrow X \quad \lambda Y' [X' (Y')] (Y') \Rightarrow X' (Y')$$

Application combines a complex functor category with an argument category to form a derived category (with one less (back)slashed argument category). So, for example, the category associated with an English intransitive verb encodes the fact that it can combine with a subject NP to its left to form a sentence. Grammatical constraints of order and agreement are captured by only allowing directed application to adjacent matching categories. Application is paired with a corresponding determinate semantic operation, shown here in terms of the lambda calculus, which compositionally builds a logical form from the basic meanings associated with lexical items.<sup>3</sup> A simple derivation is shown in Figure 4.1. A trigger sentence is defined as a surface form (SF), a string of words, with an associated logical form (LF), a possibly underspecified formula of the lambda calculus:  $t_i = \{ \langle w_1, w_2, \dots, w_n \rangle, LF_i \}$ . In the case of the example in Figure 4.1 these are (1a) and (1b), respectively.

|                     |  |        |
|---------------------|--|--------|
| Kim                 | loves  | Sandy  |
| NP                  | (SNP)/NP                                     | NP     |
| kim'                | $\lambda y, x [\text{love}' (x y)]$          | sandy' |
|                     |  | FA     |
|                     | SNP  |        |
|                     | $\lambda x [\text{love}' (x \text{sandy}')]$ |        |
|                     |  | BA     |
| S                   |  |        |
| love' (kim' sandy') |  |        |

FIGURE 4.1. CG Derivation for *Kim loves Sandy*

- (1) (a) Kim loves Sandy  
 (b) love' (kim' sandy')  
 (c) Kim:NP loves:SNP<sub>3</sub>/NP<sub>0</sub> Sandy:NP

A valid category assignment to a trigger ( $VCA(t_i)$ ) is defined as a pairing of a lexical syntactic category with each word in the SF of  $t_i$ ,  $\langle w_1 : c_1, w_2 : c_2, \dots, w_n : c_n \rangle$  such that the parse derivation,  $d_i$  for this sequence of categories yields  $LF_i$ , as in

<sup>3</sup> Thus, I adopt a deterministic syntax-driven compositional LF construction framework in common with Montague Grammar and most work with CGs (see e.g. Dowty, Wall, and Peters 1981, Wood 1993: 29–33). However, the details are not essential to an understanding of what follows, beyond the fact that the LF is determined by the derivation and, given a derivation, a LF is recovered.

(1c).<sup>4</sup> Given  $VCA(t)$ , the parse derivation in CG (and thus the LF) will be unique, so the parsing algorithm,  $P$ , can be defined precisely and deterministically in terms of a simple shift-reduce parser that orders reduction via forward/backward application before shifting new words onto the analysis stack.<sup>5</sup>

The generation procedure,  $G$ , selects a trigger (i.e. an SF:LF pairing) given the agent's grammar and lexicon. A trigger is defined as any one of the finite proper subset of strings generated by a grammar and lexicon which involves at most one level of recursive application, in terms of a single recursive category or a chain of categories involving recursive application.<sup>6</sup> I will assume a highly skewed distribution over such degree-0 and degree-1 triggers so that a learning agent has a very high probability of being exposed to a fair and effective sample of them for any given target grammar and lexicon. Given a space of possible grammars,  $UG$ , and a learning procedure,  $LP$ , a fair and effective sample of triggers,  $t_1 \dots t_n$ , from the language defined by a target grammar,  $L(g')$ , will allow a learner to converge on  $g'$  with high probability (i.e.  $p > 1 - \epsilon$ —where  $\epsilon$  denotes a small error probability), because it will contain enough information to select the target grammar uniquely from others in  $UG$  using  $LP$ :<sup>7</sup>

$$p[LP(UG, t_1 \dots t_n \in L(g')) = g'] > 1 - \epsilon$$

The acquisition procedure,  $LP$ , is error-driven and incremental. A learning agent begins with an empty lexicon and empty category set and incrementally hypothesizes new category types and/or word:category associations. On each trigger presentation,  $LP$  finds a  $VCA(t)$  yielding the appropriate LF. If this can be done using word:category associations available in the current lexicon, then no change takes place. Otherwise, new word:category associations are hypothesized and retained if these lead to successful recovery of the appropriate LF. For

<sup>4</sup> I will write SVO for S(ubject), O(bject), etc. to informally indicate relevant aspects of both SF and LF. I will also use the same abbreviations to indicate the LF associated with particular CG categories where it is convenient to suppress details of the semantic framework employed.

<sup>5</sup> Briscoe (1997, 1998) gives a more detailed and precise definition of such a parsing algorithm. In fact, the correct fully-specified and determinate LF cannot always be recovered from  $VCA(t)$ . For example, if this includes a sequence like: *almost*:(SNP)/(SNP) *smiled*:SNP *deliberately*:(SNP)/(SNP), the parsing algorithm outlined yields the left-branching derivation and interpretation where the second adverb has wide scope. Such complications are not relevant here.

<sup>6</sup> Thus, triggers will not involve derivations such as  $N/N \ N/N \ N \Rightarrow N$  or  $NP/S \ NP/S \ S \Rightarrow NP$ . This restriction is in accord with psycholinguistic evidence that children are exposed to a preponderance of unembedded (degree-0) triggers with about 16% of child-directed utterances involving one level of (degree-1) embedding (e.g. Newport 1977). Restricting possible triggers to a finite proper subset of sentences generated by a given grammar also facilitates modelling.

<sup>7</sup> This formal setting and associated assumptions concerning models of language acquisition is based on recent work on formal learnability—see, for example, Niyogi (1996) for a particularly thorough treatment—though its antecedents go back at least to Wexler and Culicover (1980). The assumption that the learner has access to a fair and effective sample circumvents most of the substantive issues of language acquisition. However, our focus here is not on these issues but rather on how the process of acquisition influences language change.

concreteness, I will assume  $LP$  only hypothesizes one new word:category association per trigger, tries existing category types before creating new ones, and never deletes an association.<sup>8</sup> For example, a learning agent presented with the trigger in (2a,b), with the word:category associations in (2c) as well as, say: *tall*:N/N might hypothesize and retain *red*:N/N.

- (2) (a) give me the red sock  
 (b) give' (me' x)  $\wedge$  red' (sock' (x))  
 (c) give:(S/NP)/NP me:NP the:NP/N red:? sock:N

On the other hand, an agent without any instance of N/N would need to hypothesize this new category type in the grammar before being able to add the appropriate word:category association to the lexicon. Thus,  $LP$  incrementally expands the lexicon and, if necessary, the category set to find the smallest grammar and lexicon (i.e. that containing the least number of category types and word:category associations) compatible with the analysable subset of the trigger sequence seen so far. The current  $g \in UG$  hypothesized by a learning agent is entirely defined by the category set (and lexicon) since  $UG$  specifies forward/backward application as the only means of grammatical combination.

Though learning agents may be exposed to different triggers in different orders, given  $LP$  a learning agent must be exposed to a (not necessarily continuous) sequence of triggers in which the addition of one new word:category association per trigger leads to  $g'$ . This implies that such incremental trigger sequences must be fairly common in the more likely subsets of triggers which will be sampled for  $g \in UG$  otherwise  $LP$  will not be able to converge with high probability on exposure to a finite specific sequence,  $t_n$ . This requirement follows directly from the twin requirements that *one* hypothesized word:category association must yield the *complete* correct LF for a trigger.<sup>9</sup>

$LP$ , as outlined, has no way of guaranteeing that the correct  $VCA(t)$  will be recovered for each trigger. Even given the correct LF, there is still ambiguity in the assignment of  $VCA(t)$  given arbitrary sequences of triggers. A well-known example (e.g. Clark 1992) is the ambiguity of SVO triggers when  $UG$  includes  $V_2$  grammars.  $LP$  could 'prematurely' learn categories like  $S/NP_2/NP_0$  for such sequences, although  $g'$  might be a  $V_2$  grammar and also generate OV triggers. With CG there will always be indeterminacy concerning the form of the new category that should be hypothesized. For example, a learner could infer a type-raised category like  $(NP/N)/(NP/N)$  with semantics  $\lambda P \lambda x \ NP/N' \ [(NP/N)/(NP/N)' \ P(x)]$  for *red* in (2a, b) yielding the same LF (e.g. Wood 1993: 42–6).

<sup>8</sup> The restriction to a single word:category association per trigger entails that the learner must acquire a lexicon of names,  $N(P)$ , before acquiring some one-place predicates,  $S/N(P)$ .

<sup>9</sup> Gibson and Wexler (1994), following earlier work on formal learnability, incorporate both these requirements into the Trigger Learning Algorithm. However, Niyogi and Berwick (1996), Frank and Kapur (1996), Drescher (1999), and Fodor (1998) have all questioned one or both and made alternative proposals.

Again the assumption that the learner infers the simplest category (i.e. the one requiring the least number of atomic categories and (back)slash operators) would often suffice for this type of indeterminacy. Since we are not currently concerned with how the learner resolves such indeterminacies, I will assume (unrealistically) that a trigger comes labelled with the correct (partial)  $VCA(t)$ , as in (2c) above, and that the learner always determines the correct new category.

