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Optimality Theory (OT)
(in phonology)

1. Roots: generative and connectionist

OT is a theory of computation that applies the connectionist principle of parallel computation to language, and especially to phonology, while being couched in the generative paradigm. In cognitive science, connectionism (Rumelhart *et al.* 1986) opposes the standard theory of the (human) mind (modularity: Fodor 1983) since the mid 1980s on the issue of computation: the extraordinary number of operations and the little time in which they are carried out, connectionists argue (e.g. Rumelhart 1989), leaves no space for serial computation that is foundational for post-war cognitive science (as well as modern micro-computers) and holds that individual computational events are necessarily performed one after another (the Turing-von Neumann model and artificial intelligence, e.g. Haugeland 1989:133ff, Pylyshyn 1989). The alternative is Parallel Distributed Processing (PDP) whereby several computational actions are carried out simultaneously.

A goal of connectionism is to build a theory that is more realistic, i.e. brain-style. We know that neurons are not serially ordered in the brain, but rather multiply interconnected. Hence in order to get to grips with a realistic theory of computation, several things must be done simultaneously, just like many neurons fire at the same time and thus transmit information simultaneously. Artificial neuronal networks that implement the PDP programme thus ambition to mimic the actual workings of the brain.

The reduction (or elimination by reductionists, e.g. Churchland 1984) of the distance between mind and brain is a landmark of empiricism in philosophy, which connectionism (and by cascade OT) are representatives of. At the same time, however, OT is firmly anchored in the generative and Chomskyan tradition, an explicitly rationalist approach to language that applies the standard theory of cognitive science to language. Two souls are thus dwelling in the breast of OT, with consequences for its view on the architecture of grammar (see sections 15 and 16).

In the founding statement of OT, Prince & Smolensky (1993:217ff) provide discussion of the relationship of the theory with connectionism. They argue for cherry-picking: while parallel computation is taken over, other major connectionist tenets are rejected. For example, Prince & Smolensky do not accept the connectionist anti-symbolic stance according to which the only relevant level where decisions are made is neuronal. According to this view, neurons only react on activation levels, hence cannot parse, or distinguish between, symbolic objects (on the symbolic debate, see e.g. Fodor & Pylyshyn 1988 and Dinsmore 1992).

Just like the standard theory of Cognitive Science, OT recognizes a symbolic level of representation. The place for connectionist non-symbolic computation, then, is intermediate between the symbolic level and the physiologically neural workings of the brain. This conciliatory position that rejects reductionism (i.e. the denial of the mind as an independent level of analysis) is defended by Paul Smolensky since his earliest work (Smolensky 1987, 1988) and up to the present day (Smolensky & Legendre 2006).

Also, Prince & Smolensky reject the neo-behaviourist take of connectionism regarding acquisition according to which "knowledge of language can be empirically acquired through statistical induction from training data" (Prince & Smolensky 1993:217).

The connectionist and standard theories of cognitive science are discussed e.g. in Fodor & Pylyshyn 1988 and Smolensky 1988). OT was unearthed by Paul Smolensky, Alan Prince and John McCarthy. The founding statement of the theory is the aforementioned 1993 manuscript (Prince & Smolensky 1993, published as a book in 2004). The other article that is usually mentioned in this context is McCarthy & Prince (1993).

2. Genesis: anti-derivationalism

In generative grammar, serialism incarnates as extrinsically ordered rules in phonology, and in early syntax as extrinsically ordered transformations. The latter have been abandoned in the early 80s when GB replaced them by so-called move α, i.e. a system where movement (computation) is free in itself, but marshalled by constraints on representations (e.g. Newmeyer 1986:163ff). Move α represents an important turn in syntactic theory away from restrictions on computation itself (Chomsky's 1973 original Strict Cycle Condition, extrinsically ordered rules) in favour of a central role of well-formedness constraints on representations such as barriers, the ECP and so forth. The autosegmental evolution in phonology since the late 70s follows the same track: representations are marshalled by well-formedness conditions such as the OCP. On the first page of their manuscript, Prince & Smolensky (1993) explicitly draw on the evolution in syntax and declare that their new theory extrapolates the timid phonological precedent into a formal system:

"[o]ur goal is to develop and explore a theory of the way that representational well-formedness determines the assignment of grammatical structure. […] The basic idea we will explore is that Universal Grammar consists largely of a set of constraints on representational well-formedness" Prince & Smolensky 1993:1f).

