

Co-evolution of lexical meaning & pragmatic use

Abstract

According to standard linguistic theory, the meaning of an utterance is the product of conventional semantic meaning and general pragmatic rules on language use. To investigate how cultural evolution of language plays out under this picture of the semantics-pragmatics interface, we present a game-theoretic model of the competition between types of language users, each endowed with a selection of lexical representations and a particular pragmatic disposition to act on them. Our model traces two evolutionary forces and their interaction: (i) pressure towards communicative efficiency and (ii) learning biases during the transfer of linguistic knowledge. We illustrate the model based on a case study on scalar implicatures. [The relationship between underspecified semantics and pragmatic inference that this study suggests is one of co-evolution. The maintenance of such semantics depends on pragmatic reasoning for their enrichment. In the opposite direction, complex semantics that can do away with mutual reasoning do not necessarily foster pragmatic reasoning and may even be encumbered by it.](#)

1 Introduction

2. This is true. We are grateful that this was pointed out, as our previous rendering could lead to confusion, e.g., as to why L_{all} , being the *a priori* more likely type to be inferred, did not come out strongly even when considering learnability alone. Throughout the article, we now stress more that what matters is the posterior – and discuss the role of the prior mainly when contrasting targets and competitor, who crucially differ mostly in this respect.

3. These questions tie in with Reviewer 1’s request for a clearer exposition and the explanation of why we speak of co-evolution in this case. In a nutshell, pressure for learnability alone does not put the types found in a population in competition. Instead, the population comes to be inhabited by types that are faithfully transmitted – of which there might be many (e.g., all variants of a kind are equally learnable). What fitness-relative selection adds to this process is the competition that learnability alone lacks, independent of the type space we look at. Now, in the case of our type space we have a slight

(modulo λ) communicative disadvantage for targets *when in direct competition with competitors*, for instance. However, the fact that they are inferred more faithfully by naïve learners leads (i) to the existence of less competitors, counteracting this functional disadvantage, as well as (ii) to the existence of less variants of a kind (contra learning-alone).

What is conveyed usually goes beyond what is said. A request for a blanket can be politely veiled by uttering “I’m cold;” a temporal succession of events can be communicated by the order in which conjuncts appear as in “I traveled to Paris and got married;” an invitation can be declined by saying “I have to work.” An influential explanation of the relation between the literal meaning of expressions and what they may convey in context is due to Grice (1975), who characterizes pragmatic use and interpretation as a process of mutual reasoning about rational language use. For instance, under the assumption that the speaker is cooperative and relevant, “I have to work” may be interpreted as providing a reason why the speaker will not be able to accept an invitation, going beyond its literal meaning. Some of these enrichments are rather *ad hoc*. Others show striking regularities, such as the use of ability questions for polite requests (“Could you please . . .?”), or certain enrichments of lexical meanings such as *and* to convey *and then*.

A particularly productive and well studied class of systematic pragmatic enrichments are scalar implicatures (Horn 1984, Hirschberg 1985, Levinson 1983, Geurts 2010). Usually, the utterance of a sentence like “I own some of Johnny Cash’s albums” will be taken to mean that the speaker does not own all of them. This is because, if the speaker instead owned them all, she could have used the word *all* instead of *some* in his utterance, thereby making a more informative statement. Scalar implicatures, especially the inference from *some* to *some but not all*, have been studied extensively, both theoretically (e.g., Sauerland 2004, Chierchia et al. 2012, van Rooij and de Jager 2012) as well as experimentally (e.g., Bott and Noveck 2004, Huang and Snedeker 2009, Grodner et al. 2010, Goodman and Stuhlmüller 2013a, Degen and Tanenhaus 2015). This makes them particularly suitable candidates for the study of the evolution of regular pragmatic inferences. While there is much dispute in this domain about many details, a position endorsed by a clear majority is that a scalar item like *some* is underspecified to mean *some and maybe all* and that the enrichment to *some but not all* is part of some regular process with roots in pragmatics.

If this majority view is correct, the question arises how such a division of labor between semantics and pragmatics could have evolved; why it would be so pervasive across natural languages; and why it is that some expressions systematically draw from it while others semantically conventionalize. Models of language evolution abound. There are simulation-based models studying populations of communicating agents (Hurford 1989, Steels 1995, Lenaerts et al. 2005, Steels and Belpaeme 2005, Baronchelli et al. 2008, Steels 2011, Spike et al. 2016) and there are mathematical models of language evolution, many

coming from game theory (Wärneryd 1993, Blume et al. 1993, Nowak and Krakauer 1999, Nowak 2006, Huttegger 2007, Skyrms 2010). Much of this work has focused on explaining basic properties such as compositionality and combinatoriality (e.g., Batali 1998, Nowak and Krakauer 1999, Nowak et al. 2000, Kirby and Hurford 2002, Kirby 2002, Smith et al. 2003, Gong 2007, Kirby et al. 2015, Verhoef et al. 2014, Franke 2016), but little attention has been paid to the interaction between conventional meaning and pragmatic use. What is more, many mathematical models explain evolved meaning as a regularity in the overt behavior of agents, abstracting from complex interactions between semantic representations and pragmatic use. In contrast, we will here look at language users with a richer linguistic make-up. More precisely, We spell out a model of the co-evolution of conventional meaning and pragmatic reasoning. The objects of replication and selection are pairs consisting of a set of lexical meanings and a manner of pragmatic behavior, which together define agents’ linguistic choices. Pragmatic behaviors are represented using probabilistic models of pragmatic language use (Frank and Goodman 2012, Franke and Jäger 2016, Goodman and Frank 2016). Replication and selection are described by the *replicator mutator dynamic*, a general and established model of evolutionary change in large and homogeneous populations (Hofbauer 1985, Nowak et al. 2000; 2001, Hofbauer and Sigmund 2003, Nowak 2006). This approach allows us to study the interaction between (i) pressure towards communicative efficiency and (ii) infidelity in the transmission of linguistic knowledge, caused by factors such as inductive learning biases and sparse learning data (Kirby and Hurford 2002, Smith et al. 2003, Kirby et al. 2014). Considering the effects that the transmission of linguistic knowledge through (iterated) learning have is important because neither semantic meanings nor pragmatic usage patterns are directly observable. Instead, language learners have to infer these unobservables – lexical meanings and manners of pragmatic behavior – from the observable behavior in which they result – overt linguistic choice in a context of interaction. We formalize this process as a form of Bayesian inference. Our approach thereby contains a well-understood model of iterated Bayesian learning (Griffiths and Kalish 2005; 2007), but combines it with functional selection, here formalized as the most versatile dynamic from evolutionary game theory, the replicator dynamic (Taylor and Jonker 1978). Section 2 introduces this model.

Section 3 applies this model to a case study on scalar implicatures. We discuss a setting in which the majority view of underspecified lexical meanings and systematic pragmatic enrichments emerges if selection and transmission infidelity are combined. In particular, we show that inductive learning biases of Bayesian learners that favor simpler lexical meanings may play a role in preventing the lexicalization of scalar inferences and thereby lead to the emergence of Gricean-like pragmatic reasoning types. The results of this case study are critically assessed in the light of the assumptions that feed our model in

2 A model of co-evolving lexical representations and pragmatic behavior

2.1 Communicative success and learnability

The emergence and change of linguistic structure is influenced by many intertwined factors. These range from biological and socio-ecological to cultural ones (Benz et al. 2005, Steels 2011, Tamariz and Kirby 2016). Social and ecological pressures determine communicative needs, while biology determines the architecture that enables and constrains the means by which they can be fulfilled. In the following, our focus lies on cultural aspects, wherein processes of linguistic change are viewed as shaped by language use and its transmission, i.e., as a result of a process of cultural evolution (Pagel 2009, Thompson et al. 2016).

The idea that language is an adaptation to serve a communicative function is fundamental to many synchronic and diachronic analyses at least since Zipf's (1949) explanation of word frequency rankings as a result of competing hearer and speaker preferences (e.g., in Martinet 1962, Horn 1984, Jäger and van Rooij 2007, Jäger 2007a, Piantadosi 2014, Kirby et al. 2015). If processes of selection, such as conditional imitation or reinforcement, favor more communicatively efficient types of behavior, languages are driven towards semantic expressivity (e.g., Nowak and Krakauer 1999, Skyrms 2010). But pressure towards communicative efficiency is not the only force that shapes language. Learnability is another, as natural languages need to be learnable to survive their faithful transmission across generations. Furthermore, the effects of even small learning biases implicit in acquisition can build up and have quite striking impact on an evolving language in a process of iterated learning (Kirby and Hurford 2002, Smith et al. 2003, Kirby et al. 2014).

While natural languages are pressured for both communicative efficiency and learnability, these forces may pull in opposite directions (Christiansen and Chater 2008:§7). Their opposition becomes particularly clear when considering the extreme (Kemp and Regier 2012, Kirby et al. 2015). A language consisting of a single form-meaning association is easy to learn but lacking in expressivity. Conversely, a language that lexicalizes a distinct form for a large number of different meanings is highly expressive but challenging to acquire.

2.2 The replicator mutator dynamic

An elegant formal approach to capture the interaction between communicative efficiency and learnability is the *replicator mutator dynamic* (Hofbauer 1985, Nowak et al. 2000; 2001, Hofbauer and Sigmund 2003, Nowak 2006). The RMD is a population dynamic, which is to say that it describes change in the composition of a community made up of different types of agents. The population vector \vec{x} codifies proportions or frequencies of types in a population, with x_i being the frequency of type i . This population is infinite; its carrying capacity is held constant, $\sum_i x_i = 1$. This allows us to track change that does not depend on varying population sizes nor their growth rates (but see, e.g., Nowak 2006 and Skyrms 2010:§5 for alternatives that consider, among others, population size and its growth). In its simplest, discrete-time formulation, the RMD defines the frequency x'_i of each type i in a population at the next time step as a function of: (i) the frequency x_i of each type i before the update step, (ii) the fitness f_i of each type i before the update, and (iii) the probability Q_{ji} that an agent who observes the behavior of an agent with type j ends up acquiring type i :

$$x'_i = \sum_j Q_{ji} \frac{x_j f_j}{\sum_h x_h f_h}. \quad (1)$$

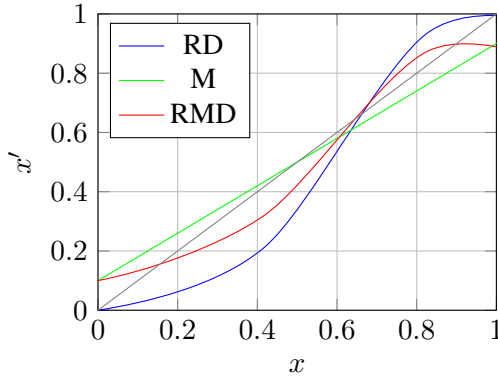
The RMD consists of two components: fitness-based selection and transmission biases encoded in the so-called mutation matrix Q . This becomes most transparent when we consider an equivalent formulation in terms of a step-wise application of the discrete-time replicator dynamic (Taylor and Jonker 1978) on the initial population vector \vec{x} and its subsequent multiplication with a mutation matrix Q :

$$x'_i = (\mathbf{M}(\mathbf{RD}(\vec{x})))_i, \quad (2)$$

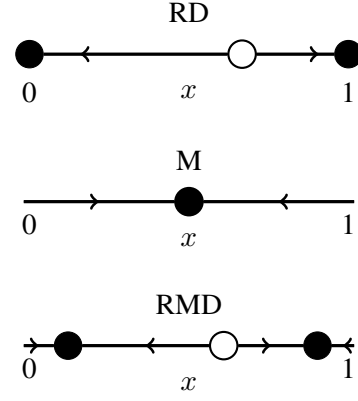
where

$$(\mathbf{RD}(\vec{x}))_i = \frac{x_i f_i}{\sum_k x_k f_k} \quad \text{and} \quad (\mathbf{M}(\vec{x}))_i = (\vec{x} \cdot Q)_i = \left(\sum_j x_j Q_{ji} \right)_i.$$

If the transmission matrix Q is trivial in the sense that $Q_{ji} = 1$ whenever $j = i$, the dynamic reduces to the replicator dynamic. This situation is one where types are always replicated faithfully. The replicator dynamic is a model of fitness-based selection in which the relative frequency of type i will increase with a gradient proportional to its average fitness in the population. In other words, selection comes into play whenever two or more types replicate at different rates due to differences in their fitness. This



(a) Update functions: the population state x is mapped onto x' in one update step.