$LP$ , as defined, is a lexically conservative learner because variant category assignments to a word token will not be generalized to other words of the same type. For example, if a learning agent has acquired the word:category associations: *nicely*:(SNP)/(SNP) and *quickly*:(SNP)/(SNP) (where  $l$  is a variable which can be instantiated as slash or backslash), then  $LP$  will not generalize the association for *quickly*. I will assume that  $LP$  includes lexical (redundancy) rules of the general form:  $Cat \Rightarrow Cat$  which get hypothesized appropriately. This assumption allows us to abstract away from lexical issues and the lexical content of triggers, which are also not our primary concern.<sup>10</sup>

This completes the linguistic part of our definition of a language agent. I extend this definition with an age, between 1 and 10, and a communicative success ratio (CSR), between 0 and 1, for reasons which will become clear in the next section. So, to summarize, a language agent has the following components:

LAgt:  
 $LP(UG, t) = g$   
 $P(g, t) = LF$   
 $G(g, LF) = t$   
 Age: [1-10]  
 CSR: [0-1]

Of course, there is much that is questionable about this simple model, the choice of  $UG$ ,  $LP$ , and so forth. However, my intention is to explore what happens when such relatively simple and comprehensible models of language learners and users form speech communities, and then show how these predictions can be used to refine the model of a language agent.

#### 4.1.2. Populations of language agents

A population is simply a set of language agents. However, we want this set to change over time as new agents are added ('born') and old agents are removed ('die'). One way of achieving this is to disallow generations of learning and adult agents to overlap; that is, to remove all adult agents from the population

<sup>10</sup> Of course, the issue of when to hypothesize a (potentially semi-productive) lexical rule and how to determine its range of application is complex (e.g. Pinker 1989, Schütze 1997, Briscoe and Copestake 1999). They are also relevant to diachronic syntax, since most accounts of lexical rule induction will predict initially slow lexical diffusion, followed by more rapid syntactic change when triggering data licenses induction of the rule, rather than just induction of specific word:category associations.

once the learning period is finished, declare the learners the adults, and add a new batch of learners. This makes the population dynamics simple but unrealistic. My model supports overlapping generations because demographic dynamics, for example altering the proportion of learners to adults, may well be a factor in some types of language change (see e.g. §4.4 below).

The constitution of the population changes over time according to some prespecified rules; agents are usually removed at age 10, and two distinct adult (age  $\geq 4$ ) agents 'reproduce' one and only one new (age 1) learning agent during each of their adult ages (so agents can help create up to seven offspring). We have already effectively defined a dynamical system; that is, a system which changes over time in a manner determined by the previous state. The system has a set of states, corresponding to distinct agent ages, and an update rule which determines the state of the system at time  $t+1$  in terms of its state at  $t$ :

$$s^{t+1} = Update(s^t)$$

$Update$  will update the age of the agents at each time step of the system, remove any over age 10, and reproduce new agents from the set of adults. To see how the system behaves, suppose that we start in  $s^0$  with four agents all aged 4. Table 4.1 shows the behaviour of the system through the first 20 states. Each row shows the state number, the total population size, the number of learners

TABLE 4.1. Growth and composition of a population of agents

| State | Population size | Learners | Non-learners | Ratio    |
|-------|-----------------|----------|--------------|----------|
| 0     | 4               | 4        | 0            | $\infty$ |
| 1     | 6               | 2        | 4            | 0.5      |
| 2     | 8               | 4        | 4            | 1.0      |
| 3     | 10              | 6        | 4            | 1.5      |
| 4     | 12              | 8        | 4            | 2.0      |
| 5     | 15              | 9        | 6            | 1.5      |
| 6     | 19              | 11       | 8            | 1.375    |
| 7     | 18              | 12       | 6            | 2.0      |
| 8     | 22              | 14       | 8            | 1.75     |
| 9     | 27              | 16       | 11           | 1.454    |
| 10    | 34              | 19       | 15           | 1.266    |
| 11    | 40              | 24       | 16           | 1.5      |
| 12    | 47              | 29       | 18           | 1.611    |
| 13    | 55              | 34       | 21           | 1.619    |
| 14    | 66              | 40       | 26           | 1.538    |
| 15    | 78              | 47       | 31           | 1.516    |
| 16    | 92              | 56       | 36           | 1.555    |
| 17    | 110             | 67       | 43           | 1.55     |
| 18    | 132             | 80       | 52           | 1.53     |
| 19    | 158             | 96       | 62           | 1.54     |
| 20    | 187             | 114      | 73           | 1.56     |

(aged 1–4), the number of non-learners (aged 5–10), and the ratio of learners over non-learners.

From  $s^1$  to  $s^4$ , *Update* simply adds two new agents reproduced by the four original adults. At  $s^5$  and  $s^6$ , three and then four new agents are added. At  $s^7$  the total number of agents drops because the original four agents have reached age 10 and are removed. At this point learners outnumber non-learners two to one. The population continues to expand exponentially. However, the ratio of learners over non-learners lies between 1.51 and 1.57 from  $s^{14}$  onwards. Thus, these few apparently simple linear rules have some quite surprising and unintuitive properties, highlighting both the need for simulation and/or mathematical analysis in order to understand the behaviour of even very simple dynamical systems, and the need to keep the model as simple as is consonant with our modelling purposes.

The *Update* rule above is unrealistic because there is no bound on population growth. Real populations compete for finite resources and, therefore, typically show approximately logistic or S-shaped growth (e.g. Maynard-Smith 1998: 15–18; Peak and Frame 1994: 132–9). We can impose a limit (crudely) by specifying an upper bound to the total number of agents that can be reproduced in a single time step. If we do this then we place an upper bound on the size of the population defined by the age of death multiplied by this limit. Furthermore the maximum number of learners is defined by this limit multiplied by the age at which learning ceases (i.e. the end of the critical period). From these two upper bounds we can derive the ratio of learners to non-learners once the population has converged to these upper bounds. For example, if we set an upper bound of ten new agents per time step, then the example above will converge to a population of a hundred, forty of whom are learners, giving a learner–non-learner ratio of 0.66. These two linear components of *Update* now define a non-linear dynamical system.

The first plot in Figure 4.2 shows the composition of a population constructed as described, starting from two age 4 agents. Superimposed on this plot of total population size across time is an S-shaped curve constructed using the logistic map. This represents an approximation of the actual population growth; for example, it does not model the drop in population which occurs when the original agents die. The number of learners and non-learners is shown in the second plot. As can be seen there is fluctuation in the ratio until the population settles into its steady state.

The choices I have made here are different from those taken by Niyogi and Berwick (1997) in which a speech community is modelled using non-overlapping generations in a population of fixed size. These and other abstractions enable them to simulate the behaviour of the model in terms of update rules which reduce to quadratic or higher polynomial maps, and thus prove analytically properties of the resulting dynamics. In effect, they simulate the *average* behaviour of a learner at each time step of the system given the probability distribution of triggers predicted from the adult population. If we simply took the logistic map as a correct model of population growth, then we could abstract away from the

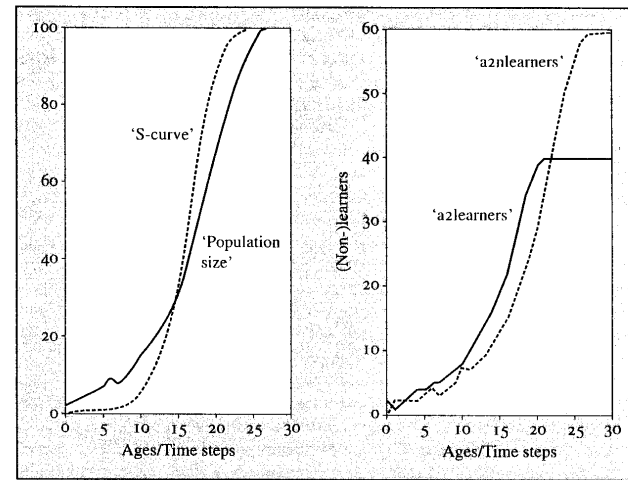


FIGURE 4.2. Population dynamics

specific rules of birth, death, and reproduction presented in this section and model the population dynamics abstractly. However, we would lose the flexibility and low-level variation inherent in the ‘microscopic’ rules introduced above. Below we will see that this flexibility is important for modelling some types of language change.<sup>11</sup>

In all versions of the model, agents in the population attempt to interact with each other a prespecified number of times during each time step of the system; therefore, the time steps will be called interaction cycles. The *Update* rule then maps the population to the next state, and another interaction cycle commences. Note that a generation, defined as the time between birth and reproductive age, is four interaction cycles. The number of times agents interact during an interaction cycle is set so that, with high probability, each learning agent will be

<sup>11</sup> Maynard-Smith (1998: 15–18) discusses the difference between modelling at the microscopic and the macroscopic level with respect to population dynamics. As modelling at the macroscopic level inevitably builds in more (perhaps unwarranted) assumptions and abstraction, I prefer the microscopic approach. In the long run derivation of mathematical laws of language change may, though, warrant macroscopic modelling. In the short run, we need microscopic modelling to discover the appropriate (if any) macroscopic model(s). In fact, the dynamics of the *Update* rule I have adopted here are probably better modelled macroscopically by the tent map (see Peak and Frame 1994) for discussion and a general accessible introduction to non-linear dynamical systems).

exposed to enough triggers to acquire any  $g \in UG$  during the critical period. Thus if it takes one hundred triggers to guarantee convergence to the 'hardest' grammar with  $p > 0.99$ , then the number of interactions might be set to a mean of seventy-five per agent per cycle, giving a mean of three hundred interactions per learner during the critical period. In a mean hundred and fifty of these interactions, a learning agent will be the listening/parsing agent. Therefore, with high probability, learners will be given adequate triggering data to converge accurately to an adult grammar.<sup>12</sup>

The precise number of interactions per cycle depends on population size, so is calculated after each time step of the model. For each interaction, two distinct agents are randomly chosen from the population and one is randomly selected to be the speaking agent, the other the listening agent.<sup>13</sup> The speaking agent generates a trigger given its current grammar (if any) and the listening agent attempts to parse it. If the listening agent is able to recover the same LF from the trigger that the speaking agent associates with it, the interaction is successful. If not, and the listening agent is still learning, then it attempts to modify its grammar and reparse the trigger. If this results in recovery of the right LF, then the interaction is successful, otherwise it fails. A population of agents constitutes a speech community if >90% of interactions between adult agents are successful. This is a fairly arbitrary cut-off, but nevertheless some such definition is needed to distinguish a population with no language or not much (shared) language from a speech community. The communicative success of an agent is just the ratio of successful to all interactions in which it has participated, regardless of whether it was the parsing or generating agent. The CSR is recalculated after each interaction cycle for each agent. For the moment, the only role that this ratio will play is to track whether a population constitutes a speech community.