There is thus a red line running from the emergence of autosegmental representations over well-formedness conditions to constraint-based computation. In practice, Prosodic Morphology (McCarthy & Prince 1986), which fully explores the autosegmental tool, was instrumental as a precursor of constraint-based computation. It developed at least two central devices of OT: correspondence theory and alignment of prosodic and morphological constituents (the foreword to the 2001 edition of the manuscript, McCarthy & Prince 2001, explains this evolution in greater detail).

In sum, while generative syntax has abandoned serial computation since 1981, the representational blossoming of the early 80s has left serial computation entirely untouched in phonology. In the second half of the 80s, though, a diffuse discomfort with ordered rules arose, which quickly turned into a vigorous and lasting antipathy. Strangely enough, though, it looks like this evolution occurred without exchange of arguments in print. It is a matter of speculation where the general antipathy against serial computation came from, how it spread in absence of written record, and how an entire field could throw over board a fundamental piece of its identity without discussion. In his article *In defense of serialism*, Clements (2000:193f) makes the obvious point that the rise of connectionism on the Cognitive Science scene has played an important role in the development of anti-derivationalism in phonology.

In any event, defenders of serial computation reacted on the anti-derivational atmosphere by exposing arguments in favour of ordered rules. Bromberger & Halle (1989) discuss the question whether the abandon of ordered instructions by GB syntax should lead phonology to follow the same track. The authors reject this perspective because, as they try to show, the subject matter of phonology and syntax is intrinsically different.

Latent anti-derivationalism of the late 80s was the driving force of the events in the early 90s that was now made explicit, but there was still no discussion of comparative merits with serial computation, or of the reasons why serial computation is a bad thing to have. For example, Prince & Smolensky (1993) introduce parallel computation as an alternative to ordered rules, but leave it at this juxtaposition.

3. Constraint-based theories, with and without anti-derivational background

Three theories that have emerged in the early 90s are based on anti-derivationalism: Optimality Theory (Prince & Smolensky 1993), Declarative Phonology (Scobbie 1991, Scobbie *et al.* et al. 1996) and Government Phonology (Kaye *et al.* et al. 1990). The computation in all three cases is based on constraints, which however do not have the same status: while they are ranked and violable (i.e. soft) in OT, they are non-violable (i.e. hard) in Declarative Phonology. Computation in Government Phonology was not explicitly regulated for some time (Kaye's 1992:141 statement according to which processes "apply whenever the conditions that trigger them are satisfied" is vague), but its constraint-based character is obvious since the mid-90s (Licensing Constraints, Charette & Göksel 1994, 1996, Kaye 2001). Constraints in Government Phonology thus apply whenever a form may be modified by them, eventually recursively, but with no inherent ranking, and without being able to be violated: the derivation ends when no constraint can be applied anymore, or when all constraints apply vacuously.

Note, however, that Prince & Smolensky (1993) consider so-called Harmonic Serialism all through their manuscript: Harmonic Serialism works like regular OT, except that the candidate set produced by GEN is much more local, and the winner of the strictly parallel evaluation procedure is fed back into GEN. This procedure is repeated until no harmonic improvement can be achieved anymore. Harmonic Serialism was revived by McCarthy (2007a) under the label of OT-CC (on which more below). Prince & Smolensky (1993:6) write that

"[d]efinitive adjudication between parallel and serial conceptions, not to mention hybrids of various kinds, is a challenge of considerable subtlety, as indeed the debate over the necessity of serial Move-α illustrates plentifully […], and the matter can be sensibly addressed only after much well-founded analytical work and theoretical exploration".

Two other constraint-based theories are a more direct application of connectionism to phonology: Harmonic Phonology (Goldsmith 1992, 1993, Larson 1992) and Harmonic Grammar (Legendre *et al.* et al. 1990, Smolensky & Legendre 2006). The former is derivational: the successive application of rules progressively increases harmony, and the well-formedness of representations is measured in gradient, rather than in categorical terms. Gradience is also central for Harmonic Grammar, where weighted constraints are promoted. Like Goldsmith's gradual well-formedness, these are a direct transcription of the central connectionist notion of connection weight (and the activation level of neurons which defines their output). In this perspective, the relationship between constraints is one of lesser or greater prominence, rather than of strict dominance (more on this in section 6).

Finally, a number of hybrid theories have been proposed where serial rules and constraints are combined. Calabrese (2005) for example holds the principled position that a sound theory of phonology must have both serially ordered rules and constraints: while the former are instructions to create a given configuration, the latter specify which configurations must be avoided (constraints apply only to Kisseberth's 1970 conspiracies, see section 12). This idea was first implemented by Sommerstein (1974) and is indeed the naturally-grown state of affairs in the 80s: cohabitating with traditional rule-based computation, well-formedness constraints (i.e. output filters) were a direct consequence of (autosegmental) representations and the notion of well-formedness (see Scheer 2011b:412ff).