(b) Phase portraits for RD, M and RMD: unstable rest points are hollow, attractors are solid.

Figure 1: Example.

dynamic is popular and versatile because it can be derived from many abstract processes of biological and cultural transmission and selection (for overview and several derivations see Sandholm 2010), including conditional imitation (e.g., Helbing 1996, Schlag 1998) or reinforcement learning (e.g., Börgers and Sarin 1997, Beggs 2005). If fitness f_i is the same for all types i , the replicator step is the identity map $(RD(\vec{x}))_i = x_i$. In words, no difference in fitness translates into a lack of functional pressure: the population's type composition stays the same after the replicator step. In such cases the dynamic reduces to a process of iteration of the transmission bias encoded in Q : the rate by which one type changes into another after a generational turnover. As detailed below, in this way, the process in (1), and its equivalent in (2), can contain a model of iterated learning (Griffiths and Kalish 2005; 2007).

Example. Consider a simple and abstract coordination game. Agents are of two types: positive or negative. If agents of different type interact with each other, they obtain a payoff of 0. If negative meets negative, each receives a payoff of 1. If positive meets positive, they get a payoff of 2. A population state is completely characterized by the proportion x of negatives. The fitness of negatives in population state x is $f_n(x) = x$, that of positives is $f_p(x) = 2 - 2x$. The average fitness is $\Phi(x) = x f_n(x) + (1 - x) f_p(x) = 3x^2 - 4x + 2$. Without mutation, the replicator dynamic will update x to $RD(x) = f(x)x/\Phi(x) = x^2/\Phi(x)$. The update function $RD(x)$ of the replicator step is plotted in Fig. 1a as the blue line. Rest points, for which $RD(x) = x$, are at $x = 0$, $x = 1$ and $x = 2/3$. The former are attractors as nearby points converge to them. Points near $x = 2/3$ also move towards 0 or 1. This is schematically pictured in the topmost phase portrait in Fig. 1b. Adding mutation changes the dynamic and its rest points. Let us assume that $Q_{ji} = .9$ when $j = i$. This is the proportion of types that are replicated faithfully. Conversely, a proportion of .1 will change their type from positive to negative, and vice-versa. The update effect of mutation on its

own are described by $M(x) = .9x + .1(1 - x) = .8x + .1$, plotted as the linear green line in Fig. 1a. As shown in Fig. 1b, in this example mutation alone has only one stable rest point. It is located at $x = .5$. If we first take the replicator step and then the mutation step in sequence, we obtain the replicator mutator dynamic $RMD(x) = M(RD(x)) = .9x^2 - .2x + .2 / 3x^2 - 4x + 2$, which is plotted in red in Fig. 1a. The rest points are at $x = .121$, $x = .903$ and $x = .609$. The former two are attractors (see Fig. 1b).

2.3 Fitness & learnability of lexical meanings & pragmatic strategies

Moving beyond an abstract example, our goal is to apply the RMD to investigate the co-evolution of lexical representations and pragmatic behavior. To do so, we need to fix three things: (i) what the relevant types are that populate x , (ii) how fitness derives from communicative success and (iii) how the mutation matrix Q is computed. These issues are addressed, one by one, in the following.

2.3.1 Types: Lexica and pragmatic strategies

Types are what evolution operates on. They define an agent's fitness, usually through a payoff accrued in single interactions with other agents. Often types can be identified as the possible acts in a game, e.g., either cooperating or defecting in a prisoner's dilemma. In other cases, they may be thought of as general properties of an agent that influence her fitness, such as being positive or negative in our previous example (whatever that means). For our present purposes, types are identified by specific assumptions about their cognitive make-up. More concretely, since we are interested in the evolutionary competition between different lexical representations and ways of using them in communication, a type is here defined as a pair consisting of a lexicon and a pragmatic strategy of language use.

Agents play signaling games, in which the speaker wants to communicate a world state s with a message m to a hearer who receives m but does not know s (e.g. Lewis 1969, Skyrms 2010). A lexicon associates each message with a (possibly fuzzy) set of states. A pragmatic behavior specifies a probabilistic speaker rule (a probabilistic choice of message for each state) and a probabilistic hearer rule (a probabilistic choice of state for each message) given a lexicon. There are many ways of making these general notions more concrete. Broadly speaking, there are models of pragmatic language use coming from a game-theoretic tradition (e.g., Benz 2006, Benz and van Rooij 2007, Jäger 2007b, Franke and Jäger 2014) and ones from a Bayesian tradition (e.g., Frank and Goodman 2012, Goodman and Stuhlmüller 2013b, Goodman and Frank 2016). We will not focus on the particular design choices that make up each approach (Qing and Franke 2015). Instead, we will stress how the approach, common to all of these models, of pragmatic language use as *rational language use* can be embedded within the replicator mutator

dynamic to answer evolutionary questions at the semantics-pragmatics interface. Here is what we will assume in the remainder of this paper.¹

Lexica codify the truth-conditions of expressions. A convenient way to represent lexica is by $(|S|, |M|)$ -Boolean matrices, where S is a set of states (meanings) and M a set of messages (forms available in the language). For example, suppose that there are two relevant world states $S = \{s_{\exists-\forall}, s_{\forall}\}$. In state $s_{\exists-\forall}$ Chris owns some but not all of Johnny Cash’s albums while in s_{\forall} Chris owns them all. Suppose that there are two messages $M = \{m_{\text{some}}, m_{\text{all}}\}$ where m_{some} is short for a sentence like *Chris owns some of Johnny Cash’s albums* and m_{all} for the same sentence with *some* replaced by *all*. Lexica for this case would assign a Boolean truth value, either 0 for false or 1 for true, to each state-message pair. The following two lexica are minimal examples for the distinction between a lexicalized upper-bound for *some* in L_{bound} and the widely assumed logical semantics with only a lower-bound in L_{lack} .

$$L_{\text{bound}} = \begin{array}{c} m_{\text{some}} \quad m_{\text{all}} \\ s_{\exists-\forall} \quad s_{\forall} \end{array} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \qquad L_{\text{lack}} = \begin{array}{c} m_{\text{some}} \quad m_{\text{all}} \\ s_{\exists-\forall} \quad s_{\forall} \end{array} \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix}$$

Pragmatic strategies define dispositions to produce and interpret messages given a lexicon. We distinguish between two kinds of pragmatic strategies. *Literal interlocutors* produce and interpret messages literally, being guided only by their lexica. *Pragmatic interlocutors* instead engage in mutual reasoning to inform their choices. Recent probabilistic models of rational language use (Frank and Goodman 2012, Franke and Jäger 2016, Goodman and Frank 2016) capture different types of pragmatic behavior in a reasoning hierarchy. The hierarchy’s bottom, level 0, corresponds to literal language use, as in Equations (3) and (4). Pragmatic language users of level $n + 1$ act (approximately) rational with respect to level- n behavior of their interlocutors, as in Equations (5) and (6).

$$H_0(s \mid m; L) \propto pr(s) L_{[s,m]} \tag{3}$$

$$S_0(m \mid s; L) \propto \exp(\lambda L_{[s,m]}) \tag{4}$$

$$H_{n+1}(s \mid m; L) \propto pr(s) S_n(m \mid s; L) \tag{5}$$

$$S_{n+1}(m \mid s; L) \propto \exp(\lambda H_n(s \mid m; L)) \tag{6}$$

¹Readers more familiar with the Bayesian tradition should note that the definitions below follow the game-theoretic tradition in assuming rational sender choice to consist in sending messages that maximize expected utility, rather than message informativity (see Qing and Franke 2015 for detailed discussion).

According to (3), a literal hearer's interpretation of a message depends on her lexicon and her prior over states, $pr \in \Delta(S)$, which is here assumed flat for simplicity. Literal interpreters thereby choose an arbitrary true interpretation for each message according to their lexicon. Pragmatic hearers, defined in (5), instead use Bayes' rule to weigh interpretations based on a conjecture about speaker behavior. Speaker behavior is regulated by a soft-max parameter $\lambda \geq 0$ (Luce 1959, Sutton and Barto 1998). As λ increases, choices approximate strict maximization of expected utilities. Expected utility of a message m in state s for a level $n+1$ speaker is here defined as $H_n(s|m; L)$, the probability that the hearer will assign to or choose the correct meaning. For literal speakers, utility only tracks truthfulness. Literal speakers choose any true message with equal probability but may send false messages as well with a probability dependent on λ .

In words, an agent's linguistic behavior – what message to send when / which message to interpret how – is defined by (i) her reasoning level and (ii) her lexicon. In what follows, this is what we identify an agent's type with in order to analyze under which conditions combinations of (i) and (ii) emerge through cultural evolution. Intuitively, literal behavior (level-0 reasoning) results from unreflected language use. Such agents produce and comprehend solely based on the truth-conditions of their lexicon. In a Gricean spirit, pragmatic behavior (level- $n+1$ reasoning) results from mutual reasoning about rational language use. Such agents produce and comprehend by reasoning about their interlocutor's likely behavior interpretation/production patterns. This reasoning is based on a conjecture resulting from their own behavior if they were in the role of their interlocutor. Higher order behavior is therefore, even if in tendency rational, quite simple. Crucially, we do not assume that agents know each other's types when interacting (e.g., what lexicon the interlocutor is using).

The following examples illustrate these behaviors numerically. A literal interpreter with lexicon L_{bound} assigns $s_{\exists-\forall}$ a probability of $H_0(s_{\exists-\forall} | m_{\text{some}}; L_{\text{bound}}) = 1$ after hearing m_{some} , while a literal interpreter with L_{lack} has $H_0(s_{\exists-\forall} | m_{\text{some}}; L_{\text{lack}}) = 0.5$:

$$H_0(\cdot | \cdot, L_{\text{bound}}) = \begin{array}{cc} & \begin{array}{cc} s_{\exists-\forall} & s_{\forall} \end{array} \\ \begin{array}{c} m_{\text{some}} \\ m_{\text{all}} \end{array} & \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \end{array} \quad H_0(\cdot | \cdot, L_{\text{lack}}) = \begin{array}{cc} & \begin{array}{cc} s_{\exists-\forall} & s_{\forall} \end{array} \\ \begin{array}{c} m_{\text{some}} \\ m_{\text{all}} \end{array} & \begin{bmatrix} .5 & .5 \\ 0 & 1 \end{bmatrix} \end{array}$$

By contrast, pragmatic hearers of level 1 have the following interpretative behavior for $\lambda = 1$:

$$H_1(\cdot \mid \cdot, L_{\text{bound}}) \approx \begin{matrix} & s_{\exists-\forall} & s_{\forall} \\ m_{\text{some}} & \begin{bmatrix} .73 & .27 \end{bmatrix} \\ m_{\text{all}} & \begin{bmatrix} .27 & .73 \end{bmatrix} \end{matrix} \quad H_1(\cdot \mid \cdot, L_{\text{lack}}) \approx \begin{matrix} & s_{\exists-\forall} & s_{\forall} \\ m_{\text{some}} & \begin{bmatrix} .59 & .41 \end{bmatrix} \\ m_{\text{all}} & \begin{bmatrix} .35 & .65 \end{bmatrix} \end{matrix}$$

This is the outcome of reasoning about their level-0 speaker counterparts with $\lambda = 1$:

$$S_0(\cdot \mid \cdot, L_{\text{bound}}) \approx \begin{matrix} & m_{\text{some}} & m_{\text{all}} \\ s_{\exists-\forall} & \begin{bmatrix} .73 & .27 \end{bmatrix} \\ s_{\forall} & \begin{bmatrix} .27 & .73 \end{bmatrix} \end{matrix} \quad S_0(\cdot \mid \cdot, L_{\text{lack}}) \approx \begin{matrix} & m_{\text{some}} & m_{\text{all}} \\ s_{\exists-\forall} & \begin{bmatrix} .73 & .27 \end{bmatrix} \\ s_{\forall} & \begin{bmatrix} .5 & .5 \end{bmatrix} \end{matrix}$$

