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Optimization in Neural Networks and in Universal Grammar

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An Integrated Cognitive Architecture

The adversarial relationship characteristic of the past two decades (e.g., the ongoing debate initiated by Rumelhart McClelland, 1986; Pinker Prince, 1988) is here replaced by a collaboration between symbolic generative linguistics and connectionist theories of mental representations and processes. These theories converge in a symbolic grammatical framework, Optimality Theory (OT, Prince Smolensky 1993/2004, 1997), which is realized in a connectionist substrate. Relative to alternative symbolic theories, OT provides stronger explanations of many empirical generalizations and linguistic universals. OT also provides a platform for explaining linguistic performance. The higher level structure of OT grammars offers the networks that realize them improved empirical adequacy relative to the large body of data addressed by linguistic theory, and the connectionist processing in these networks promises models of linguistic processing that are more empirically adequate relative to the data of psycholinguistics.

Pursuing the view proposed in Smolensky (1988) of the proper role in cognitive science of parallel distributed processing (McClelland, Rumelhart, the PDP Group 1986, Rumelhart, McClelland, the PDP Group 1986), the Integrated Connectionist/Symbolic Cognitive Architecture (ICS; Smolensky Legendre, 2005) crucially employs two levels of description in its account of computation in the mind/ brain. At the lower level, mental representations are patterns of activity over simple processing units, and mental processes are massively parallel processes of spreading activation. For certain cognitive domains including grammatical phenomena, the connectionist level is organized in such a way as to realize a higher-level cognitive system. This system contains symbolic representations and symbolic functions. But in general the system contains no symbolic algorithms that compute these functions; detailed, psychologically real accounts of mental processing, even in grammatical domains, require connectionist description at the lower level. Thus the division of explanatory labor is, to first approximation, that representations and functions are accounted for at the higher level, symbolically, and processing and learning is accounted for at the lower level, subsymbolically. The principles defining the ICS architecture at the connectionist level explain the general properties of cognition such as systematicity and unbounded productivity that were

identified as a challenges for connectionism by Fodor Pylyshyn (1988) (the objections of Fodor McLaughlin, 1990 and Fodor, 1997 notwithstanding).

Optimization. Because the symbolic level is realized in a connectionist substrate, cognitive functions at the symbolic level inherit subsymbolic properties. Crucially, the connectionist level is governed by processing principles that entail optimization behavior: given an input activation pattern, the network computes the output pattern that maximizes Harmony with respect to that input and the connection strengths (Geman Geman, 1984; Golden, 1986; Hinton Sejnowski, 1983; Hopfield, 1982; Smolensky, 1983; et seq.). Harmony measures the well-formedness of network states. Connections realize soft constraints and the Harmony-maximizing state optimally satisfies these constraints. In general, the relevant constraints are highly conflicting; their relative strengths determine how conflicts are resolved.

The optimization character of this substrate percolates up to the symbolic level. The functions computed by grammars produce outputs that maximize Harmony given the input and the soft constraints of the system: these constraints, together with their relative strengths, constitute a Harmonic Grammar (Legendre, Miyata, Smolensky, 1990ab et seq.)

Strict domination hierarchies and universality. Two central empirical discoveries about the actual Harmonic Grammars found in human languages form the foundation of Optimality Theory (Prince Smolensky, 1991). First, the strength of each constraint is sufficiently greater than that of all weaker constraints that weaker constraints can never gang up and overpower the preference of a stronger constraint. Thus, in actual grammars, constraints form a strict domination hierarchy, each constraint having absolute priority over all lower-ranked constraints combined. Secondly, the grammars of actual languages contain the same constraints; grammars differ only in how the constraints are ranked, that is, only in how conflicts among the constraints are resolved. This yields OTs formal theory of cross-linguistic variation: a grammatical domain is governed by a set of universal constraints, identical in all languages; the typology of possible grammatical systems in this domain is that given by all possible strict domination hierarchies of the universal constraints. This is factorial typology, the first general, formal theory of typology in linguistics.

Contributions. OT has been applied to many grammatical phenomena in pragmatics (Blutner Zeevat, 2003), semantics (Hendriks, de Hoop, de Swart, 2000), syntax (Legendre, Grimshaw, Vikner, 2001), morphology (Burzio, 2002), and especially phonology, which has been pervasively addressed by OT research (McCarthy, 2004). Replacing arbitrary sequential rules for manipulating symbol structures and language-specific hard constraints with parallel, conflicting universal soft constraints strengthens explanation in much of linguistics (McCarthy, 2002).

At the symbolic level, the formal properties of the OT learning problem and the complexity of computing optimal outputs have been extensively studied (e.g., Tesar, 1995 et seq.; Frank Satta, 1998). Work addressing on-line sentence comprehension (Gibson Broihier, 1998; Stevenson Smolensky, 2004), phonological production (Davidson, Jusczyk, Smolensky, 2004), and infants phonological preferences (Jusczyk, Smolensky, Allocco, 2002) illustrate how the OT grammatical framework is well-suited to theories of linguistic performance.

Future work aims to build explicit connectionist networks that realize OT grammars, applying parallel activation-based models of processing to systems employing the kinds of grammatical knowledge and structured representations that enable linguistic competence.

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