Hale & Reiss (2008:209ff) provide more discussion of the rules-cum-constraints option. Incarnations are the aforementioned Harmonic Phonology and Calabrese (2005) as well as Grounded Phonology (Archangeli & Pulleyblank 1994) and the Theory of Constraints and Repair Strategies (TCRS, Paradis 1998).

4. Evolution and status in the field

OT has been most widely applied to phonology, but there is also work in syntax, and nothing in principle prevents constraint interaction to also run computation in other fields such as sociology, chemistry etc. Work in syntax is represented for example in the volume edited by Legendre *et al.* (2001) (see also McCarthy 2002: 55f, 193ff, McCarthy *et al.* 2003), When compared to phonology, OT syntax has remained quite marginal in the field.

In phonology, OT became the leading theory almost over night in 1993-94. It then dominated the field maybe as no other theory before, including SPE. All domains of phonology were recast in terms of constraint interaction, and OT is considered especially successful in the area above the skeleton: syllable structure, stress, interface with morpho-syntax. Successful in this context means that new insight, new empirical generalizations and new analytic paths were produced.

From hindsight it appears that the founding statement of OT, connectionist-inspired anti-derivationalism, also induced its decline into a current state where a number of OT-inspired approaches are spread over a scattered landscape that lacks uniform motion towards a common goal or shared interests.

In recent years, OT constraints are used as a descriptive standard when phonologists talk about data, much like rules were in the post-SPE period. It does not really matter today, as it did not matter in the 70s, whether in such conversations the participants believe(d) in the tools as a theoretical device. Also, conference presentations frequently introduce an analysis in prose using OT terms, which however is not fleshed out in tableaus since these are quite interchangeable. The presenter may then refer to an appendix where relevant tableaus appear, which however are not crucial to the analysis, adding that if the audience likes better other tableaus with other constraints, that could be worked out.

This is indicative of the fact that the theory itself is not really developed anymore: the times where the engine was subject to debate regarding devices such as constraint conjunction, sympathy, indexed constraints and the like appear to be behind. Today the discussion in OT-inspired environments revolves around different issues: weighted constraints, stochastic approaches, computational modelling, artificial language experiments.

Below a number of issues relevant for the development of OT, its relationship with other theories and its two endowments (connectionist and generative) are discussed.

5. Workings (of classical OT)
Overviews: Kager (1999, early textbook), McCarthy (2002, 2007b), McCarthy et al (2003), de Lacy (2007a), Uffmann (2011).
In OT, (a)grammaticality is exclusively determined by constraint interaction.
Constraints
1. are universal, i.e. part of UG (as opposed to emergent from environmental stimuli)
2. are violable, i.e. soft (as opposed to absolute, or hard, as in Declarative Phonology)
3. are freely ranked (all different rankings are possible grammars)
4. are ranked by dominance, i.e. irreversibly (rather than by weight, i.e. gradiently)
5. apply only to surface forms (as opposed to underlying or derivationally intermediate forms)
6. belong to one of two major families, markedness and faithfulness constraints.

The idea is that a number of candidates compete and are refereed by a constraint hierarchy, which selects the one that incurs the least harmful (set of) violation(s): this is the optimal (or most harmonic) candidate, i.e. the output of the grammar. Here is a simple non-linguistic example: suppose somebody wants to watch a football game and cannot lose a minute because he could miss a goal, but at the same time needs to go to the bathroom. Both wishes are in conflict, and both cannot be satisfied. If the fear to miss a goal is more important than the attraction of the bathroom, our football fan will wait until the half time break. If the natural need outranks footballistic completeness, the bathroom will be visited during the match. In either case, there is an inconvenient and some frustration: given the priorities set, the winning configuration is bad, but the best possible.

Final devoicing may be used as a simple linguistic example (the following is adapted from Uffmann 2001:189). Let us consider the fate of an underlying form /bad/, the input to the grammar, which produces the candidates [bad] (fully faithful), [bat] and [pat]. These are evaluated by two markedness constraints, *CodaVoi ("voiced obstruents in codas are prohibited") and *ObsVoi ("obstruents must be voiceless"), as well as by one faithfulness constraint, Ident(voi) ("the voicing of an input segment must not be changed"). The ranking *CodaVoi >> Ident(voi) >> *ObsVoi produces a final devoicing grammar as is found e.g. in Turkish, Polish or German (by convention dominance is indicated by ">>").