With low λ speakers choose true messages with more slack. Reasoning over this behavior therefore also results in a weaker association of messages with only true states in receivers, but also in a slightly stronger association of m_{some} with $s_{\exists-\forall}$ over s_{\forall} for L_{lack} users because they reason that $S_0(m_{\text{some}} \mid s_{\exists-\forall}; L_{\text{lack}}) > S_0(m_{\text{some}} \mid s_{\forall}; L_{\text{lack}})$. For $\lambda = 20$, there will be less slack in literal speaker behavior:

$$S_0(\cdot \mid \cdot, L_{\text{bound}}) \approx \begin{matrix} & m_{\text{some}} & m_{\text{all}} \\ s_{\exists-\forall} & \begin{bmatrix} 1 & 0 \end{bmatrix} \\ s_{\forall} & \begin{bmatrix} 0 & 1 \end{bmatrix} \end{matrix} \quad S_0(\cdot \mid \cdot, L_{\text{lack}}) \approx \begin{matrix} & m_{\text{some}} & m_{\text{all}} \\ s_{\exists-\forall} & \begin{bmatrix} 1 & 0 \end{bmatrix} \\ s_{\forall} & \begin{bmatrix} .5 & .5 \end{bmatrix} \end{matrix}$$

And accordingly less slack in level 1 pragmatic interpretation:

$$H_1(\cdot \mid \cdot, L_{\text{bound}}) \approx \begin{matrix} & s_{\exists-\forall} & s_{\forall} \\ m_{\text{some}} & \begin{bmatrix} 1 & 0 \end{bmatrix} \\ m_{\text{all}} & \begin{bmatrix} 0 & 1 \end{bmatrix} \end{matrix} \quad H_1(\cdot \mid \cdot, L_{\text{lack}}) \approx \begin{matrix} & s_{\exists-\forall} & s_{\forall} \\ m_{\text{some}} & \begin{bmatrix} 0.67 & 0.33 \end{bmatrix} \\ m_{\text{all}} & \begin{bmatrix} 0 & 1 \end{bmatrix} \end{matrix}$$

Lastly, turning to types that have no bearing on the choices of hearers of level 1, with $\lambda = 1$ pragmatic speakers of level 1 have:

$$S_1(\cdot \mid \cdot, L_{\text{bound}}) \approx \begin{matrix} & m_{\text{some}} & m_{\text{all}} \\ s_{\exists-\forall} & \begin{bmatrix} .73 & .27 \end{bmatrix} \\ s_{\forall} & \begin{bmatrix} .27 & .73 \end{bmatrix} \end{matrix} \quad S_1(\cdot \mid \cdot, L_{\text{lack}}) \approx \begin{matrix} & m_{\text{some}} & m_{\text{all}} \\ s_{\exists-\forall} & \begin{bmatrix} .62 & .38 \end{bmatrix} \\ s_{\forall} & \begin{bmatrix} .38 & .62 \end{bmatrix} \end{matrix}$$

For $\lambda = 20$, pragmatic speaker behavior of level 1 is instead as follows:

$$S_1(\cdot \mid \cdot, L_{\text{bound}}) \approx \begin{matrix} & m_{\text{some}} & m_{\text{all}} \\ \begin{matrix} s_{\exists \neg \forall} \\ s_{\forall} \end{matrix} & \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \end{matrix} \quad S_1(\cdot \mid \cdot, L_{\text{lack}}) \approx \begin{matrix} & m_{\text{some}} & m_{\text{all}} \\ \begin{matrix} s_{\exists \neg \forall} \\ s_{\forall} \end{matrix} & \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \end{matrix}$$

There are two particularly important things to note. First, in contrast to their literal counterparts of level 0, pragmatic agents of level 1 using L_{lack} associate m_{some} preferentially with $s_{\exists \neg \forall}$. This association is not perfect, and usually less strong than what agents with a lexicalized upper bound in L_{bound} can achieve – with or without pragmatic reasoning. Higher order reasoning beyond level 1 leads to stronger associations of m_{some} and $s_{\exists \neg \forall}$ also for the receiver. Still, the case study presented in Section 3 will consider sender and receiver behavior at levels 0 and 1, as the latter are the simplest pragmatic reasoning types which show a tendency to communicatively attuned pragmatic enrichment. Using only level 1 reasoning and possibly small λ is therefore a conservative choice that works against the fitness-based selection of pragmatic language use for a notion of fitness defined as communicative success, which is introduced next. Second, when it comes to competition between types of use of lexicon L_{bound} , pragmatic reasoning at level 1 is not advantageous. The reason for this is that literal use of L_{bound} already endows agents with a behavioral strategy that associates a single state with a single message (in tendency; depending on λ for senders). For L_{bound} -receivers of level 1, reasoning over stochasticity introduced at S_0 will generally decrease the association of one state with one message. This decrease is only slight if λ is high, but nevertheless present. That is to say, level-1 reasoning does not necessarily confer a functional advantage. For some types, such as users of L_{bound} , literal signaling is preferable.

2.3.2 Fitness & fitness-based selection based on communicative success

Under the replicator dynamic the proportion of type i in a population will increase or decrease as a function of its relative fitness f_i . In the context of language evolution, fitness is usually associated with the ability to successfully communicate with other language users from the same population (e.g., Nowak and Krakauer 1999, Nowak et al. 2000; 2002). Under a biological interpretation the assumption is that organisms have a higher chance of survival and reproduction if they are able to share and receive useful information via communication with peers. Under a cultural interpretation the picture is that agents themselves strive towards communicative success and therefore occasionally adapt or revise their behavior to achieve higher communicative success (see Benz et al. 2005:§3.3 for discussion).

The replicator equation gives us the means to make the ensuing dynamic precise, without necessarily committing to a biological or cultural interpretation. As above, the proportion of types in a given population is codified in a vector \vec{x} , where x_i is the proportion of type i . The fitness of type i is its average expected communicative success, or *expected utility* (EU), given the frequencies of types in the current population:

$$f_i = \sum_j x_j \text{EU}(t_i, t_j) .$$

In signaling games, the expected utility $\text{EU}(t_i, t_j)$ for type i when communicating with type j is the average success of i when talking or listening to j . If, as standardly assumed, agents are speakers half of the time, this yields:

$$\text{EU}(t_i, t_j) = 1/2 \text{EU}_S(t_i, t_j) + 1/2 \text{EU}_H(t_i, t_j) ,$$

where $\text{EU}_S(t_i, t_j)$ and $\text{EU}_H(t_i, t_j)$ are the expected utilities for i as a speaker and as a hearer when communicating with j , defined as follows, where n_i and n_j are type i 's and type j 's pragmatic reasoning types and L_i and L_j are their lexica:

$$\begin{aligned} \text{EU}_S(t_i, t_j) &= \sum_s P(s) \sum_m S_{n_i}(m \mid s; L_i) \sum_{s'} H_{n_j}(s' \mid m; L_j) \delta(s, s') , \\ \text{EU}_H(t_i, t_j) &= \text{EU}_S(t_j, t_i) . \end{aligned}$$

As usual, we assume that agents are cooperative: $\delta(s, s') = 1$ iff $s = s'$ and 0 otherwise.

In words, expected utility $\text{EU}(t_i, t_j)$ quantifies how successful communication between agents of types i and j is, with each type being a combination of a lexicon and a reasoning level (Section ??). Fitness f_i indicates how well type i fares in a population given what other types are found in it: it is type i 's weighted expected utility.

2.3.3 Learnability

Languages are shaped not only by functionalist forces towards greater communicative success. Another important factor is the fidelity with which linguistic knowledge is transmitted. Among others, linguistic production can be prone to errors, states or messages may be perceived incorrectly, and multiple languages may be compatible with the data learners are exposed to. These sources of uncertainty intro-

duce variation in the transmission of linguistic knowledge from one generation to the next. In particular, learning biases in the iterated transmission process can influence language evolution substantially.

In biological evolution, where types are expressed genetically, transmission infidelity comes into the picture through infrequent and mostly random mutation and genetic drift (Kimura 1983). However, an agent’s lexicon and pragmatic reasoning behavior is likely not inherited genetically. They need to be learned from observation. Concretely, when agents learn from type j , they observe the overt linguistic behavior of type j and need to infer the covert type that most likely produced the observed behavior. As in biology, this transmission process is not perfectly accurate.

Iterated learning is a process in which languages are learned repeatedly from the observation of linguistic behavior of agents who have themselves acquired their behavior from observation and inference. In the simplest case there is a single teacher and a single learner in each generation (e.g., Kirby 2001, Brighton 2002). After sufficient training the learner becomes a teacher and produces behavior that serves as input for a new learner. Due to the pressure towards learnability it exerts, iterated learning alone generally leads to simpler and more regular languages (see Kirby et al. 2014 and Tamariz and Kirby 2016 for recent surveys).

Following Griffiths and Kalish (2005; 2007) we model language acquisition as a process of Bayesian inference in which learners combine the likelihood of a type producing the witnessed learning input with prior inductive biases. In a Bayesian setting these biases can be codified in a prior $P \in \Delta(T)$, which reflects the amount of data a learner requires to faithfully acquire the language of the teacher (cf. Griffiths and Kalish 2007:450). Put differently, types favored by the prior are easier to learn because they require less data than less favored types to be inferred, even if they are both compatible with the learning data at hand.

The extent of the prior’s influence has been shown to heavily depend on the learning strategy assumed to underlie the inference process. On the one hand, early simulation results suggested that weak biases could be magnified by exposing learners to only small data samples (e.g. in Brighton 2002). On the other, Griffiths and Kalish’s (2007) mathematical characterization showed that iterated learning converges to the prior in the limit, i.e., that the resulting distribution over types corresponds to the learners’ prior distribution and is not influenced by the amount of input given to them. This difference in predictions can be traced back to differences in the selection of hypotheses from the posterior. Griffith & Kalish’s convergence to the prior holds for learners that sample from the posterior. More deterministic strategies such as the adoption of the type with the highest posterior probability, so-called *maximum a posterior estimation* (MAP), increase the influence of both the prior and the data (Griffiths and Kalish 2007, Kirby

et al. 2007). In the following, we use a parameter $l \geq 1$ to modulate between posterior sampling and the MAP strategy. When $l = 1$ learners sample from the posterior. The learners' propensity to maximize the posterior grows as l increases.

The way the posterior over types is formed and how learners employ it thereafter are important design choices. There are other alternatives as well. For instance, instead of adopting a single type, learners could keep her uncertainty over types and base her production behavior on the formed posterior (Burkett and Griffiths 2010). A straightforward operationalization of this idea would then see production defined as a two-step process wherein a speaker first samples from her posterior over types and then produces an utterance based on the type she sampled, as done in (Kirby et al. 2015). Beyond added complexity to the model, a disadvantage of this approach is that it could a speaker that first used a Hungarian utterance to speak Quechua in the next, so to speak. We stick to the simpler assumption of a single type being acquired, which is defined as follows.

Let D be the set of possible data that learners may be exposed to. This set D contains all sequences of state-message pairs of length k , e.g., $\langle \langle s_1, m_1 \rangle, \dots, \langle s_k, m_k \rangle \rangle$. As k increases, learners have more data to base their inference on and so tend to recover the true types that generated a given sequence with higher probability. The mutation matrix Q of the replicator mutator dynamic in (1) can then be defined as follows: Q_{ji} is the probability that a learner acquires type i when learning from an agent of type j . The learner observes a length- k sequence d of state-message pairs, but the probability $P(d \mid t_j)$ with which sequence $d = \langle \langle s_1, m_1 \rangle, \dots, \langle s_k, m_k \rangle \rangle$ is observed depends on type j 's linguistic behavior:

$$P(d = \langle \langle s_1, m_1 \rangle, \dots, \langle s_k, m_k \rangle \rangle \mid t_j) = \prod_{i=1}^k S_{n_j}(m_i \mid s_i; L_j),$$

where, as before, n_j is j 's pragmatic reasoning type and L_j is j 's lexicon. For a given observation d , the probability of acquiring type i is $F(t_i \mid d)$, so that:

$$Q_{ji} \propto \sum_{d \in D} P(d \mid t_j) F(t_i \mid d).$$

Q is a stochastic $n \times n$ matrix, with n equal to the amount of types. The acquisition probability $F(t_i \mid d)$ given datum d is obtained by probability matching $l = 1$ or a tendency towards choosing the most likely type $l > 1$ from the posterior distribution $P(\cdot \mid d)$ over types given the data, which is

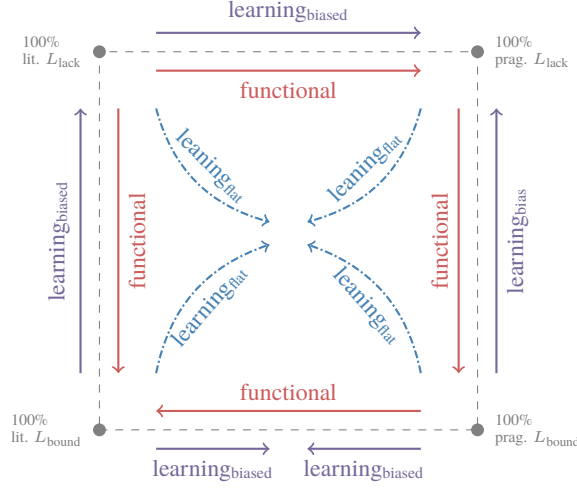


Figure 2: Sketch of dynamics on a two-dimensional type space with four types. The x -axis represents the proportion of types with L_{lack} ; the y -axis that of pragmatic ones. Arrows sketch the directionality of population trajectories through the space under functional pressure (replicator steps) and learnability pressure (mutator steps), both with a flat prior and one that favors L_{lack} .

calculated by Bayes' rule:

$$F(t_i | d) \propto P(t_i | d)^l \text{ and}$$

$$P(t_i | d) \propto P(t_i)P(d | t_i).$$

2.4 Example

Section 3 shows how these components and their interaction can shed light on the evolution of scalar implicatures. Before moving on, we will illustrate the model's workings in a constrained type space in order to showcase the effect that pressure for communicative success and learnability have on types. To this end, we focus only on the four types from Section 2.3.1. These types are made up of a combination of either lexicon L_{lack} or L_{bound} and either literal (level-0) or pragmatic (level-1) behavior.