For now, I will assume that reproduction simply creates a new agent with identical properties to all the other agents in the population. That is, the population of agents changes, and the ratio of learners to non-learners can vary, along with factors such as age of reproduction, death, and so forth. However, the population does not *evolve* at the genetic level because all agents have the same  $UG$ ,

<sup>12</sup> We could try to characterize this probability more precisely via a probabilistic analysis in terms of the (normal) distribution and standard deviation on triggers. However, it is also straightforward to find values which yield a stable model empirically.

<sup>13</sup> By random here and below, I mean randomly sampled with uniform probability, so that any two distinct agents have an equal chance of interacting during every interaction and each interacting agent has an equal chance of being the speaker or listener. Randomly sampling with respect to a uniform distribution is tantamount to making the weakest assumptions; in this case, about who talks to whom. We could, for example, assume that learners talk more to their parents and siblings or that populations are structured into subgroups with greater interactions within rather than across such groups. However, though these moves would make the model more concrete, they would also potentially make it less general if such assumptions do not hold in every situation. Niyogi (2000) contrasts the dynamics which result if learners are exposed to triggers just from their parents, from the entire adult community, or according to a spatial distribution of adults.

$LP$ ,  $G$ , and  $P$ . In this case, it is irrelevant which agents reproduce new agents. Nevertheless, I define reproduction in terms of two parent agents to facilitate extension to a model in which agents' language faculties do evolve. Figure 4.3 summarizes the main properties of the model introduced in §§4.1.1 and 4.1.2.

|                           |  |
|---------------------------|--|
| LAgt:                     |  |
| $LP(UG, t)$               | $= g$  |
| $P(g, t)$                 | $= LF$   |
| $G(g, LF)$                | $= t$  |
| Age:                      | {1-10}   |
| CSR:                      | {0-1}  |
| Pop:                      |  |
| POP <sub><i>n</i></sub> : | {LAgt <sub><i>i</i></sub> , LAgt <sub><i>j</i></sub> , ... LAgt <sub><i>k</i></sub> }  |
| INT:                      | Gen (LAgt <sub><i>i</i></sub> , LF <sub><i>i</i></sub> ), Parse (LAgt <sub><i>j</i></sub> , t <sub><i>i</i></sub> ), $i \neq j$ .  |
| SUCC-INT:                 | Gen (LAgt <sub><i>i</i></sub> , LF <sub><i>i</i></sub> ) = t <sub><i>i</i></sub> $\wedge$ Parse (LAgt <sub><i>j</i></sub> , t <sub><i>i</i></sub> ) = LF <sub><i>i</i></sub> |
| REPRO:                    | Create-LAgt (LAgt <sub><i>i</i></sub> , LAgt <sub><i>j</i></sub> ), $i \neq j$   |

FIGURE 4.3. The basic model

#### 4.1.3. A simple example of language change

Before we begin to study language change, it is important to consider under what conditions a speech community will be maintained, and under what conditions a language will *not* change. In general, speech communities do not seem to undergo such fundamental language change that communication breaks down significantly, even if during periods of major change there may be a small degree of intergenerational miscommunication (e.g. Lightfoot 1999: 7-9). An intuitive requirement for maintenance of a speech community is that if there is no initial linguistic variation in that community and learners are presented with enough triggers, then they should converge to  $g'$ . However, this is not necessary to maintain a speech community, nor sufficient to preclude language change in our model. It is possible for most learning agents in several overlapping generations to 'misconverge' to  $g'$  and still maintain >90% successful interactions when adults. For example, a community in which learning agents outnumber adults may fixate on a proper subset grammar of  $g'$ , because a high proportion of the triggers the learners are exposed to come from the 'intermediate' subset grammars of other learners.<sup>14</sup> Thus, linguistic stasis requires not only a high probability of convergence to  $g'$  during learning—which, in turn, requires little or no variation in triggers—but also population stability too. We will begin by considering stable models, in which the ratio of learning agents to adults will not

<sup>14</sup> Briscoe (1998) discusses change via contraction of this type in more detail and argues that a realistic model of a language agent must incorporate a counteracting pressure for expressivity to prevent communities fixating on easily learnable but more restrictive subset languages.

significantly skew the distribution of triggers, and where the size of the population means that very occasional misconvergence by a single learner, typically to a subset language, will not skew the subsequent distribution of triggers to further learners enough to cause a chain reaction. In this situation, both the speech community and a homogeneous language will be maintained if there is little or no initial linguistic variation.<sup>15</sup>

As a first example, consider the following scenario. Initially there are sixty adult agents, of whom half have acquired grammar,  $g^1$ , and half  $g^2$ , in equal proportions. These grammars are identical except that  $g^1$  generates nominal postmodifiers by associating them with category  $\text{N}\backslash\text{N}$ , and verbal postmodifiers  $(\text{S}\backslash\text{NP})\backslash(\text{S}\backslash\text{NP})$ , while  $g^2$  generates nominal and verbal premodifiers by replacing the (highest-level) backslash operator with slash for these categories. The model is set up to be stable so that a learning agent exposed to triggers exclusively from  $g^1$  (or  $g^2$ ) would converge to that grammar with very high probability; so, in the absence of variation, linguistic homogeneity would be maintained within the speech community. However, once the variation is introduced (perhaps through contact between previously isolated communities) the situation is very different. A learner will, on average, be exposed to equal numbers of variant triggers, such as (3a) and (3b) with the same logical form (3c) but variant VCAs (3d) or (3e).

- (3) (a) Daddy gave you the sock red nicely  
 (b) Daddy nicely gave you the red sock  
 (c) nicely' (give' (daddy' you' x)  $\wedge$  red' (sock' (x)))  
 (d) daddy:NP gave:((S\NP)/NP)NP you:NP the:NP/N sock:N  
 red:N\N nicely:(S\NP)\(S\NP)  
 (e) daddy:NP nicely:(S\NP)/(S\NP) gave:((S\NP)/NP)NP you:NP  
 the:NP/N red:N/N sock:N

For example, if we assume that  $1/12$  of triggers generated from  $g^1$  (or  $g^2$ ) exemplify the variation, then a learning agent has, on average, a  $1/24$  chance of seeing data distinguishing  $g^1$  from  $g^2$  every time it is exposed to a trigger (since, on average, half the triggers will be generated by agents who have acquired  $g^1$ ). If the mean number of triggers the learning agent is exposed to is one hundred, then it will be exposed to both variations one or more times with probability  $p = 0.971$ .<sup>16</sup>

<sup>15</sup> Briscoe (1998, 2000) discusses the conditions required for linguistic stasis in more detail within a very similar model. Taking a stable model of this form as the starting point for the study of change represents a rather different philosophy from that of Niyogi and Berwick (1997) in which, given the learning procedure and conditions they model, a population initially speaking a  $-V_2$  language always fixates on  $+V_2$  grammars. See also Robert Clark (1996) for further discussion.

<sup>16</sup> We think of the triggering data as one hundred Bernoulli trials in which success, i.e. a variant trigger, has probability  $1/24$  for each trial. Then by the binomial theorem, the probability that the learner will see one or more variants from  $g^1$  (equivalently  $g^2$ ):

$LP$ , as defined in §4.1.1, will acquire both variants if it sees each at least once during the learning period, so learning agents will almost certainly converge to a grammar,  $g^3$ , capable of generating triggers like (4) as well as all the original variant triggers in (3).<sup>17</sup>

- (4) (a) Daddy nicely gave you the sock red  
 (b) nicely' (give' (daddy' you' x)  $\wedge$  red' (sock' (x)))  
 (c) daddy:NP nicely:(S\NP)/(S\NP) gave:((S\NP)/NP)NP you:NP  
 the:NP/N sock:N red:N\N

The introduction of  $g^3$  into the community represents language change in two ways. Firstly, (4a) is a new type of potential trigger; previously it was not possible for a single speaker to combine pre/postmodifiers. Secondly and consequently, the distribution of trigger types will change because the distribution of grammars amongst agents in the community has changed. Once grammar,  $g^3$ , has entered this community, the overall proportion of triggers exhibiting pre/postmodifier variation will rise. Subsequent learners will be exposed to triggers like (3) from the original adult agents and to triggers like (3) and (4) from new adults who have acquired  $g^3$ . This creates a chain reaction, that is, positive feedback, so that, unless further variation is introduced, the community will soon fixate on  $g^3$  (in the sense that all adult agents will have acquired  $g^3$ ). The first generation of learners will each acquire  $g^3$  with  $p = 0.971$ . The joint probability that all will acquire  $g^3$ , assuming ten learners, is  $p = 0.745$ . The probability that more than half will is  $p = 0.999$ . Subsequent generations of learners, exposed to  $g^1$ ,  $g^2$ , and increasingly  $g^3$ , will converge to  $g^3$  with increasingly higher probability. Then the original adult population of  $g^1$  and  $g^2$  agents will begin to die, so the proportion of  $g^3$  agents will increase further. If no learner acquires a subset grammar, or  $g^1$  or  $g^2$ , then the community can fixate on  $g^3$  within six interaction cycles.<sup>18</sup>

$$\begin{aligned} P(X>0) &= (1 - P(X) = 0) \\ &= 1 - \binom{100}{0} (1/24)^0 (1 - 1/24)^{100} \\ &= 1 - (23/24)^{100} \\ &= 0.985 \end{aligned}$$

So the probability of seeing both variants one or more times is 0.985 multiplied by itself. (See for example McColl (1995) for a straightforward introduction to probability theory, Bernoulli experiments, and the binomial theorem.)