(1)
a) final devoicing grammar b) grammar without final devoicing

/bad/	*CodaVoi	Ident(voi)	*ObsVoi	/bad/	Ident(voi)	*CodaVoi	*ObsVoi
bad	*!		**	☞ bad		*	**
☞ bat		*	*	bat	*!		*
pat		**!		pat	**!		

In OT tableaus, the underlying form appears in the top-left cell. In the tableau under (1)a, the candidate [bad] incurs a violation of the top-ranked constraint *CodaVoi (the violation of a constraint is indicated by an asterisk in the appropriate cell). Since no other candidate does ([bat] and [pat] have voiceless codas), this violation is critical and eliminates the candidate: no matter what the refereeing by other constraints, [bad] cannot win the competition anymore. The violation at hand is therefore said to be fatal, and this is indicated by an exclamation mark after the asterisk. The fate of the two remaining candidates is decided by Ident(voi): [bat] incurs one violation (because of its final -t), but [pat] violates the constraints twice (initial p- and final -t). Multiple violation of the same constraint is relevant in OT, and marked by the corresponding number of asterisks. The double violation of Ident(voi) by [pat] is thus fatal, and the winner of the overall competition is identified by elimination: [bat]. This is indicated by the pointing hand in the leftmost column.

Using the same constraints but reversing the ranking of *CodaVoi and Ident(voi) produces a different grammar, without final devoicing, as found in English for example. This is illustrated in the tableau under (1)b. The candidate [bat] is less offending than [pat] with respect to the top-ranked constraint Ident(voi), but this does not matter since the third candidate, [bad], does not violate this constraint at all. Hence the competition is decided by just one single constraint, top-ranked, since two of the three candidates incur fatal violations.

Given these workings, an obvious question is why these three candidates are considered and not others. Or, put differently, the question is how candidates come into being: obviously they are somehow related to the underlying form, but what exactly is their relationship? In OT, the generator function GEN produces candidates on the basis of the input, i.e. the underlying form.

(2) architecture of an OT grammar

input	→	$\boxed{\text{GEN}}$	→	candidates	→	$\boxed{\text{EVAL}}$	→	output
(underlying form)								(surface form)

Computational systems in the diagram are boxed: GEN and EVAL. The latter is the component of the architecture that runs and decides the competition among candidates (constraint interaction). This is usually done with the help of tableaus as under (1), although tableaus are only a visual crutch for the human linguist, who is rapidly lost when the number of constraints and candidates increases: various computer programs have been designed in order to handle complex candidate competition (one of them is OTSoft by Hayes *et al.* 2013).

Finally, the universal set of constraints whose free ranking is assumed to describe the variation found across languages (factorial typology, see section 13) is called CON.

The precise workings of GEN are not specified in the literature, and no explicit algorithm has been devised or hypothesized. All that is known is that GEN produces variation on the basis of the underlying item, i.e. somehow pays attention to its properties. Its workings are not restricted in any way: this is called Freedom of Analysis. Therefore its output is an infinite set of candidates, a fact that causes evident problems of implementation when it comes to concrete computation in the brain (see section 14 on computational complexity). In practice, though, only those candidates are examined that show variation relevant to the demonstration (hence [ʕar] for example is not considered in the final devoicing example under (1)).

In this context, it is interesting to compare the evolution of computation in syntax and phonology (see Hale & Reiss 2008:202ff, McCarthy 2002:55f). The Pisa turn in syntax (Chomsky 1981) and the anti-derivational movement in phonology not only did away with extrinsically ordered computational instructions (rules in phonology, transformations in syntax). They also replaced rule-based serialism by free generation-cum-filters. In GB syntax, morphemes could "freely" be concatenated, and Move-α could "freely" apply. Ill-formed results were then filtered out by global constraints (on locality, case etc.). The minimalist version of this conception of computation focuses on the interfaces, PF and LF, which impose conditions that make the derivation either crash or converge. Constraint-based computation in phonology follows the same track: in OT GEN does the free generation, and constraints filter out the optimal candidate. Unlike in syntax where filters are equal-righted and inviolable (hard), though, OT constraints are ranked and violable (soft).

Finally, the principle of Richness of the Base concerns inputs. It is parallel to Freedom of Analysis in that it prohibits any restriction on underlying forms (while Freedom of Analysis rules out restrictions on candidate generation). The idea is that the only locus of grammatically relevant generalizations is computation. Hence whatever the input, constraint interaction must produce a well-formed output for the language at hand. Underlying forms in English may thus be /cat/ as much as /ʘalʕukdsç/ or /kdgsiewʕjs/. Since the constraint set is universal, English will also have a constraint against clicks, which is ranked in a way that no click can ever make it to the surface. McCarthy (2002:241) explains that the absence of restrictions on inputs amounts to saying that inputs are the same in all languages.