A population will be made up of frequencies of these four types. We may think about such a population as a point in a two-dimensional space. In Fig. 2 this space is outlined by the grey dotted square. The first dimension determines the proportion of types that lexicalize ambiguous m_{some} (the x -axis in Fig. 2). That is, the proportion of types with L_{lack} . The second dimension determines the proportion of pragmatic language users (the y -axis in Fig. 2). Populations at the either corner of this space are monomorphic, consisting purely of a single type. If we move from away from edges toward the center of the space, then this two-dimensional representation underspecifies the proportion of types found in a population. The space's center, for instance, could be composed 50% of pragmatic L_{lack} and of an equal proportion

of literal L_{bound} ; but it could equally well be a population that has each type with the same frequency. This will be sufficient for our purposes, as we are only interested in showcasing the rough trajectories of populations through this space after replicator or mutator steps.

From Section 2.3.1, we already know some things about this type space. When it comes to communicative success, types with L_{bound} have a functional advantage over L_{lack} ; literal L_{bound} has a slight advantage over pragmatic L_{bound} ; all have a sizable advantage over literal L_{lack} . The red arrows in Fig. 2 sketch out these relationships. They depict the rough trajectories we may expect if there is only pressure for communicative success. How much each replicator step moves a population ultimately depends on the rationality parameter λ . In particular, functional differences decrease as λ increases: if λ is sufficiently high, all types except for literal L_{lack} speakers will show a strong tendency to associate $s_{\exists-\forall}$ with m_{some} and s_{\forall} with m_{all} . As a consequence, when it comes to learnability and transmission fidelity, the likelihood that any of the three remaining types produces a given datum d will be approximately equal. In other words, the likelihood offers little differentiation for learners if λ is high. We can therefore expect that, if the prior is flat, no type is passed on very faithfully. This would lead populations to gravitate toward the space’s center after mutator steps. This is sketched by the blue dash-dotted arrows in Fig. 2. Neither prior nor posterior alone, but their combination, are what determines the effects of (iterated) Bayesian learning. If, instead of a flat prior, there is a prior that favors, say, L_{lack} over L_{bound} we can expect mutator steps to be skewed toward the upper-half of the space. This is suggested by the purple arrows in Fig. 2. Taking stock, the effects of iterated learning will depend not only on λ , affecting the likelihood, but also on the prior, how strong the bias is, and the degree to which learners tend to maximize the posterior, controlled by parameter l .

Fig. 3 shows actual trajectories, showcasing how they are modulated by parameter values. The replicator steps make the functional disadvantage of L_{lack} against L_{bound} apparent, particularly for literal types and/or low λ . They also highlight that the functional difference between literal and pragmatic L_{bound} is small. Under functional pressure only, populations move toward the lower part of the square but the steps become small as the edge, representing populations of only L_{lack} , are reached. As for the mutator diagrams, there are two main things to note. As expected, a small bias for a type will lead to larger proportions to adopt it provided that likelihood offers little to no differentiation between types. This is the situation the right-most space in Fig. 3 depicts. However, the bias is far from absolute. If, instead, certain types are more likely to be recovered based on the linguistic input they produce, they will be passed on more faithfully. This is why, for instance, populations move toward a majority of L_{lack} -types for $\lambda = 5$ and $l = 10$.

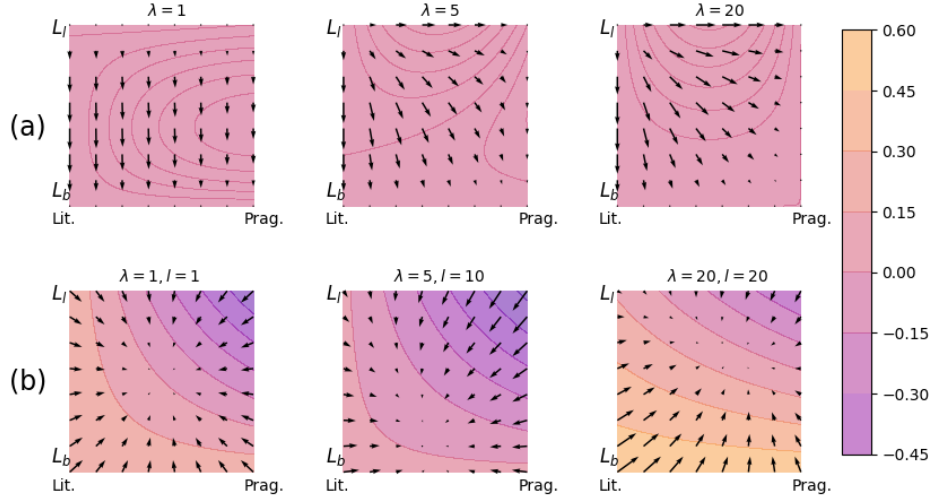


Figure 3: Dynamics on a two-dimensional type space with four types. The x -axis represents the proportion of types with L_{lack} ; the y -axis that of pragmatic ones. Arrows indicate directionality of trajectories after (a) replicator steps and (b) mutator steps with a prior that favors L_{lack} by a factor of 1.05. Colored contours show the proportion of pragmatic L_{lack} users after a step [TB: I don't think the contours are adding too much, so they could be removed. Then again, I think they are rather non-intrusive and look nice.]

Fig. 2 and 3 depict replicator and mutator steps in isolation to better showcase their effects. Their combination will expectedly yield different outcomes, which we now turn to in a case study on scalar implicatures.

2.5 Model summary

Communicative success and learnability are central to the cultural evolution of language. These components can be modelled, respectively, as replication based on a measure of fitness in terms of communicative efficiency and iterated Bayesian learning. Their interaction is described by the discrete time replicator mutator dynamic in (1), repeated here:

$$x'_i = \sum_j Q_{ji} \frac{x_j f_j}{\sum_h x_h f_h}.$$

This equation defines the frequency x'_i of type i at the next time step, based on its frequency x_i before the step, its fitness f_i , and the probability that a learner infers i when observing the behavior of a type- j agent. Fitness-based selection is here thought of not as biological (fitness as expected relative number of offspring) but cultural (fitness as likelihood of being imitated or repeated) evolution, since the types that the dynamic operates on are pairs consisting of a lexicon and a pragmatic use pattern. A type's

communicative success depends on how well it communicates within a population while its learnability depends on the fidelity by which it is inferred by new generations of learners. The learners’ task is consequently to perform a joint inference over types of linguistic behavior and lexical meaning.

The model has three parameters: λ regulates the degree to which speakers choose messages that appear optimal from the point of view of the agent’s own utility measure (which may be unrelated to the expected utility when communicating with a given population); k is length of observations for each language learner; l regulates where the learners’ inference behavior lies on a spectrum from probability matching to acquisition of the most likely teacher type.

3 Case study: scalar implicatures

The model of the previous section formalizes the evolutionary competition between different sets of lexical representations and ways of using them. This section looks at a case study on scalar implicatures. It engages in a formal thought experiment to address the question: if a population of language users could freely combine different lexica with different dispositions to act on them, what are conditions under which the majority view of scalar implicatures could have evolved?

Recall that the majority view is that scalar implicatures are non-lexicalized pragmatic enrichments. Scalar implicature triggers like *some*, *warm* or *may* are semantically weak expressions for which logically stronger expressions are salient, e.g., *all*, *hot* or *must*. For instance, *some* is entailed by *all*. If the sentence “Chris owns all of Johnny Cash’s albums” is true, then “Chris owns some of Johnny Cash’s albums” is also true. However, while weaker expressions such as *some* are truth-conditionally compatible with stronger alternatives such as *all*, this is not what their use is normally taken to convey. Instead, the use of a less informative expression when a more informative one could have been used can license a defeasible inference that stronger alternatives do not hold (cf. Horn 1972, Gazdar 1979). In this way, “Chris owns some of Johnny Cash’s albums” is strengthened to convey that she owns *some but not all* albums. According to the majority view, this is a pragmatic inference, not part of the conventional meaning.

In the following we consider a specific application of the model from Section 2 which allows us to address the question if or when scalar inferences might (not) lexicalize. We consider what is perhaps one of the simplest non-trivial setups that speak to this matter and reflect on its limitations in Section 4. The setup is introduced in Section 3.1. Section 3.2 describes simulations and their results.

3.1 Setup

To fill the model from Section 2 with life, we need to specify the sets of states, messages and lexica we consider (Section 3.1.1). Additionally, we want to explore the effects of a learning bias in favor of simple lexical representations. One way of motivating and formalizing such a bias is introduced in Section 3.1.2.

3.1.1 States, messages, lexical representations, and lexica

Consider a state space with three states $S = \{s_\emptyset, s_{\exists-\forall}, s_\forall\}$ and think of it as a partition of possible worlds into cells where none, some or all of the A s are B s, for some arbitrary fixed predicates A and B . Enlarging the setup from Section 2.3.1 by another state will enable us to discern the difference between three kinds of lexica we will use to unravel the model's dynamics (see below). Eight lexical representations can be distinguished based on their truth or falsity in three world states, six of which are not contradictory or tautological (see Table 2 below).

A lexicon L is a mapping $M \rightarrow R$ from messages to representations. With three messages there are $6^3 = 216$ possible lexica. Some assign the same representations to more than one message and others lexicalize the same representations but associate them with different messages. Out of these possible lexica, three kinds are of particular relevance. First, lexica that assign the same lexical representations to more than one message. Such lexica lack in expressivity but may be favored by particular learning biases nonetheless (see below). Second, lexica that conventionalize upper-bounds to realize a one-to-one mapping of messages to states. Finally, lexica that do not lexicalize an upper bound but allow it to be conveyed pragmatically due to the presence of a stronger lexical item. There are six lexica of the second kind and six of the third. The following three lexica exemplify each kind:

| | <u>L_{all}</u> | | | <u>L_{bound}</u> | | | <u>L_{lack}</u> | | |
|-----------------------|------------------------------------|-------------------|------------------|--------------------------------------|-------------------|------------------|-------------------------------------|-------------------|------------------|
| | m_{none} | m_{some} | m_{all} | m_{none} | m_{some} | m_{all} | m_{none} | m_{some} | m_{all} |
| s_\emptyset | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 |
| $s_{\exists-\forall}$ | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 |
| s_\forall | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 1 |

Lexicon L_{all} is clearly bad for communication: all message and interpretation choices will be equally likely for all types; no information about the observed world state will be conveyed by its users. In contrast, users of L_{bound} can communicate world states perfectly, no matter whether they are literal or pragmatic users. Users of L_{lack} can also communicate information about the actual world state but need

| | | |
|---------------------------------|------------------------------------|---------------------------------|
| $R \rightarrow_2 R \wedge R$ | $R \rightarrow_2 \neg R$ | |
| $R \rightarrow_1 X \subseteq X$ | $R \rightarrow_1 X \neq \emptyset$ | $R \rightarrow_1 X = \emptyset$ |
| $X \rightarrow_1 \{A, B\}$ | $X \rightarrow_1 X \cap X$ | $X \rightarrow_1 X \cup X$ |

Table 1: Toy grammar in a set-theoretic LOT with weighted rules.

pragmatic language use to approximate a one-to-one mapping between message use and states (see Section 2.3.1).