<sup>17</sup> Notice that an assumption that either appropriate lexical rules are induced or the triggering data is sufficiently lexically uniform is critical to maintenance of the speech community in this case. Otherwise different learning agents exposed to different triggers may acquire incompatible word: category associations for the same nominal and verbal modifiers. That is, one agent may only be exposed to *nicely* as a postmodifier and another as a premodifier during the learning period. As adults these agents would not be able to interact successfully using any sentence containing *nicely*.

<sup>18</sup> Analytically characterizing the exact behaviour of the model given such scenarios is very complex because of the use of overlapping generations and 'horizontal' (learner  $\rightarrow$  learner) as well as 'vertical' (adult  $\rightarrow$  learner) interactions. However, in this fairly clear-cut case the lower bound on fixation within six cycles is  $p = 0.994$ .

Now consider what happens if we start with fifty-nine adult agents with  $g^1$  and one agent with  $g^2$ . The initial generation of learning agents each has a  $1/60$  times  $1/12$  chance of being exposed to the variant triggers in  $g^2$  so the probability of this happening during the learning period is  $p = 0.130$ . Assuming ten new learners again, the probability of half or more of them being exposed to the  $g^2$  variant is  $p = 0.005$ , so the probability of subsequent generations of learners acquiring the  $g^2$  variant is lower not higher, as the relative frequency of the variant trigger(s) will decline as long as more than half of the new agents acquire  $g^1$ . Thus, it is very unlikely that a variant seen this infrequently during acquisition would ever spread through the community. Another way of saying this is that the community (as defined by the model) is unlikely to acquire variations based on individual innovations. However, in this community if  $1/12$  of the adult agents (i.e. five) generate a variant trigger with a  $1/12$  chance, a new grammar is quite likely to be acquired by subsequent generations of learners; that is, the probability that more than half of the first generation of learners will acquire a grammar covering the variant is  $p > 0.6$ , so the positive feedback dynamics have a reasonable chance of getting started. This type of analysis allows us to characterize more precisely the degree of variation that a stable model, maintaining linguistic stasis, will tolerate, given  $LP$  and the population dynamics.

To close this section, let us consider what happens if we introduce a sequence of variations into such a speech community. Suppose that every sixteen interaction cycles the current adult population is increased by around  $1/3$  new adult agents who have acquired a grammar with variant trigger(s) exemplified in their output  $1/12$  of the time. I will call such events migrations and introduce ongoing variation into the model via such 'population movements'. Each of these successive variant triggers has a good chance of being incorporated into a new grammar acquired by subsequent learners. If the variant grammars are otherwise close, it is very likely that the speech community will be maintained; such migrations model contact between dialects, rather than mutually incomprehensible languages. Nevertheless, language change will be characterized by the acquisition of increasingly large 'covering grammars' which successively incorporate more and more variation and allow successively greater interactions between variants originally localized in earlier smaller grammars. This is a profoundly unrealistic dynamic for grammatical change, and probably much lexical change too. It implies that as languages change, grammars will tend to incorporate more and more of the possibilities defined by  $UG$ . There is no evidence that grammars grow monotonically in this fashion, incorporating ever increasing variation and optionality (e.g. Lightfoot 1999: 77–92). Yet there is abundant evidence that linguistic heterogeneity rather than homogeneity is the norm during language acquisition.

#### 4.2. DATA-SELECTIVE LEARNING PROCEDURES

A fundamental principle of change and variation is that most variation is mutually exclusive; that is, grammars or linguistic variants tend to compete rather

than coexist as optional variants (e.g. Kroch 1989*b*, Lightfoot 1999: 92–101). A grammar-learning procedure which selects between variants rather than acquiring them all (at least by default) will model this aspect of language change better. There are several ways in which agents could be modified to yield data-selective learners. Firstly,  $UG$  could be parameterized so that the sets of categories defining full grammars was disjoint. For example, at the moment there is nothing to prevent a learning agent acquiring both categories,  $(S/NP_2)/NP_1$  and  $(S/NP_1)/NP_2$ , either for overlapping or disjoint sets of transitive verbs, thus acquiring I-languages with mixed VOS or SVO clause orders. However, if the set of categories available is parameterized so that once the order of subjects is determined for one (verbal) category all other (verbal) categories must conform to this ordering, then  $UG$  will not include grammars with mixed subject ordering in canonical clauses, and thus  $LP$  will not be able to acquire them. Secondly,  $LP$  could be modified so that there is data-driven competition between variant categories. For example,  $LP$  might count the instances in which variant categories (i.e. ones generating the same LF up to lexical variation) occur, and  $G$  might select the current most frequent one for trigger generation.

These alternatives would lead to different outcomes assuming once again the scenario of §4.1.3. Given a  $UG$  which parameterized cross-categorially for head-initial/final modification, then a learning agent could acquire  $g^1$  or  $g^2$ , but not  $g^3$ .<sup>19</sup> If we assume that  $LP$  sets such parameters deterministically, never altering a parameter once it has been set via triggering data (e.g. Briscoe 1997), then the first variant trigger a learning agent is exposed to will determine the relevant part of the category set available thereafter. Thus, learning agents will each select  $g^1$  or  $g^2$  solely on the basis of the specific sequence of triggers they are exposed to. Agents of the initial generation each have an equal chance of seeing a post-modifier or premodifier first, so on average learners have an equal chance of selecting  $g^1$  or  $g^2$ . However, the actual probability of exactly half the learning agents acquiring  $g^1$  is only  $p = 0.246$ , so the probability that the first generation of learners will alter the subsequent distribution of triggers in favour of either  $g^1$  or  $g^2$  is  $p = 0.754$  (rising to  $p = 0.999$  by the fifth generation). Similarly, if, following Gibson and Wexler (1994) and others, we assume that parameters are continuously reset on parse failure (i.e. that the learning procedure is 'memoryless' and free to revisit previous hypotheses), then the dynamics remain identical but the grammar selected is now dependent on the last variant trigger seen. We could also posit a different parameterization in conjunction with either

<sup>19</sup> Once we posit parameterization of  $UG$  or, more generally, a data-selective learner, then it may no longer be possible to characterize the E-language of the community in terms of any I-language grammar which can be acquired by an individual learning agent. Lightfoot (1999: 81–2), for example, argues that 'social grammars' are, at best, fictitious linguistic constructs and will probably have to embody very different properties from 'biological grammars' generating I-languages. This section amplifies this point and demonstrates how either properties of  $UG$  and its parameterization or of  $LP$  may make it true. However, 'social grammars' might still turn out to be useful constructs for modeling triggering data succinctly.



of these models of *LP*, such as one that licensed, say, verbal postmodifiers and nominal premodifiers but not both types of modifier for one type of head: then learning agents could acquire one of four possible grammars. However, the dynamics of which grammar the community fixated on would remain essentially the same. The model of language change developed by Niyogi and Berwick (1997) and Niyogi (2000) is of the type just outlined. Learners select between variants (i.e. set a parameter) on the basis of the last relevant trigger they see before the learning period ends. This accounts for the (unrealistic) preference for +V2 over -V2 languages in their simulations, because in the *UG* fragment developed by Gibson and Wexler (1994) +V2 languages have more determinate +V2 triggers than -V2 languages have determinate -V2 triggers. Therefore, a learner is more likely to see +V2 triggers, on average, if +V2 grammars are present in the adult population and trigger generation is random.