Recall that types are a combination of a lexicon and a manner of language use. We analyze the model’s predictions in populations of types with one of the two behaviors introduced earlier: literal or pragmatic. The former correspond to level-0 reasoners and the latter to level 1. Accordingly, there is a total of 432 types. Six types are variants of pragmatic language users with L_{lack} -like lexica. We refer to these as *target types* because they represent lexica and language use that conform to the majority view of scalar implicatures. Twelve types are either literal or pragmatic users of lexica of the L_{bound} kind. We refer to these as *competitor types*, because they are expected to be the target types’ main contenders in evolutionary competition. Finally, note that while different types may lexicalize the same representations, they may nevertheless map different states to different overt messages. More informally, they speak different languages that lexicalize the same concepts. Consequently, more often than not different types of the same kind fail to understand each other.

3.1.2 An inductive learning bias for semantic simplicity

There is a growing effort to develop empirically testable representational languages that allow for the measure of semantic complexity. For instance, so-called *languages of thought* (LOTs) have been put to test in various rational probabilistic models that show encouraging results (see, e.g., Katz et al. 2008, Piantadosi et al. under review; 2012, and Piantadosi and Jacobs 2016 for recent discussion). At its core, a LOT defines a set of operations and composition rules from which lexical representations can be derived. As a first approximation and for the sake of concreteness, we follow this approach to motivate and formalize a preference of learners for simpler semantic representations (Feldman 2000, Chater and Vitányi 2003, Piantadosi et al. 2012, Kirby et al. 2015, Piantadosi et al. under review). In a weighted generative LOT a representation’s complexity is a function of its derivation cost.

Our toy grammar of lexical representations is given in Table 1. This grammar uses basic set-theoretic operations to form expressions which can be evaluated as true or false in states s_\emptyset , $s_{\exists-\forall}$, or s_\forall from above. Applications of generative rules have a cost attached to them. Here we simply assume that the formation

| intuitive name | s_{\emptyset} | $s_{\exists-\forall}$ | s_{\forall} | least complex formula | complexity |
|--------------------|-----------------|-----------------------|---------------|---|------------|
| “all” | 0 | 0 | 1 | $A \subseteq B$ | 3 |
| “some but not all” | 0 | 1 | 0 | $A \cap B \neq \emptyset \wedge A \neq \emptyset$ | 8 |
| “some” | 0 | 1 | 1 | $A \cap B \neq \emptyset$ | 4 |
| “none” | 1 | 0 | 0 | $A \cap B = \emptyset$ | 4 |
| “none or all” | 1 | 0 | 1 | $\neg(A \cap B \neq \emptyset \wedge A \neq \emptyset)$ | 10 |
| “not all” | 1 | 1 | 0 | $\neg(A \subseteq B)$ | 5 |

Table 2: Available lexical representations and their minimal derivation cost.

of Boolean combinations of representations incurs 2 cost units, while all other rule applications incur only 1 cost unit. Table 2 lists all six lexical representations relevant here, their truth conditions and the simplest formula that expresses this representation in the grammar in Table 1.

A complexity measure for lexical representations from Table 2 is used to define a learning bias that favors simpler representations over more complex ones. The prior probability of a type is just the prior probability of its lexicon. The prior of a lexicon is a function of the complexity of the lexical representations in its image set. Lexica with simpler representations accordingly have a higher prior. One simple way of defining such priors over lexica (and thereby types) is:

$$P(L) \propto \prod_{r \in Im(L)} P(r), \text{ with } P(r) \propto \max_{r'} Compl(r') - Compl(r) + 1,$$

where $Compl(r)$ is the complexity of the minimal derivation cost of representation r according to the LOT-grammar (see Table 2). Applied to our space of lexica, this construal assigns the highest probability to a lexicon of type L_{all} , which only uses the simplest lexical representation “all” for all messages. Lexica of type L_{lack} are less likely, but more likely than L_{bound} .

The menu of inductive biases argued to shape language acquisition is steadily being refined. Apart from simplicity, prominent examples include mutual exclusivity (Merriman and Bowman 1989, Clark 2009), regularization (Hudson Kam and Newport 2005), and generalization (Smith 2011). Even viewed in isolation, there are still many ways to define priors over lexica (see, e.g., Goodman et al. 2008, Piantadosi et al. 2012, Kirby et al. 2015). The key assumption here, common to all ways to define simplicity-biased priors, is that simple representational expressions should be favored over more complex ones. However, in view of the menu of possible operationalizations, other biases and their potential interplay, we should stress that these details – from the generative grammar to its complexity measure – are to be regarded as one convenient operationalization of one general approach to explicating learning biases; this is not a commitment that this general approach is necessarily superior or that, within it, this partic-

ular instrumentalization is the single most plausible. We return to this issue in relation to our results in Section 3.1.2.

3.2 Simulation results

Change plots and captions from prag. Llackers to lit. Llackers

The figures (especially Figure 4, but the others as well) are difficult to read, because of the changing scales. I would recommend finding a way to share the same scale between subfigures, or make it visually clearer that the subfigures cannot be directly compared.

We have thoroughly revised the article to make the contrast between these three predictions clearer, as well as the predictions themselves. Concretely, This should be the new figure as well as a clearer contrast when discussing the simulation outcomes. The questions are: Why do learnability pressures not have the same effect in the joint learnability/fitness model, as they do in the lesioned model? Why is high speaker optimality necessary for scalar implicatures to evolve, when it does not have this effect in the fitness-only model?

Recall that there are three parameters, which we hold constant across types: soft-max parameter λ affects how strongly speakers favor messages that appear best from their subjective point of view; the bottleneck size k influences how faithfully learners can identify their teacher type; l defines the learners' disposition towards choosing the most likely teacher type from the posterior distribution. We expect that competitor types (types with lexica of the kind L_{bound}) have a fitness advantage over target types (pragmatic types with lexica of the kind L_{lack}), especially for very low levels of λ (see Fig 2). Selection based on fitness alone may therefore not lead to prevalence of target types in the population. On the other hand, lexica of type L_{lack} are simpler than those of type L_{bound} by the postulated measure from above. This may make them more likely to be adopted by learners, especially when l is high. Still, lexica of the kind L_{all} are in turn even more likely *a priori* than lexica of the kind L_{lack} . As showcased in Section 2.4, the prior is not all that counts for learnability. Simulation results will shed light on the question whether target types can emerge, and for which parameter constellations.

To better understand the workings of a pressure towards communicative efficiency and a pressure towards learnability, we look at the behavior of the replicator and mutator step first in isolation, and then in combination. All simulation runs are initialized with an arbitrary distribution over types, constituting a population's first generation. All reported results are the outcome of 50 update steps. These outcomes correspond to developmental plateaus in which change is, if not absent, then at least very slow. In other words, even if the resulting states do not correspond to an eventual attracting state, they characterize

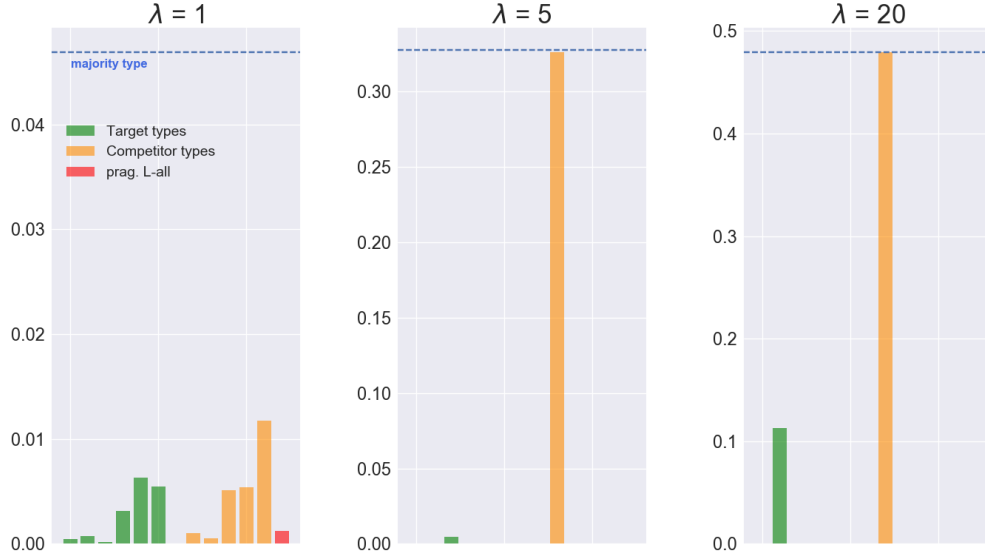


Figure 4: Proportion of target types, **pragmatic** competitor types, **pragmatic** L_{all} , and the population’s majority type, in representative populations after 50 generations under only a pressure for communicative success. **Flip plots, change plot generation to show the highest 6 Lbound users and the highest Lall, irrespective of ling. behavior, change text surrounding these things**

population states in which the system remains for a long time. As specified in Section 2.3.3, the mutation matrix Q can be obtained by considering all possible state-message sequences of length k . Given that this is intractable for large k , the sets of data which learners are exposed to are approximated by sampling 250 k -length sequences from each type’s production probabilities.

3.2.1 Replication only: selection based on communicative success

Selection based on communicative success is sensitive to λ since λ influences signaling behavior, which in turn determines communicative success. This is showcased in Fig. 4, which shows the proportion of target types, **pragmatic** competitor types and **pragmatic** L_{all} in a representative population after 50 replicator steps. The plot also indicates the proportion of the *majority type*: the type with the highest proportion in the final population. With low λ many types have very similar behavior, so that evolutionary selection lacks grip and becomes very slow. The result is a very long transition with near stagnancy in a rather homogeneous population with many types. Conversely, higher λ promotes less-stochastic linguistic behavior, widening the gap in expressivity between some types and promoting more homogeneous populations. As suggested by Fig. 4, the majority in most populations is not one of the six pragmatic L_{lack} -style types. That is, a pressure only for communicative success does not lead to a prevalence of target types under any λ -value. For instance, with $\lambda = 20$ 1000 independent populations only had 11 cases in which the target type was the majority type, corresponding to a mean proportion of .003 across

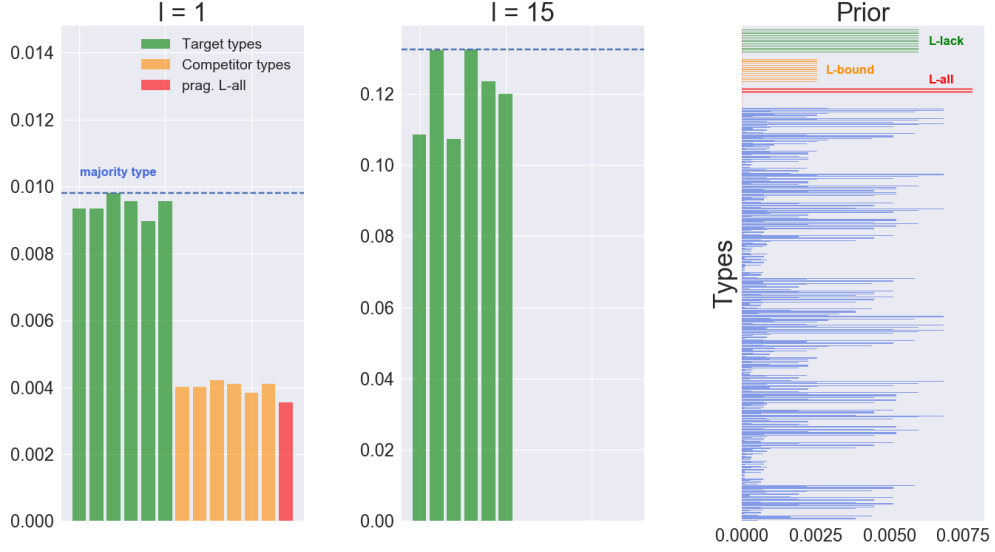


Figure 5: Proportion of target types, pragmatic competitor types, pragmatic L_{all} , and the population’s majority type in representative populations after 50 generations under only a pressure for learnability ($\lambda = 20, k = 5$). The learning prior is shown in the right-most plot with top-most groupings corresponding to types, literal and pragmatic, with lexica of kinds L_{lack} , L_{bound} , and L_{all} .

populations. By contrast, in 913 cases the majority types had L_{bound} with close to an even share between literal (454) and pragmatic types (459), corresponding to a mean proportion of about .48 taken together.