Learners of this type predict that a speech community will drift randomly between variant grammars until one or other variant reaches fixation. Even though there will be positive feedback favouring any variant which is slightly better exemplified in the learner's data, random effects, such as the particular sequences of triggers seen by individual learners, may override an incipient trend towards one variant. However, at some point, one or other variant will become dominant enough to fixate with virtual certainty. This pattern is well known and well studied in population genetics and evolutionary theory as (random) *genetic drift* (e.g. Maynard-Smith 1998: 24–6). Eventual fixation on one variant is inevitable in finite populations, so we would typically expect to see a longish period of random fluctuations followed by an exponential increase in the frequency of one variant, leading to fixation. Notice that this pattern is very different from S-shaped logistic growth. As far as I know, this pattern of 'grammatical drift' has not been attested.<sup>20</sup>

The alternative approach of modifying *LP* to track the frequency with which variant categories are exemplified in the learning data will yield different dynamics again. Consider first a non-parameterized learner as defined in §4.1.1 with a modified version of *LP* which records the number of times each word:category association hypothesized is used in a successful parse of a trigger. At any given point, the learning agent generates using only the most frequent word:category association when there are variant alternatives generating the same LF. At the end of the learning period, the agent stops counting, so the most frequent word:category associations at that point are the ones which define the acquired grammar. This 'statistical' learning procedure will acquire the 'majority grammar' which incorporates the most frequent variants from potentially multiple source grammars. For the pre/postmodification example, four grammars would be avail-

<sup>20</sup> The notion of drift being employed here is, of course, very different from that introduced into (historical) linguistics by Sapir (1921: 150), who used this term to designate stereotypical and thus apparently 'directed' processes, such as loss of case marking leading to increased periphrasis.

able to the learning agent representing the possible combinations of pre/postmodification with nominal/verbal heads. Thus, superficially this approach resembles the weaker parameterization discussed above. However, the dynamics of language change will now depend much more closely on the frequency with which variants are exemplified across the whole learning period, and thus on the true frequency of the variants in the community. If initially variants are equally represented in the community, then the grammar acquired by a learner will depend on random fluctuations in triggering data. However, as soon as one variant is incorporated into more than half of the grammars, learners will tend more consistently to acquire that variant, because their final hypothesis will be much less sensitive to the particular sequence of triggers they were exposed to. Thus the amount of random drift will decrease and patterns of change should, other things being equal, show less fluctuation and proceed more consistently towards fixation on one variant.

The differences between these dynamics are illustrated graphically in Figure 4.4 which shows the spread of a single variant grammar through a stable population of one hundred agents, forty of whom are learners (see §4.1.2). The y-axis of the left-hand graph indicates the proportion of all agents who have acquired the variant; that of the right-hand graph, the proportion of learning agents acquiring the variant in the same simulation run. The S-Learner curve shows the spread of the variant when learning agents use the statistical version of *LP* described above. R-Learner1 models this spread when *LP* acquires the

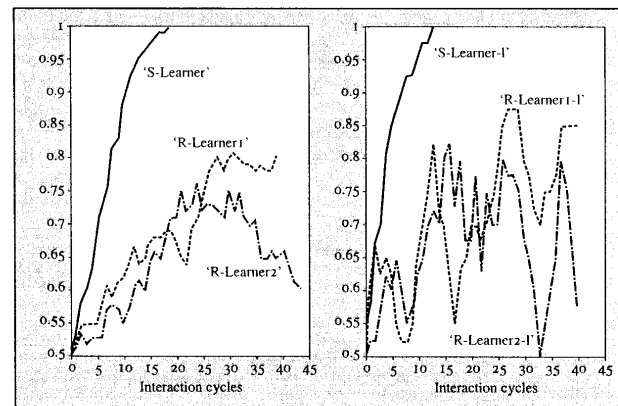


FIGURE 4.4. Spread of a variant

variant determined by the first (or last) relevant trigger, and R-Learner<sub>2</sub> represents the effect of *LP* selecting a grammar as a probabilistic function of the proportion of agents who have acquired each variant grammar at that point. The simulations were initialized with equal proportions of adult agents with  $g^1$  and  $g^2$ . In each of the three runs selected, representing the three different variants of *LP*,  $g^1$  spreads at the expense of  $g^2$  and the y-axis starts at 0.5.

The statistical version of *LP* shows steep, though still logistic spread of  $g^1$  until all learners are acquiring this variant (by interaction cycle 13 on the right hand graph). Fixation in the adult population is slower (as indicated in the left hand graph) because once all new learners are reliably acquiring  $g^1$ , the remaining  $g^2$  adult population must die out. This slope can be made more gradual by increasing the age of death relative to the critical period or by increasing the proportion of adults to learners. The dynamics of the spread of  $g^1$  with the other versions of *LP* are more random, with downward as well as upward fluctuations and no fixation within the time scale plotted, as predicted by the analysis above. Niyogi and Berwick (1997) argue that logistic spread follows from but is not 'built into' the model of language change they develop. Robert Clark (1996) shows that in many situations their model actually produces exponential rather than logistic growth. These microscopic simulations suggest that their framework, and in particular the Trigger Learning Algorithm, will also frequently predict random grammatical drift. The particular derivation of logistic spread proposed here follows from a more realistic modelling of the composition of the population (with overlapping generations and variant proportions of learners to non-learners).<sup>21</sup>

The statistical version of *LP* is quite compatible with (any) parameterization of *UG*. For example, if, as before, we posit a head-initial/final parameter which selects for pre/postmodifiers cross-categorially, then the learning agent will simply select between two rather than four grammars on the basis of the frequency with which pre/postmodification is exemplified cross-categorially in the triggering data. In general, parameterization will yield a more efficient *LP* which explores a smaller hypothesis space and thus more robustly selects a final grammar on the basis of a smaller number of associated cues in triggering data (e.g. Dresher 1999). Therefore, there are independent reasons for expecting *UG* to be

<sup>21</sup> Whether this is a correct account of any particular case of syntactic change remains to be seen. Kroch (1996b) demonstrates that logistic change via competition between grammatical subsystems occurs, but is not explicit about whether this competition is between grammars internalized by single speakers, across speakers, or a mixture of both. This account does not address the bilingual or diglossic scenario. However, diglossia is much easier to account for if learners track parameters of variation rather than utilizing a 'memoryless' *LP* because it is straightforward to augment the statistical version of *LP* so that the evidence for alternative settings of each parameter is recorded. Simon Kirby (p.c.) points out that logistic change would also be expected if learners acquired both variants but produced one in preference to the other. Hurford (2000) discusses such 'production bottlenecks' in the context of a detailed comparison of the various ways in which language changes have been modelled computationally.

parameterized, apart from data-selectivity. Nevertheless, parameterized or not, a *LP* which selects between grammars using single trigger instances predicts very random dynamics in language change. These have not been observed to my knowledge, and certainly would not lead us to generally expect logistic patterns of change.<sup>22</sup>

#### 4.3. LEARNING PROCEDURES WITH INDUCTIVE BIAS

So far we have explored the interaction of population dynamics and *LP* in determining the dynamics of selection or absorption of linguistic variants exemplified in a speech community, assuming that *LP* has no preferences concerning the grammars it learns. That is, that within the space defined by *UG*, there is no inductive bias favouring some grammars over others. Formal learnability work on language acquisition has tended, at least implicitly, to take the position that there is no such bias, by assuming that the starting point for learning is arbitrary or random (e.g. Gold 1967, Gibson and Wexler 1994) and by defining learnability in terms of reachability of any  $g \in UG$  (given triggers from  $g$ ) from any such starting point.<sup>23</sup> More substantively oriented work on parameters has tended to assume that some, perhaps most, parameters will have unmarked or default values (e.g. Chomsky 1981: 7–11, Hyams 1986, Wexler and Manzini 1987). Such an assumption is a form of inductive bias, or soft constraint, over and above the hard constraints determined by *UG*, as it creates a preference ordering on the acquisition of  $g \in UG$  by *LP*. For example, if we assume that there is a  $V_2$  parameter which has an initial unmarked or default  $-V_2$  value, we are saying that  $-V_2$  grammars will be ordered higher and considered before  $+V_2$  grammars within the space of possible grammars defined by *UG*. So a learner must be exposed to robust positive evidence to reset this parameter to the non-default or marked value. The unmarked default value, however, will dictate the shape of the acquired grammar in the absence of (robust enough) evidence.

Inductive bias can also be introduced by assuming that parameters of *UG* are set in a particular order and that the effects of parameters are partly dependent on the settings of others (e.g. Briscoe 1997, 1998, Dresher 1999). For example,

<sup>22</sup> A statistical learning procedure of the type outlined can also account for robust acquisition in the face of indeterminacies of parameter expression (e.g. Clark 1992), such as the ambiguity of SVO triggers given  $V_2$  grammars discussed in §4.1.1 (see Briscoe 1999). Deterministic and/or local parameter setting procedures of the type described by Gibson and Wexler (1994), Niyogi and Berwick (1996), Dresher (1999), and Briscoe (1997, 1998) suffer from possible 'premature' and irrecoverable convergence to an incorrect grammar in the face of such indeterminacies.

<sup>23</sup> In fact, an assumption of inductive bias is the norm rather than the exception in learning theory; for example Cosmides and Tooby (1996) and Staddon (1988) argue that evolution equips organisms with specialized domain-specific learning mechanisms incorporating inductive bias assimilated from the environment of adaptation for the learning mechanism. More statistically oriented approaches to language learnability also often rely on an assumption of 'closeness' or informativeness of prior knowledge in proofs of learnability or high probability convergence (e.g. Muggleton 1996).

if the effects of a head-initial/final parameter, having been (re)set, can be partly overridden by the setting of a more specific parameter which determines the order of heads and arguments for a specific category, then *LP* will first consider 'harmonic' head-initial/final grammars, but adopt 'mixed' grammars on the basis of positive evidence of specific categorial exceptions.<sup>24</sup> Similarly, a statistical approach to the setting of parameters (or choice between variants) can naturally be extended to incorporate inductive bias by positing a Bayesian approach to learning in which the final (posterior) setting (or choice) rests on the interplay between a prior probability of a setting (or choice) and its probability given the triggering data (e.g. Briscoe 1999). For example, if a head-initial/final parameter has a prior probability of 2/3 for the value head-initial (and thus a prior probability of 1/3, i.e. 1-2/3, for head-final), then we can quantify precisely the degree of evidence required for *LP* to reset the parameter from its default value using Bayes theorem. In this case, the probability derived from the triggering data must be >2/3 for the posterior probability to favour the marked setting.<sup>25</sup>

If *LP/UG* includes inductive bias, then the dynamics of language change will no longer be determined so directly by properties of the triggering data (within the overall space defined by *UG*). Instead the relative frequency with which a variant is exemplified in triggering data will interact with the bias inherent in *LP*,

<sup>24</sup> Briscoe (1997, 1998) details how *UG* can be modelled using a default inheritance hierarchy describing possible categories of a CG. In this model, the setting of more general cross-categorial parameters, by default, sets more specific parameters, so that the learner predicts harmonic grammars and only revises such predictions if subsequent triggers force this.

<sup>25</sup> We assume that 'relevant' triggers provide positive evidence for head-final or positive evidence for head-initial. Therefore the so-called likelihood probability (derived from the triggering data) for head-final is given by:

$$P_f(X = \text{final}) = \frac{f(t_{\text{final}})}{f(t_{\text{multinomial}})}$$

where  $f$  denotes frequency counts (i.e. the maximum likelihood estimate over the relevant triggers). The posterior probability is given by:

$$P_{\text{ps}}(X = \text{final} | t_i) = \frac{P_{\text{ps}}(X = \text{final}) P_f(X = \text{final})}{P(t_{\text{multinomial}})}$$

(i.e. by Bayes theorem). The probability of the relevant triggers,  $P(t_{\text{multinomial}})$ , is a constant normalizing factor which can be ignored. We need only compare the unnormalized posterior for head-final to that for head-initial and choose the highest. As the prior,  $P_{\text{ps}}$ , is multiplied by the likelihood,  $P_f$ , the unnormalized posterior for head-final will only exceed that for head-initial (when  $P_{\text{ps}}(X = \text{final}) = 1/3$ ) if the associated likelihood probability is >2/3. For example, if five out of six relevant triggers are head-final, then the two unnormalized posteriors are computed as follows:

$$P_{\text{ps}}(X = \text{final} | t_i) = 1/3 \times 5/6 = 10/36$$

$$P_{\text{ps}}(X = \text{initial} | t_i) = 2/3 \times 1/6 = 4/36$$

Briscoe (1999, 2000a) develops a Bayesian approach to parameter setting in greater detail. Sivia (1996) provides a good introduction to Bayesian data analysis.

as well as, of course, the population dynamics. Returning to the example of pre/postmodification, if we assume, as is natural in CG, that the same *UG* parameter also selects between head-final/initial modifiers, that head-initial is the default unmarked value, and that this default has a relatively strong prior of 4/5, then in a community fixated on  $g'$ , a premodifier grammar would need to be swamped by migrating agents generating postmodifiers so that the triggering data to the next generation contained >4/5 triggers exemplifying postmodification. Thus, the Bayesian approach is one way of making concrete and precise Kiparsky's (1996) proposal that change results from the interplay of triggering data with internal preferences created by *LP/UG*.

To address the question of how likely it is that the language faculty incorporates inductive bias, the population model introduced in §4.1.2 can be modified to incorporate natural selection for language agents by using the CSR as a measure of fitness and making reproductive success relative to fitness. For this to be meaningful there must be variation in the language faculty with which language agents are initially endowed. In Briscoe (1997, 1998) I describe in detail an encoding of *UG* which allows the 'starting point' for learning to be varied, in terms of what counts as a principle or parameter and which parameters have default or unset values. Mutation and crossover operators are defined over this encoding so that the creation of new agents can both introduce and spread (the analogue of) genetic variants. Thus, we modify the basic population model with a more evolutionarily realistic version of reproduction (see Figure 4.3 above for comparison):

REPRO: Create-LAgT(Mutate(Crossover(LAgT, LAgT))),  $i \neq j$ , CSR,  $\wedge$  CSR,  $>$  Mean-CSR

The cross-over operator combines the encoding of *UG* randomly from the two higher than average fitness 'parent' agents, while the mutate operator with equal and low probability converts a parameter to a principle, or vice versa, flips the value of a default parameter, or converts a default to an unset parameter. Once such genetic variation is introduced, it is essential to posit natural selection for language agents on the basis of their CSR, otherwise populations inevitably cease to learn and communicate after a few hundred cycles, as random variation in language faculties builds up. However, with natural selection, the population evolves to a (local) optimum in the predefined space of *UGs*, determined in part by the range of grammars/languages sampled before they cluster around such an optimum. For example, if the languages sampled during a significant period during adaptation are OV, then the population is likely to genetically assimilate an unmarked OV parameter setting, since this speeds up learning.

This is an example of genetic assimilation (e.g. Waddington 1942), or the so-called Baldwin Effect (Baldwin, 1896), in which changes in a species' behaviour (the advent of language) create new selection pressures (the need to learn

language efficiently).<sup>26</sup> When language change is as rapid as is consonant with maintenance of a speech community during adaptation, genetic assimilation results in around twice as many soft constraints (inductive bias) as hard constraints (incorporation of principles into *UG*); as the former have a less fatal effect on successful learning if subsequent change renders an assimilated principle incorrect. Additionally, genetic assimilation slows and ultimately ceases once a near optimal balance between learning speed and the speed of linguistic change has been found; in this model, when around half of the possible parameters in the predefined space of *UGs* have been converted to principles or default-valued parameters. Without continuous linguistic change, there is no reason why the process of genetic assimilation should not proceed until the need for (grammatical) learning is eradicated (*pace* Pinker and Bloom 1990). However, with constant linguistic change, too much constraint on learning becomes maladaptive.

These simulations cannot, of course, *prove* that the language faculty incorporates inductive bias via genetic assimilation, but they do help to clarify the (pre-historic) conditions under which this would have been likely. In particular, the relative speed of language change compared to biological evolution and the size of the relevant population during the period of adaptation are unlikely to have been critical factors (*pace* Deacon 1997: 328–40), and the possibility that the language faculty arose *de novo* via a single macromutation or exaptation (e.g. Berwick 1998, Bickerton 1998) does not affect the argument because organs which arise via exaptations of spandrels or by macromutations are still susceptible to *subsequent* modification by natural selection (e.g. Ridley 1990, Lieberman 1991, Kirby 1998). Indeed in these simulations, language agents do begin with language faculties (either random or converged) and these are merely refined by subsequent evolution. However, the current model does assume a one to one correlation between changes to the genetic encoding and phenotypic changes to *LP/UG*. Such a close correlation would be unlikely in nature, and has the effect of speeding up genetic assimilation effects (e.g. Mayley 1996). Until we know more about the genetic encoding and neurological basis of the language faculty, it is impossible to quantify how long it might actually have taken for assimilation to occur.

If we accept that there is inductive bias in language acquisition, as I think we should, given both the evidence from the simulation work and from empirical studies of language acquisition (e.g. Wanner and Gleitman 1982) and general considerations of learning theory (e.g. Cosmides and Tooby 1996), how does this affect our view of language change?<sup>27</sup>

<sup>26</sup> Waddington (1975) and Pinker and Bloom (1990) both propose that genetic assimilation played a role in the formation of the language faculty. Kirby and Hurford (1997) and Briscoe (1997, 1998, 2000b) develop detailed models of this process and provide a more thorough discussion of the effect and its likely relevance.

<sup>27</sup> Lightfoot (e.g. 1999: 165–7) criticizes some specific arguments for inductive bias as an explanation of grammatical change and also makes the general point that if a bias explains how a variant was eradicated, we also need an account of how the variant can arise. I address the more general point

#### 4.4. LANGUAGES AS ADAPTIVE SYSTEMS

So far I have argued that (E-)languages are dynamical systems, the aggregate output of a set of grammars which change over time as the membership of a speech community changes. However, if grammar learning is data-selective and biased, then languages are better seen as *adaptive* systems which will inevitably evolve to fit their unique ecological niche—the human language faculty and wider cognitive system. Under this view, languages are evolving on a *historical* rather than biological timescale, and the primary source of *linguistic selection* is the language acquisition ‘bottleneck’ through which successful grammatical variants must pass repeatedly with each new generation of language learners. Evolution and selection are not being used here metaphorically, but in their technical ‘universal Darwinist’ sense (e.g. Cziko 1995, Dawkins 1983, Dennett 1995: 343) of (random) variation, selection amongst variants, and thus differential inheritance. These terms are potentially applicable to any dynamical system, whether that system is ‘implemented’ in biological organisms, silicon, or cognitive linguistic representations.<sup>28</sup>

Returning to the example of pre/post-modification and the Bayesian parameter setting learner outlined in the previous section, assume again that *LP/UG* incorporates a cross-categorical head-initial/final parameter with a bias for head-initial and also category-specific parameters which, by default, pick up their value from the more general cross-categorical parameter, but can be reset by positive evidence in triggering data. This creates a bias for harmonic head-initial grammars. Change in (E-)languages can now be seen in terms of selection amongst grammatical variants which are more or less ‘natural’ with respect to *LP/UG*. There will clearly be an asymmetry in terms of the dynamics of change as non-harmonic and head-final grammatical variants will need to be exemplified in the triggering data frequently enough to overcome the bias in *LP* and to force the resetting of more specific parameters. Thus, the competition between grammatical variants is biased. Assuming, as in §4.3, that the prior bias for head-initial is 4/5 and this bias is inherited by all the more specific parameters, yielding harmonic head-initial settings, then a community fixated on a (partially) disharmonic or head-final grammar can begin shifting to a more harmonic head-initial one if variant triggers are exemplified with > 1/5 likelihood probability to any given learner. That is, there is differential linguistic selection in favour of

in §4.5. The detail of the specific arguments are beyond the scope of this paper, but I also agree with Lightfoot (1999: 218–20) that if there is bias, this must interact with triggering data in explaining change. The Bayesian model of *LP* allows us to quantify precisely the interplay of data and bias.