3.2.2 Iterated learning only: transmission fidelity

The effect of iterated learning without a pressure for communicative success using either posterior sampling ($l = 1$) or a stronger tendency towards posterior maximization ($l = 15$) is shown in Fig. 5 together with the prior over types. The prior shows that while users of L_{lack} are not the most favored by the inductive bias (compared, e.g., to L_{all}) they are nevertheless more advantaged than others, such as L_{bound} , in virtue of the relatively simple semantics they conventionalize (see Section 3.1.2). Crucially, L_{lack} enables its users to convey each state with a single message when combined with pragmatic reasoning and sufficiently high λ . This makes it less likely to be confused with other types if the learning data is not too sparse ($k \geq 5$). Put differently, learners have a higher propensity to infer pragmatic L_{lack} when the teacher’s type produces very similar data, such as when using L_{bound} . Moreover, L_{lack} is less likely to be confused with types with different observable behavior because its pragmatic use approximates a one-to-one form-meaning mapping. As a consequence, a stronger propensity to maximize the posterior increases their proportion in the population.

However, in contrast to a pressure only for communicative success with high λ (see Fig. 4), learnability alone does not succeed in selecting for a single prevalent type. Indeed, all six target types tend to

coexist at roughly equal proportion. Each is passed on to the next generation with the same faithfulness and, differently from a pressure for communicative success, they do not stand in competition with each other. In 1000 independent populations with $\lambda = 20$ all majority types were target types, with each reaching approximately the same proportion of users in the population.

As with a pressure only for communicative success, low values of λ make the differences in observable behavior across types less pronounced and therefore reflect the learners' inductive bias more faithfully. This favors functionally deficient but a priori preferred types such as those that use L_{all} . A pressure for learnability alone may consequently lead to a spread of communicatively suboptimal types that are easier to learn. In the extreme, when $l = 1$ and $\lambda = 1$ all of 1000 independent populations had users of L_{all} as majority types. For higher λ , it becomes clear that a high prior (e.g., L_{all}) is not the only thing that counts for learnability. As soon as there is information for learners to discern whether one type is more likely to have generated the data (depending on λ and k), it becomes paramount for types to produce data that makes them easily identifiable if they are to be transmitted faithfully. This is to say that the learning prior is important but far from being the only element that regulates how iterated learning plays out.

3.2.3 Combining pressures of communicative success and learnability

Pressure for communicative success and learnability are not sufficient on their own to have a single target type dominate the population. When pressured for communicative success, the communicative advantage of L_{bound} users leads to their prevalence. When pressured for learnability, pragmatic L_{lack} is promoted over functionally similar but semantically more complex alternatives such as L_{bound} . However, learnability alone does not foment the propagation of a single target type across the population.

Fig. 6 illustrates the combined effects of both pressures for a sample of λ and l values. These results show that an inductive learning bias for simpler semantics in tandem with functional pressure can lead to the selection of a single target type, and so to a division of labor between semantics and pragmatics. The proportion of a single majority target type increases with λ and l . Pressure for communicative success magnifies the effects of iterated learning and dampens the proliferation of multiple types of a kind that are equal in expressivity *and* learnability. A pressure towards learnability favors the transmission of simpler semantics and thereby selects for pragmatic language use.

As before, low λ and l lead to the prevalence of communicatively suboptimal types that are a priori favored, such as L_{all} . An increase in λ leads to the selection of target types but does not lead to monomorphic populations if learners sample from the posterior (see the uppermost row in Fig. 6). Fi-

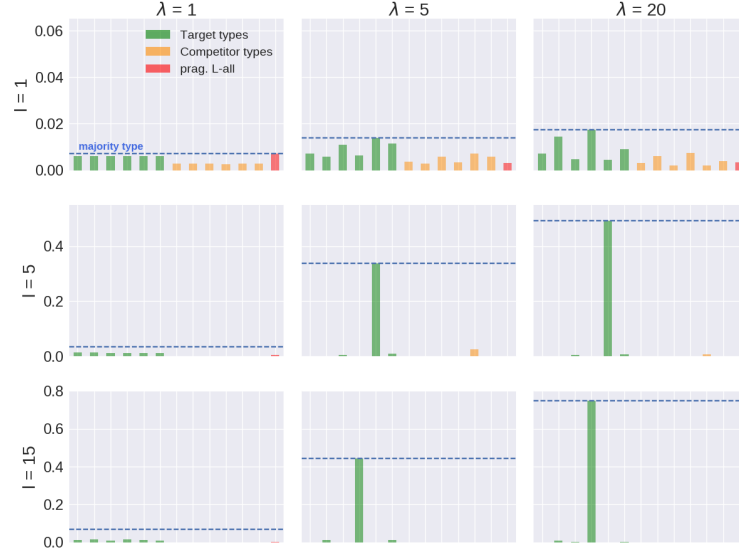


Figure 6: Proportion of target types, pragmatic competitor types, pragmatic L_{all} , and the population’s majority type in representative populations after 50 generations under both pressures ($k = 5$).

nally, a combination of high λ and l leads to increasing proportions of a single majority target type. This joint influence is summarized in Fig. 7, which shows the mean difference between the highest target type and the highest proportion of a type of a different kind in 1000 independent populations across λ and l values. Higher values of λ and l increase the prevalence of a single target type, whereas lower values lead to less pronounced differences, with a valley resulting from low λ and high l (cf. Fig. 6 with $\lambda = 1$ and $l = 15$).

Effects of manipulating the sequence length k have not been addressed so far, but are rather predictable: small values lead to more heterogeneous populations that reflect the learner’s prior more faithfully. This is due to the fact that the likelihood that a small sequence was produced by any type is relatively uniform (modulo prior). By contrast, larger values increasingly allow learners to differentiate types with different signaling behaviors.

To recapitulate, other than the involvement of pressure on both communicative success and learnability, the resulting proportion of pragmatic L_{lack} speakers primarily hinges on three factors. First, the degree, captured by λ , to which agents try to maximize communicative success from their own subjective point of view. Second, the inductive bias, which leads learners to prefer simpler over more complex semantic representations in acquisition. Lastly, the learning behavior, captured by parameter l , where approximating a MAP strategy magnifies the effects of the learning bias in tandem with replication.

More broadly, target types, which represent the majority view of scalar implicatures, can come to dominate the population if three assumptions are met: (i) language is pressured toward both communica-

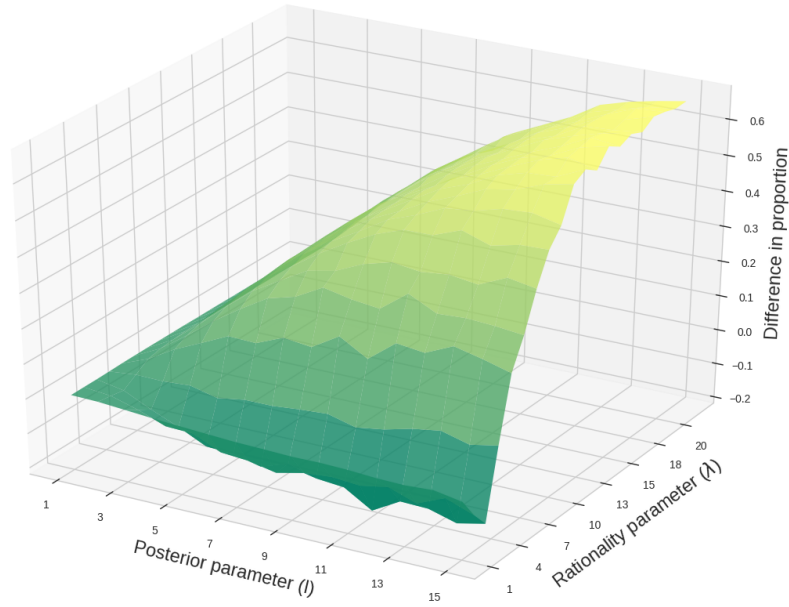


Figure 7: Mean difference between proportion of highest target type and highest other type in 1000 independent populations after 50 generations under both pressures ($k = 5$).

tive success and learnability; (ii) pragmatic language use is an option; (iii) learners prefer simpler over more complex lexical representations and exhibit a tendency towards the acquisition of the type that best explains the learning data.

4 General discussion

We do not believe that, ultimately, we should assume the non-parsimonious view that there are different complexity measures for different structures. However, with previous work in iterated learning tradition, we do assume that (i) inductive learning biases can play a role in shaping culturally transmitted knowledge and that, as the reviewer notes, (ii) biases can be of manifold nature; another well-studied example being the mutual exclusivity bias, which could be expected to work against targets and in favor of competitors.

At present, it is impossible to disentangle the complex interaction of multiple biases. We therefore focus on the effects of a single plausible contributing factor to a preference of target lexica over competitors: a well-motivated bias favoring simplicity (Feldman 2000, Chater and Vitányi 2003, Piantadosi et al. 2012, Kirby et al. 2015, Piantadosi et al. view). By assumption, this translates to a preference not to lexicalize linguistic material over lexicalizing it; simpler formulae over complex ones. As mentioned in Section 3.1.2, we acknowledge that the complexity measure that the prior is based on is just a convenient

operationalization of this particular hypothesis.

Lastly, we should stress that, just as models of iterated learning make different predictions under the assumption of different inductive biases, so does our model. The assumption and operationalization of a particular bias should, of course, always be seen critically (Section 4).

As now made explicit in Section xx.xx, we chose three messages for illustrative purposes mainly. In particular, we wanted to inspect a type space where targets are not the most likely *a priori* as this may mislead readers into thinking that learnability alone, in particular the prior alone, drives the outcome. This is related to our answer to reviewer 2, comment 7. The reason why we did not go beyond $n > 2$ is for computational tractability, as calculating Q , even if approximated, is expensive. The question whether increasing the type space will decrease the frequency to which we expect to see pragmatic *some* users is interesting. It now figures in Section X.X. At present, we have no answer.

Mention that they have the same k , λ and l : They do not have to but they do in our case study. Variation across parameter values would mean that we would have many more types: one for each combination of possible lexicon, pragmatic strategy, λ -, l - and k -value. This would allow us to trace the evolutionary trajectory (and competition) of not only lexica and pragmatic strategies, which is our goal here, but of all these factors combined. As our focus is not to show that, say, a particular λ value leads to a particular evolutionary outcome we restrict our attention to a homogeneous population where all agents have the same parameter values. We discuss this issue in Section 3.2. Maybe take this from thesis.

The approach introduced here combines game-theoretic models of functional pressure towards successful communication (Nowak and Krakauer 1999), effects of transmission perturbations on (iterated) language learning (Griffiths and Kalish 2007), probabilistic speaker and listener types of varied degrees of pragmatic sophistication (Frank and Goodman 2012, Franke and Jäger 2014) as well as reasoning about unobservable lexical representations (Bergen et al. 2012; 2016). This allows for a conceptual investigation of the co-evolution of conventional meaning and pragmatic language use. Main contributions of the model are (i) its modular separation of communicative success and learnability on evolutionary trajectories, (ii) the characterization of language learning as a joint inference over pragmatic behavior and lexical meaning, and (iii) the possibility to trace the co-evolution of conventional semantics and pragmatic use.

Redo around here. See commented out

With respect to (i), Kirby et al. (2015) propose a comparable model of the interaction between a lexicon's expressivity and its learnability. A main difference is that here we considered a pressure for mutual understanding within a generation that may indirectly select for expressive types, i.e., those that

can convey states unequivocally, whereas Kirby et al. only consider the bearing that the latter ability has on the production of learnable data. We see two main reasons for considering communicative success rather than just expressivity, and over only considering it in learning. First, learnability alone can lead to the acquisition of functionally defective languages, as showcased by L_{all} (cf. Kirby et al. 2008, Silvey et al. 2014, and see Fay and Ellison 2013 for review of laboratory results). Second and more importantly, types may be equally expressive but their performance as means of information transfer crucially depends not only on themselves but on the population they find themselves in (cf. the competition of target types in Fig. 6 and their lack of competition in Fig. 5). That is, we contend that having an expressive lexicon that generates learnable data does not in itself capture a type’s arguably central communicative function of transferring information to peers. Taking communication into consideration in turn allows the model to be responsive to the task for which language is learned.