<sup>28</sup> As far as I am aware, Hurford (1987) is the earliest expression of this view from a syntactician, though the argument is presented much more clearly in Hurford (1999) and Kirby (1998, 1999). Lindblom (1998) and colleagues have developed a similar approach to the evolution of phonological systems. Others who have adopted similar viewpoints include Batali (1998), Deacon (1997), and Steels (1998).

head-initial harmonic grammars as a consequence of *LP/UG*, so (E-)languages are highly likely to adapt to *LP/UG* over time, given some continuing source of (random) variation.

There is no requirement that the bias, or process of change, is 'functional' in any deeper sense. For example, if *LP/UG* incorporates such a bias, this may rest on nothing more fundamental than the fact that the languages sampled during the period of adaptation for the *language faculty* were mostly harmonic and head-initial (see §4.3). Alternatively, 'harmonic' languages may have been preferred initially because they facilitate language processing (see §4.5 below), so the bias assimilated into *LP/UG* would rest ultimately not (entirely) on (pre)historical accident but on wider aspects of human cognitive capacities and limitations. Either way, (E-)languages can be said to have adapted to their niche via linguistic selection.

Superficially, characterizing (E-)language changes as an adaptive evolutionary process may not seem to add much to the view that languages change or, more specifically, that languages can be modelled as non-linear dynamical systems. However, it does commit us to the claim that language change is a process of differential selection amongst variants, so it rules out scenarios in which language acquisition is not data-selective and biased, and also ones which involve a significant amount of 'invention'; that is, going beyond the data. Perhaps, more importantly, modern population genetics provides a battery of tools to analyse the situations under which a variant with a small selective advantage manifested by a single individual, or small minority of individuals, can spread through a population. These tools can be adapted to the study of linguistic change straightforwardly once we have precise enough theories of language acquisition and processing. In particular, the move from a random drift, 'neutral' theory of change to an adaptive account may be a necessary prerequisite to an understanding of how some changes can spread from very small beginnings.<sup>29</sup>

Creolization has been characterized by Bickerton (1984: 173) as a process of 'invention' in terms of the learner's innate bioprogram; first language learners exposed exclusively to an impoverished pidgin subset language acquire a super-set creole grammar. If this view is correct, then it would undermine the claim that significant language change can be modelled as an evolutionary process. However, Lightfoot (1991: 178–80; 1999: 167–74), while accepting the abruptness of creolization, challenges the idea that it requires a special account of language acquisition, arguing that properties of the pidgin triggering data lead to reanalysis and consequent parameter resetting across generations. Roberts (1998) argues that some features of Hawaiian creole took two generations to emerge, which also supports the hypothesis that creolization is very fast language change,

<sup>29</sup> Kirby (1997, 1999) is one example of a detailed and carefully worked-out account of linguistic change based on adaptation to language acquisition.

rather than the result of a special process of consistent invention by each first language learner.

I have simulated creolization, especially the situation in Hawaii, in as much linguistic and demographic detail as is practical, given the limits of the model of *LP/UG* developed in Briscoe (1999) and what is known about the demographic factors. Creoles emerge when first language learners are born to a diverse community of indentured workers or slaves with an impoverished pidgin as their *lingua franca*. In Hawaii the proportion of such learners by the end of the first generation (i.e. twenty years constituted about 35% of this community and was increasing throughout this period. In other cases of plantation creolization this proportion may have been lower, but was probably increasing throughout the early (overlapping) generations of first language learners.<sup>30</sup>

The demographic situation is modelled by introducing six new learning agents per interaction cycle into a community of sixty-four adults who are not changed during the simulation run. Agents learn for four interaction cycles and can reproduce thereafter. The proportion of learners reaches a maximum of 28% at the sixth interaction cycle and then tails off gradually to a stable 15%. We are interested in the proportion of learners converging to a creole grammar across interaction cycles, bearing in mind that four interaction cycles is equivalent to one generation (i.e. twenty years).

The statistical version of *LP*, outlined in §4.3, was integrated with a version of *UG* which contains fifteen parameters which determine the number and type of CG categories in an acquired grammar. These categories can be divided into those that determine ordering of arguments to functor categories and those which determine the availability of specific functor categories. For example, one parameter controls the availability of a functor category which licenses relative clause modifiers of nominal heads. However, whether the *wh*-element precedes or follows the relative clause and whether this is pre/postnominal depends on potentially interdependent but distinct ordering parameters. The bias assumed in *LP* is based on Bickerton's (1984) account of Saramaccan, as the prototypical creole grammar, and models a preference for simple SVO right-branching grammars.

<sup>30</sup> The estimate of 35% is based on census figures for 1890, 1900, and 1910 kindly supplied by Derek Bickerton. These are incomplete in some areas but indicate an under-fifteen population of at least 20% by 1900 and 35% by 1910, assuming a similarly high birthrate amongst Hawaiians as amongst Portuguese immigrants (44% by 1910). (This assumption is in turn supported by school attendance records of 5–14 year olds.) Bickerton suggests that creoles emerge when the proportion of under-twelves was between 15% and 25%. The speed of spread of the creole through the learner and total population will both be increased if the proportion of learners is greater and the increase in this proportion is steeper. Therefore, it is possible that (features of) Hawaiian creole spread more rapidly (within two generations, according to Roberts 1998) because the birth rate was high. Only further demographic and linguistic work on other pidgin-creole transitions will tell, but the model predicts such speed differences.

Such learners, exposed exclusively to pidgin data, modelled as clauses with a verb and single word subjects and objects appearing in random orders, tend to acquire a grammar generating a SVO subset language with similar clauses. That is, they do not generalize the pidgin data and invent a creole superset grammar but they do converge to SVO order. Furthermore, by around the sixth interaction cycle (i.e. within two generations) all learners in these simulation runs are converging to SVO grammars. This result can be understood in terms of the interplay of the triggering data and *LP* in conjunction with the increase in SVO triggers as the population of learners grows. Faced with conflicting and equivocal evidence for basic constituent order, *LP* will tend to set parameters in terms of prior biases. However, trigger sampling variation will mean that some early learners may not acquire a SVO grammar, or may hypothesize non-SVO grammars at intermediate stages in acquisition. Nevertheless, if the majority of learners do (eventually) acquire SVO grammars, then the incidence of SVO triggers will increase causing the familiar positive feedback dynamics to take over. Thus, the inductive bias for SVO is enough to kick the system in the right direction, but it is only as the population gains SVO speakers that the chances of learners acquiring non-SVO grammars declines to negligible levels. Thus, this account is purely selectionist and predicts that the birthrate will be a factor in the speed of creolization, but as yet does not explain how first language learners can acquire a superset creole grammar.

Bickerton (1981, 1984, 1988) has argued that superstratum and substratum languages play no role in the acquisition of the creole. The evidence for this comes from the lack of a consistent grammatical relationship between the creole and these potential sources, as well as the similarities of unrelated creoles (e.g. Roberts 1998). Bickerton (e.g. 1984: 182–8) recognizes that in many cases, including Hawaii, learners would be exposed to a small proportion of superstratum and substratum utterances but downplays their role as triggers on the basis of their relative infrequency and, in the case of substratum utterances, mutual inconsistency. Nevertheless, if the triggering data to the statistical *LPIUG* model is enhanced to include a small proportion of more complex superstratum triggers, with or without a further small proportion of random substratum language triggers, exemplifying multiword phrases and subordination, learners converge to and fixate on a SVO right-branching superset grammar with essentially the same dynamic and timecourse as that discussed above.

Briscoe (2000a) discusses these simulations and their interpretation in further detail. While they are by no means conclusive and rest on rather sketchy demographic information and consequent assumptions about the nature of the triggering input, they nevertheless add weight to the argument that creolization should be seen as a case of rapid language change caused by the interaction of ordinary language acquisition with radical demographic changes. Though creolization poses the most obvious challenge to a selectionist account of language change in terms of inductive bias in language acquisition, there are other difficulties

which require us to adopt a more sophisticated model of the evolutionary process which incorporates conflicting and interacting selection pressures on language change stemming from wider cognitive capacities and limitations.

#### 4.5. LANGUAGES AS COMPLEX ADAPTIVE SYSTEMS

If languages adapt solely to innate preferences during language acquisition, we would expect the history of languages to show nearly inexorable development towards an optimal or most natural grammar. Presumably, we would expect all speech communities to fixate ultimately on creole-like grammars if these represent the most natural optimal or default solutions with respect to *LP*. Chance factors might temporarily move a language away from such a solution but, over time, constant and universal selection pressure should (re)assert itself. While supporters of grammaticalization have argued for a (prototypical) unidirectionality in change (e.g. Hopper and Traugott 1993: chapter 5) and there is evidence of skewing in the distribution of attested languages with respect to the range of possible grammars most theories of *UG* license (e.g. Hawkins 1994), no-one would argue that language change is this deterministic.