The main result of our case study is that types that correspond to the majority view of scalar implicatures (scalar readings are non-lexicalized pragmatic enrichments) can come to dominate a population. This can happen under the assumption that simpler semantic representations are more likely to be learned (cf. Chater and Vitányi 2003). Pragmatic language use can be recruited indirectly by a preference for simpler lexical representations. Under this view, semantics and pragmatics play a synergic role: pragmatic use allows maintenance of simpler representations; pressure towards representational simplicity indirectly promotes pragmatic over literal language use. As a consequence, iterated transmission and use of language lead to a regularization that may explain the lack of lexicalization of systematic pragmatic enrichments.

While the results of this case study are interesting, they also raise a number of critical issues. First of all, while many favorable parameter settings exist which lead to a prevalence of target types, other types are usually represented in non-negligible proportions. This may just be a technical quirk of the mutator step. But there is a related issue of empirical importance. Several experimental studies on scalar implicatures suggest that participants can be classified as either semantic or pragmatic users of, in particular, *some* (e.g., Bott and Noveck 2004, Nieuwland et al. 2010, Degen and Tanenhaus 2015). The former consistently accept *some* where *all* would be true as well, the latter do not. Interestingly, in our simulations when a target type is the majority type an inflated proportion of the population uses compatible lexica with a lexicalized upper bound. Particularly in those parameter settings where the prior influences the outcome less. In other words, we do find a tendency toward a similar co-existence of semantic and pragmatic types. Whether this analogy has any further explanatory value is an interesting path for future exploration.

Another important issue that is not addressed in the model are potential costs associated with pragmatic reasoning. Here, we simply assumed that literal and pragmatic reasoning strategies exist from the start and are equally costly to apply. In contrast, empirical results suggest that the computation of a scalar implicature may involve additional cognitive effort (e.g., Breheny et al. 2006, Neys and Schaeken 2007, Huang and Snedeker 2009, Tomlinson Jr. et al. 2013). Extensions of the model presented here to include processing costs for pragmatic language use would be interesting future work. It seems plausible that effects of reasoning cost may trade off with the frequency with which a given scalar expression is used. It may be that frequently drawn scalar implicatures lexicalize to avoid cost, whereas infrequent ones are derived on-line to avoid more complex lexical representations during acquisition. Such a prediction would lend itself to empirical testing in line with a recent interest in differences between various scalar implicature triggers (van Tiel et al. 2016).

Our case study could be criticized as follows: all it shows is that scalar implicatures do not lexicalize because upper bounds are dispreferred lexical representations. This criticism would be too superficial and highly unjust. Dispreferred lexical representations can thrive under evolutionary selection. Lexicalized upper-bounds can dominate a population because they may boost communicative success. But they do not have to. Moreover, even without selective pressure for communicative success, it is not necessarily the case that the types that are most likely *a priori* will dominate. The dynamics of iterated learning are not that trivial. Iterated learning does not necessarily promote the *a priori* more likely type, but tends to promote a type t based on a gradient of how many other types might likely mutate into t , so to speak. Taken together, without an explicit model of the interaction between pressure for communicative success and learnability, it is far from trivial to judge whether or when preferred or dispreferred representations can be adaptive. This is why a major contribution of this paper is the arrangement of many different ingredients into a joined model of the co-evolution of lexical meaning and pragmatic use.

What is more, it is not that we just assumed a prior disadvantage of lexicalized upper bounds. We tried to motivate and formalize a general assumption about lexical representations' complexity with a concrete, albeit provisional proposal. The specification of a learning bias in terms of a "grammar of representations" can and should be seen critically, however. Much depends on the primitives of such a grammar. For instance, the lexical representation "none or all" is the most complex in Table 2. But consider adding a new primitive relation between sets $A \smile B$ which is true if and only if $\neg(A \cap B \neq \emptyset \wedge A \neq \emptyset)$. The lexical representation "none or all" would then be one of the simplest. Clearly, further research, empirical and conceptual, into the role of representational complexity, processing costs and learning biases is needed. The model here makes a clear and important contribution nonetheless: it demonstrates how

simplicity of representations can interact with use and evolutionary selection and shows that for simple representations to emerge it may require pragmatic strategies to compensate their potential expressive deficiencies. Hence a model of co-evolving semantics and pragmatics is needed. Future work should also include the possibility that representational simplicity may itself be a notion that is subject to evolutionary pressure (cf. Thompson et al. 2016), as well for the evolution of elements that define the agents' cognitive make-up; λ and l .

Finally, this case study should not be interpreted as a proposal for a definite explanation of how scalar implicatures evolved. Other factors should be considered eventually even if they will lead to much more complex modeling. One such factor is the observation that non-lexicalized upper bounds allow a broader range of applicability. For example, when the speaker is not certain as to whether *all* is true. This may suggest an alternative and purely functionalist argument for why upper-bounded meanings do not conventionalize: should contextual cues provide enough information to the hearer to identify whether a bound is intended to be conveyed pragmatically, then this is preferred over expressing it overtly through longer expressions. For example, by saying *some but not all* explicitly. Importantly, although morphosyntactic disambiguation may be dispreferred due to its relative length and complexity (Piantadosi et al. 2012), it allows speakers to enforce an upper-bound and override contextual cues that might otherwise mislead the hearer. In a nutshell, this explanation posits that scalar implicatures fail to lexicalize because, all else being equal, speakers prefer to communicate as economically as possible and pragmatic reasoning enables them to do so (cf. Chapter ??). What this alternative argument does not explain is why functional pressure does not lead to the emergence of different, equally costly lexical items to express different knowledge states of the speaker (Horn 1984:252-267, Horn 1972, Traugott 2004, van der Auwera 2010). For instance, to the emergence of two expressions for each weak scalar expression; one with and one lacking an upper-bound. That is, it does not explain why English and other languages do not have a monomorphemic dual expression for, e.g., *some* that lexicalizes an upper-bound. If this hypothetical expression existed, it could be deployed to signal that the speaker knows that *some but not all* holds, and unbounded *some* could exclusively signal epistemic uncertainty. Looking at pressure from learnability might come in again.

Beyond scalar implicatures, the model can generate predictions about likely lexicalization trajectories of pragmatic inferences, or a lack thereof. In this realm an interesting issue is whether proposed principles, such as the semantic conventionalization of once highly context-dependent inferences if they become regular enough (Levinson 2000, Traugott 2004), can be given a formal rationale and inform postulated directionalities of change. The present chapter made a first start and gave a framework for

exploring these issues systematically.

5 Conclusion

The cultural evolution of meaning is influenced by intertwined pressures. We set out to investigate this process by putting forward a model that combines a pressure toward successful information transfer with perturbations that may arise in the transmission of linguistic knowledge in acquisition. Its objects of selection and replication are pairs of lexical meanings and patterns of language use. This allows the model to trace the interaction between conventional meaning and pragmatic use. Additionally, it takes the challenge seriously of neither semantics nor pragmatics being directly observable. Instead, learners need to infer these unobservables from overt data that results from their combination. These components and their mutual influence were highlighted in a case study on the lack of lexical upper-bounds in weak scalar expressions that showed that, when pressured for learnability and communicative success, the former force drives for simpler semantic representations inasmuch as pragmatics can compensate for lack of expressivity in use. That is, the relative learning advantage of simpler semantics in combination with functional pressure in use may offer an answer to why natural languages fail to lexicalize systematic pragmatic inferences. And, more broadly, lead to a division of labor between semantics and pragmatics.

References

- van der Auwera, J. (2010). On the diachrony of negation. In *The Expression of Negation*, pp. 73–110. Walter de Gruyter GmbH.
- Baronchelli, A., A. Puglisi, and V. Loreto (2008). Cultural route to the emergence of linguistic categories. *PNAS* 105(23), 7936–7940.
- Batali, J. (1998). Computational simulations of the emergence of grammar. In J. R. Hurford, M. Studdert-Kennedy, and C. Knight (Eds.), *Evolution of Language: Social and Cognitive Bases*. Cambridge, UK: Cambridge University Press.
- Beggs, A. (2005). On the convergence of reinforcement learning. *Journal of Economic Theory* 122(1), 1–36.
- Benz, A. (2006). Utility and relevance of answers. In A. Benz, G. Jäger, and R. van Rooij (Eds.), *Game Theory and Pragmatics*, pp. 195–219. Palgrave Macmillan.

- Benz, A., G. Jäger, and R. van Rooij (2005). *An Introduction to Game Theory for Linguists*, pp. 1–82. Palgrave.
- Benz, A. and R. van Rooij (2007). Optimal assertions, and what they implicate. A uniform game theoretic approach. *Topoi* 26(1), 63–78.
- Bergen, L., N. D. Goodman, and R. Levy (2012). That’s what she (could have) said: How alternative utterances affect language use. In *Proceedings of Thirty-Fourth Annual Meeting of the Cognitive Science Society*.
- Bergen, L., R. Levy, and N. Goodman (2016). Pragmatic reasoning through semantic inference. *Semantics and Pragmatics* 9.
- Blume, A., Y.-G. Kim, and J. Sobel (1993). Evolutionary stability in games of communication. *Games and Economic Behavior* 5(5), 547–575.
- Börgers, T. and R. Sarin (1997). Learning through reinforcement and replicator dynamics. *Journal of Economic Theory* 77(1), 1–14.
- Bott, L. and I. A. Noveck (2004). Some utterances are underinformative: The onset and time course of scalar inferences. *Journal of Memory and Language* 51(3), 437–457.
- Breheny, R., N. Katsos, and J. Williams (2006). Are generalised scalar implicatures generated by default? An on-line investigation into the role of context in generating pragmatic inferences. *Cognition* 100(3), 434–463.
- Brighton, H. (2002). Compositional syntax from cultural transmission. *Artificial Life* 8(1), 25–54.
- Burkett, D. and T. L. Griffiths (2010). Iterated learning of multiple languages from multiple teachers. In A. Smith, M. Schouwstra, B. de Boer, and K. Smith (Eds.), *The Evolution of Language: Proceedings of the 8th international conference*, pp. 58–65. World Scientific.
- Chater, N. and P. Vitányi (2003). Simplicity: a unifying principle in cognitive science? *Trends in Cognitive Sciences* 7(1), 19–22.
- Chierchia, G., D. Fox, and B. Spector (2012). Scalar implicature as a grammatical phenomenon. In C. Maienborn, K. von Steubner, and P. Portner (Eds.), *Semantics. An International Handbook of Natural Language Meaning*, pp. 2297–2332. Berlin: de Gruyter.

- Christiansen, M. H. and N. Chater (2008). Language as shaped by the brain. *Behavioral and Brain Sciences* 31(05).
- Clark, E. V. (2009). Lexical meaning. In E. L. Bavin (Ed.), *The Cambridge Handbook of Child Language*, pp. 283–300. Cambridge University Press.
- Degen, J. and M. K. Tanenhaus (2015). Processing scalar implicatures: A constraint-based approach. *Cognitive Science* 39, 667–710.
- Fay, N. and T. M. Ellison (2013). The cultural evolution of human communication systems in different sized populations: Usability trumps learnability. *PLoS ONE* 8(8).
- Feldman, J. (2000). Minimization of Boolean complexity in human concept learning. *Nature* 407(6804), 630–633.
- Frank, M. C. and N. D. Goodman (2012). Predicting pragmatic reasoning in language games. *Science* 336(6084), 998–998.
- Franke, M. (2016). The evolution of compositionality in signaling games. *Journal of Logic, Language and Information* 25(3–4), 355–377.
- Franke, M. and G. Jäger (2014). Pragmatic back-and-forth reasoning. *Semantics, Pragmatics and the Case of Scalar Implicatures*, 170–200.
- Franke, M. and G. Jäger (2016). Probabilistic pragmatics, or why Bayes’ rule is probably important for pragmatics. *Zeitschrift für Sprachwissenschaft* 35(1), 3–44.
- Gazdar, G. (1979). *Pragmatics, Implicature, Presupposition and Logical Form*. New York: Academic Press.
- Geurts, B. (2010). *Quantity Implicatures*. Cambridge, UK: Cambridge University Press.
- Gong, T. (2007). *Language Evolution from a Simulation Perspective: On the Coevolution of Compositionality and Regularity*. Chinese University of Hong Kong.
- Goodman, N., J. Tenenbaum, J. Feldman, and T. Griffiths (2008). A rational analysis of rule-based concept learning. *Cognitive Science: A Multidisciplinary Journal* 32(1), 108–154.
- Goodman, N. D. and M. C. Frank (2016). Pragmatic language interpretation as probabilistic inference. *Trends in Cognitive Sciences* 20(11), 818–829.