Lightfoot (1999: 213–18) uses similar arguments to criticize accounts of language change which rely on innate preferences or inductive bias, asking how the relevant variation might have arisen in the first place if bias is the explanation for the selection of a particular variant. He, in fact, goes on to endorse models, such as that of Kiparsky (1996), which explain change in terms of the interplay of acquisition preferences and changes in triggering data (as does the Bayesian version of *LP* outlined in §4.3). Surprisingly, he also accepts the argument of Niyogi and Berwick (1997) that historical tendencies in language change may result from dynamic trajectories caused by learners misconverging. However, Kiparsky's position and that of Niyogi and Berwick are quite different. As we noted in §4.1.2, Niyogi and Berwick explore a model in which change is inevitable even without initial 'external' perturbation of triggering data. Given a speech community fixated on a  $-V_2$  grammar some learners will misconverge, initiating a process of change. This is essentially because the Trigger Learning Algorithm will not converge, or will converge with very low probability, given a random starting point and the theory of *UG* they consider (Niyogi and Berwick 1996). Thus, the model is unstable and predicts inexorable change towards some fixed point. Robert Clark (1996) illustrates the instability of their model very clearly in a series of replicated simulations which explore the behaviour of the model when learners are given between 8 and 256 triggers. This account, then, is really an extreme version of the accounts of language change being driven by internal preferences (or failings) during acquisition. However, even accounts which predict stability under conditions of homogeneity, and require changes in triggering data as well as acquisition preferences in order for change to occur, still require some account of how apparently suboptimal variants ever arise in speech communities.

The idea that there are competing motivations or conflicting pressures deriving from the exigencies of production, comprehension and acquisition has been developed by linguists working from many different perspectives (e.g. Langacker 1977, Fodor 1981, Croft 1990: 192–202). In linguistics little progress has been made in quantifying these pressures or exploring their interaction, except in the area of phonology where Lindblom (e.g. 1998) has adopted a similar evolutionary model to that advocated here. Evolution is *not* a process of steady improvement along a single trajectory leading to a single optimal solution. Sewall Wright (1931) introduced into evolutionary theory the idea of adaptive or fitness landscapes with multiple local optima or peaks, and this idea has been considerably refined since (e.g. Kauffman 1993: 33–45). The modern picture of (co)evolution is of a process of local search or hill climbing towards a local optimum or peak in a fitness landscape which itself inevitably changes. Conflicting selection pressures will cause the fitness landscape to contain many locally optimal solutions, and thus the evolutionary pathways will be more complex and the space of near optimal solutions more varied (Kauffman 1993: 44).

A simple and well-attested example of conflicting selection pressures from biology is the case of 'runaway' sexual selection for a non-functional marker such as the peacock's tail, counterbalanced by natural selection for efficient movement (e.g. Dawkins 1989: 158f.). A simple linguistic example is given in Briscoe (1998). There are (as in §4.4) seventeen parameters to be set during learning, and only setting a subset of these parameters yields a subset language. Given some degree of linguistic variation, the speech community will tend to fixate on a subset language, optimizing learnability at the expense of expressivity. Regardless of whether there is natural selection for agents on the basis of communicative success, optimizing learnability at the expense of expressivity is highly likely. To counteract such a tendency, we can either posit that *LP* requires all parameters to be set (somehow), or that there is a counteracting pressure for expressivity. This could be introduced into the model by positing some range of logical forms that must be realizable (possibly 'economically') and penalizing agents' communicative success whenever their current grammar does not allow this. Introducing such a conflicting or competing pressure (suitably weighted) prevents unconstrained optimization for learnability. Now variants which are adaptive must improve learnability and maintain expressivity (or vice versa).

Another and perhaps better understood pressure on the evolution of grammatical systems derives from parsability (e.g. Gibson 1998, Hawkins 1994, Miller and Chomsky 1963, Rambow and Joshi 1994). A number of metrics of the relative parsability of different constructions have been proposed, both as accounts of the relative psychological complexity of sentence processing and of the relative prevalence of different construction types in attested languages. A metric of this type can be incorporated into an evolutionary linguistic model in a number of ways. Kirby (1999) argues, for example, that parsability equates to learnability, as triggers must be parsed before they can be used by a learner to

acquire a grammar. By contrast, Hawkins (1994: 83–95) argues that parsability may influence generation so that more parsable variants will be used more frequently than less parsable ones (within the space of possibilities defined by a given grammar), and presents evidence concerning the relative frequency of constructions from several languages in support of this position. This would entail that less parsable constructions would be less frequent in potential triggering data, in any case. Briscoe (1998) demonstrates that either approach, alone or in combination, can account for linguistic selection in favour of more parsable variants.

One type of common non-argument against the view that languages are adaptive is that languages exhibit dysfunctional or maladaptive properties. For example, many languages peripherally exhibit multiple centre- and self-embedding constructions (e.g. De Roeck *et al.* 1982, Hudson 1995). Yet such constructions are known to cause parsing problems (e.g. Miller and Chomsky 1963, Gibson 1998). If languages are (complex) adaptive systems why have such constructions survived? It is easy to devise models in which their survival is a mystery. For example, Kirby's (1999) equation of parsability with learnability predicts that relatively less parsable constructions will be less likely to function as triggers. As his learning model does not involve predictive generalization, it is inevitable that a less parsable construction will be replaced by a more parsable variant. However, a more complex and adequate model of grammar learning, such as that of Kirby (2000), may make very different predictions. For example, if learning involves setting parameters on the basis of degree-0 triggers (e.g. Lightfoot 1991), then embedded constructions will be learnt indirectly as a predictive consequence of simpler triggers, and thus will continue to be 'inherited' by subsequent generations if the interaction of parameter settings generates centre- and/or self-embedded constructions, even though their acceptability in the arena of language use may well be marginal in view of the desire for communicative success. The models of *LP/UG* discussed in this paper are all potentially of this type since the interaction of functor categories acquired from degree-0 or degree-1 triggers will generate such constructions. Putative examples of dysfunctional or maladaptive features are not in themselves counter-evidence to the view of (E-)languages as complex adaptive systems, any more than unanalysed strings are evidence for or against a specific syntactic theory.

Once we recognize that there are conflicting selection pressures, it is easier to see why language change does not move inexorably (and unidirectionally) towards a unique global optimum. No such optimum may exist, and in any case, change will always be relative to and local with respect to the current 'position' in the current fitness landscape. For instance, a canonical SOV grammar might evolve increasingly frequent extraposition because SOV clauses with long or 'heavy' object phrases are relatively unparsable (e.g. Hawkins 1994: 196–210). However, SVO grammars will be less likely to do so since long object phrases will mostly occur postverbally anyway and will not create analogous parsing problems. Once such a change has spread, it may in turn create further

parsability (or expressivity or learnability) issues, altering the fitness landscape; for example, by creating greater structural ambiguity, resulting perhaps in evolution of obligatory extraposition. (It is this locality or blindness in the search for good solutions that makes the evolutionary process more like tinkering than engineering.) In the framework advocated here, we can recognize that such historical pathways can be stereotypical responses to similar pressures arising in unrelated languages, in much the same way that eyes and wings have evolved independently in different lineages many times, without the need to posit a substantive theory of such changes or see them as deterministic (see e.g. Lightfoot 1999: 261–8).<sup>31</sup>

#### 4.6. CONCLUSION

Models of non-linear dynamical systems can play several useful roles in the study of language change: to characterize population dynamics during a change, to characterize the dynamics of the linguistic change within the population, and to characterize the interaction of the population and linguistic dynamics. For instance, it is clear that creolization is a type of rapid linguistic change which is also dependent on radical demographic changes. The model developed here allows characterization of the linguistic change in the context of the demographic changes. The speed of linguistic change (i.e. the spread of the variant through the relevant part of the speech community) can then be seen to be faster in this case than in the case of a more stable population. This perspective supports an account of creolization as rapid but otherwise normal selective linguistic change.

Characterizing (E-)languages as adaptive systems undergoing differential linguistic selection enriches and constrains their modelling as non-linear dynamical systems. Adaptive systems are a subset of possible dynamical systems, so this step is only justified if we can demonstrate clear selection pressure as opposed to (random) drift. Logistic growth is predicted by selection rather than by random drift. Adaptive systems which change on the basis of interactions between conflicting selection pressures in unpredictable ways, involving positive or negative feedback, with no centralized control are increasingly termed

<sup>31</sup> Lightfoot (1999: 239–49) argues that *UG* may be maladaptive because it incorporates a constraint against extraction of subjects from tensed clauses, while speakers/languages have developed idiosyncratic means to circumvent the constraint to fulfil expressive needs. He concludes: 'if maladaptive elements evolve, then we need something other than natural selection to drive evolutionary developments' (1999: 248). However, as he points out, the constraint against extraction of subjects from tensed clauses may be adaptive with respect to parsability, reducing ambiguity over the location of traces. If it is maladaptive with respect to expressivity, this is only an argument against a simplistic 'one-dimensional optimization' view of evolution. Given the framework developed here, it is quite possible that such a constraint evolved in one or more languages (and either was or was not ultimately assimilated into *UG*) as a local step in evolutionary space, which in turn created expressivity problems requiring further local adaptations of a possibly idiosyncratic and language specific nature.

complex adaptive systems. Viewing (E-)languages as complex adaptive systems promises new insights into old issues, such as prototypical unidirectionality, competing motivations, or internally motivated change, ones which do not involve teleology or a substantive theory of linguistic change *per se*.

Serious exploration of this framework is only just beginning because the requisite understanding of dynamical systems and of the tools to study them are very recent developments. It would be unfortunate if old prejudices, or misunderstanding of modern evolutionary theory, precluded the full and proper exploration of languages as complex adaptive systems.