- Goodman, N. D. and A. Stuhlmüller (2013a). Knowledge and implicature: Modeling language understanding as social cognition. *Topics in Cognitive Science* 5, 173–184.
- Goodman, N. D. and A. Stuhlmüller (2013b). Knowledge and implicature: Modeling language understanding as social cognition. *Topics in Cognitive Science* 5, 173–184.
- Grice, P. (1975). Logic and conversation. In *Studies in the Ways of Words*, Chapter 2, pp. 22–40. Cambridge, MA: Harvard University Press.
- Griffiths, T. L. and M. L. Kalish (2005). A Bayesian view of language evolution by iterated learning. In B. G. Bara, L. Barsalou, and M. Bucciarelli (Eds.), *Proceedings of the 27th Annual Conference of the Cognitive Science Society*, pp. 827–832. Cognitive Science Society.
- Griffiths, T. L. and M. L. Kalish (2007). Language evolution by iterated learning with bayesian agents. *Cognitive Science* 31(3), 441–480.
- Grodner, D. J., N. M. Klein, K. M. Carbary, and M. K. Tanenhaus (2010). “some,” and possibly all, scalar inferences are not delayed: Evidence for immediate pragmatic enrichment. *Cognition* 166, 42–55.
- Helbing, D. (1996). A stochastic behavioral model and a ‘microscopic’ foundation of evolutionary game theory. *Theory and Decision* 40(2), 149–179.
- Hirschberg, J. (1985). *A Theory of Scalar Implicature*. Ph. D. thesis, University of Pennsylvania.
- Hofbauer, J. (1985). The selection mutation equation. *Journal of Mathematical Biology* 23, 41–53.
- Hofbauer, J. and K. Sigmund (2003). Evolutionary game dynamics. *Bulletin of the American Mathematical Society* 40(04), 479–520.
- Horn, L. R. (1972). *On the Semantic Properties of Logical Operators in English*. Bloomington, IN: Indiana University Linguistics Club.
- Horn, L. R. (1984). Toward a new taxonomy for pragmatic inference: Q-based and R-based implicature. In D. Schiffrin (Ed.), *Meaning, Form and Use in Context*, pp. 11 – 42. Washington: Georgetown University Press.
- Huang, Y. T. and J. Snedeker (2009). Online interpretation of scalar quantifiers: Insight into the semantics–pragmatics interface. *Cognitive Psychology* 58(3), 376–415.

- Hudson Kam, C. L. and E. Newport (2005). Regularizing unpredictable variation: The roles of adult and child learners in language formation and change. *Language Learning and Development* 1(2), 151–195.
- Hurford, J. R. (1989). Biological evolution of the saussurean sign as a component of the language acquisition device. *Lingua* 77(2), 187–222.
- Huttegger, S. M. (2007). Evolution and the explanation of meaning. *Philosophy of Science* 74, 1–27.
- Jäger, G. (2007a). Evolutionary game theory and typology: A case study. *Language* 83(1), 74–109.
- Jäger, G. (2007b). Game dynamics connects semantics and pragmatics. In A.-V. Pietarinen (Ed.), *Game Theory and Linguistic Meaning*, pp. 89–102. Elsevier.
- Jäger, G. and R. van Rooij (2007). Language structure: psychological and social constraints. *Synthese* 159(1), 99–130.
- Katz, Y., N. D. Goodman, K. Kersting, C. Kemp, and J. B. Tenenbaum (2008). Modeling semantic cognition as logical dimensionality reduction. In *Proceedings of Thirtieth Annual Meeting of the Cognitive Science Society*.
- Kemp, C. and T. Regier (2012). Kinship categories across languages reflect general communicative principles. *Science* 336(6084), 1049–1054.
- Kimura, M. (1983). *The Neutral Theory of Molecular Evolution*. Cambridge University Press.
- Kirby, S. (2001). Spontaneous evolution of linguistic structure - an iterated learning model of the emergence of regularity and irregularity. *IEEE Transactions on Evolutionary Computation* 5(2), 102–110.
- Kirby, S. (2002). Learning, bottlenecks and the evolution of recursive syntax. In T. Briscoe (Ed.), *Linguistic Evolution Through Language Acquisition*, pp. 173–204. Cambridge University Press (CUP).
- Kirby, S., H. Cornish, and K. Smith (2008). Cumulative cultural evolution in the laboratory: An experimental approach to the origins of structure in human language. *Proceedings of the National Academy of Sciences* 105(31), 10681–10686.
- Kirby, S., M. Dowman, and T. L. Griffiths (2007). Innateness and culture in the evolution of language. *Proceedings of the National Academy of Sciences* 104(12), 5241–5245.
- Kirby, S., T. Griffith, and K. Smith (2014). Iterated learning and the evolution of language. *Current Opinion in Neurobiology* 28, 108–114.

- Kirby, S., T. Griffiths, and K. Smith (2014). Iterated learning and the evolution of language. *Current Opinion in Neurobiology* 28, 108–114.
- Kirby, S. and J. R. Hurford (2002). The emergence of linguistic structure: An overview of the iterated learning model. In A. Cangelosi and D. Parisi (Eds.), *Simulating the Evolution of Language*, pp. 121–148. Springer.
- Kirby, S., M. Tamariz, H. Cornish, and K. Smith (2015). Compression and communication in the cultural evolution of linguistic structure. *Cognition* 141, 87–102.
- Lenaerts, T., B. Jansen, K. Tuyls, and B. D. Vylder (2005). The evolutionary language game: An orthogonal approach. *Journal of Theoretical Biology* 235, 566–582.
- Levinson, S. C. (1983). *Pragmatics*. Cambridge, UK: Cambridge University Press.
- Levinson, S. C. (2000). *Presumptive meanings: The theory of generalized conversational implicature*. MIT Press.
- Lewis, D. (1969). *Convention: A Philosophical Study*. Cambridge: Harvard University Press.
- Luce, D. R. (1959). *Individual choice behavior: a theoretical analysis*. Wiley.
- Martinet, A. (1962). *Functionalist View of Language*. Oxford: Clarendon Press.
- Merriman, W. E. and L. L. Bowman (1989). The mutual exclusivity bias in children’s word learning. *Monographs of the Society for Research in Child Development* 54(3/4).
- Neys, W. D. and W. Schaeken (2007). When people are more logical under cognitive load. *Experimental Psychology* 54(2), 128–133.
- Nieuwland, M. S., T. Ditman, and G. R. Kuperberg (2010). On the incrementality of pragmatic processing: An ERP investigation of informativeness and pragmatic abilities. *Journal of Memory and Language* 63(3), 324–346.
- Nowak, M. A. (2006). *Evolutionary Dynamics: Exploring the Equations of Life*. Harvard University Press.
- Nowak, M. A., N. L. Komarova, and P. Niyogi (2001). Evolution of universal grammar. *Science* 291(5501), 114–118.

- Nowak, M. A., N. L. Komarova, and P. Niyogi (2002). Computational and evolutionary aspects of language. *Nature* 417(6889), 611–617.
- Nowak, M. A. and D. C. Krakauer (1999). The evolution of language. *Proceedings of the National Academy of Sciences* 96(14), 8028–8033.
- Nowak, M. A., J. B. Plotkin, and V. A. A. Jansen (2000). The evolution of syntactic communication. *Nature* 404(6777), 495–498.
- Pagel, M. (2009). Human language as a culturally transmitted replicator. *Nature Reviews Genetics* 10, 405–415.
- Piantadosi, S. T. (2014). Zipf’s word frequency law in natural language: A critical review and future directions. *Psychonomic bulletin & review* 21(5), 1112–1130.
- Piantadosi, S. T. and R. A. Jacobs (2016). Four problems solved by the probabilistic language of thought. *Current Directions in Psychological Science* 25(1), 54–59.
- Piantadosi, S. T., J. B. Tenenbaum, and N. D. Goodman (2012). Bootstrapping in a language of thought: A formal model of numerical concept learning. *Cognition* 123(2), 199–217.
- Piantadosi, S. T., J. B. Tenenbaum, and N. D. Goodman (under review). Modeling the acquisition of quantifier semantics: a case study in function word learnability.
- Piantadosi, S. T., H. Tily, and E. Gibson (2012). The communicative function of ambiguity in language. *Cognition* 122(3), 280–291.
- Qing, C. and M. Franke (2015). Variations on a Bayesian theme: Comparing Bayesian models of referential reasoning. In *Bayesian Natural Language Semantics and Pragmatics*, pp. 201–220. Springer International Publishing.
- van Rooij, R. and T. de Jager (2012). Explaining quantity implicatures. *Journal of Logic, Language and Information* 21(4), 461–477.
- Sandholm, W. H. (2010). *Population Games and Evolutionary Dynamics*. Cambridge, MA: MIT Press.
- Sauerland, U. (2004). Scalar implicatures in complex sentences. *Linguistics and Philosophy* 27, 367–391.
- Schlag, K. H. (1998). Why imitate, and if so, how? *Journal of Economic Theory* 78(1), 130–156.

- Silvey, C., S. Kirby, and K. Smith (2014). Word meanings evolve to selectively preserve distinctions on salient dimensions. *Cognitive Science* 39(1), 212–226.
- Skyrms, B. (2010). *Signals: Evolution, Learning, and Information*. Oxford: Oxford University Press.
- Smith, K. (2011). Learning bias, cultural evolution of language, and the biological evolution of the language faculty. *Human Biology* 83(2), 261–278.
- Smith, K., S. Kirby, and H. Brighton (2003). Iterated learning: A framework for the emergence of language. *Artificial Life* 9, 371–386.
- Spike, M., K. Stadler, S. Kirby, and K. Smith (2016). Minimal requirements for the emergence of learned signaling. *Cognitive Science*.
- Steels, L. (1995). A self-organizing spatial vocabulary. *Artificial Life* 2(3), 319–332.
- Steels, L. (2011). Modeling the cultural evolution of language. *Physics of Life Reviews* 8(4), 339–356.
- Steels, L. and T. Belpaeme (2005). Coordinating perceptually grounded categories through language: A case study for color. *Behavioral and Brain Sciences* 28(4), 469–529.
- Sutton, R. S. and A. G. Barto (1998). *Introduction to Reinforcement Learning*. Cambridge, MA, USA: MIT Press.
- Tamariz, M. and S. Kirby (2016). The cultural evolution of language. *Current Opinion in Psychology* 8, 37–43.
- Taylor, P. D. and L. B. Jonker (1978). Evolutionary stable strategies and game dynamics. *Mathematical Bioscience* 40(1–2), 145–156.
- Thompson, B., S. Kirby, and K. Smith (2016). Culture shapes the evolution of cognition. *Proceedings of the National Academy of Sciences of the United States of America* 113(16), 4530–4535.
- van Tiel, B., E. van Miltenburg, N. Zevakhina, and B. Geurts (2016). Scalar diversity. *Journal of Semantics* 33(1), 137–175.
- Tomlinson Jr., J. M., T. M. Bailey, and L. Bott (2013). Possibly all of that and then some: Scalar implicatures are understood in two steps. *Journal of Memory and Language* 69(1), 18–35.
- Traugott, E. C. (2004). Historical pragmatics. In L. R. Horn and G. Wand (Eds.), *The Handbook of Pragmatics*, pp. 538–561. Blackwell Publishing.

- Verhoef, T., S. Kirby, and B. de Boer (2014). Emergence of combinatorial structure and economy through iterated learning with continuous acoustic signals. *Journal of Phonetics* 43, 57–68.
- Wärneryd, K. (1993). Cheap talk, coordination, and evolutionary stability. *Games and Economic Behavior* 5(4), 532–546.
- Zipf, G. (1949). *Human behavior and the principle of least effort*. Addison-Wesley Press.