6. Trends in OT

The theory exposed in the previous section may be called classical OT: it represents the common ground of all work whose offspring is Prince & Smolensky (1993). No doubt de Lacy (2007b:21f) is right to point out that today OT is anything but a monolithic theory. There are many sub-theories that do not necessarily concord, and OT-style constraint interaction may also be combined with other theories: cases in point are Government Phonology (Rowicka 1999) and Lexical Phonology (DOT and Stratal OT, respectively Rubach 1997 and Bermúdez-Otero 1999, Kiparsky 2000). Also, OT has been applied to virtually all areas and domains of phonological analysis (less so in syntax, though), and there is no point in trying to keep track of this diversity here. Finally, OT-based tableaus and vocabulary have become a notational means to talk about linguistic phenomena and analyses even when no theoretical commitment is intended (see section 4).

A number of broad strands and evolutions within OT are worthwhile being reported, though. A fundamental issue raised by the architecture of OT (and which is therefore absent in other theories) is how to make sure to compare relevant pieces of the string in input and output forms when faithfulness is computed. In the example of final devoicing from section 5, the -d of /bad/ is obviously compared to the -d and -t of the candidates [bad] and [bat], respectively, in order to determine whether they violate Ident(voi). But how does the comparing mechanism know which items to compare, i.e. how do we avoid that the input -d is compared, say, to the b- of candidate [bat]? While the match is fairly intuitive in this simple case, the issue may become quite intricate when candidates show multiple epentheses and deletions. Assume for example a candidate [baat] based on the input /batan/ where the intervocalic -t- was deleted, the word-final -n has developed an epenthetic -t before being deleted. The t present in the input and the candidate are thus not the same item derivationally speaking, and the comparing mechanism must not compare them.

There are two competing mechanisms for the computation of faithfulness: containment and correspondence. While the former was favoured in early work (Prince & Smolensky 1993, McCarthy 1993), the latter has rapidly become the standard in OT (McCarthy & Prince 1995). Basic constraints based on correspondence theory are Max ("every segment in the input has a correspondent in the candidate"), Dep ("every segment in the candidate has a correspondent in the input" and Ident(F) ("correspondent segments have identical values for feature F"). van Oostendorp (2007a) provides comparative discussion of both approaches to faithfulness. Finally, note that correspondence is a relation that does not only relate input- to output forms: two output forms may also "see each other" (OO-correspondence, e.g. Benua 1995, Burzio 1998) – this is, broadly speaking, the way analogy is formalized in OT. Another type of correspondence relation that is commonly invoked in the analysis of reduplication is the one between a base form and its reduplicant (BR-correspondence, e.g. McCarthy & Prince 1995).

Other trends in OT such as phonetic (or otherwise extra-grammatical) grounding of constraints are discussed in section 7.

Across all domain- and sub-theory-specific approaches, there is a major and pervasive evolution in OT that has taken on extra speed in recent years and led to the balkanisation of the theory into the kind of scattered landscape that is mentioned in section 4 where OT is more readily understood as a cover term for quite different ways of doing phonology. OT practitioners indeed abandon one by one foundational principles that once unearthed the theory and made its identity. This is true for anti-derivationalism (see sections 9 and 10) and Freedom of Analysis (see section 15), but also for five of the six basic characteristics of constraints that are mentioned in section 5.

A recent trend is to abandon the universality of constraints in favour of environment-driven, language-specific emergence of constraints during first language acquisition (characteristic 1 of section 4, see section 11). This contrasts with the standard assumption in OT regarding acquisition: children are born with the universal set of constraints and a ranking whereby all faithfulness constraints dominate all markedness constraints. Based on environmental input, their task is to figure out which markedness constraints need to be promoted how much in order to match the target language.

The idea that all constraints are violable (i.e. soft, characteristic 2) is also abandoned when they encode a deeply rooted property that all languages seem to follow. A case in point is the Strict Layer Hypothesis (SLH) that imposes formal restrictions on prosodic arborescence (Selkirk 1981): in its classical formulation, a constituent of layer n must be exhaustively contained within a constituent of the immediately higher layer n+1, and can only exhaustively contain constituents of the immediately lower layer n-1. Hence there can be no nested constituents, nor can any association line bypass a layer. Responding to evidence that challenges the monolithic character of the SLH, Selkirk (1996:189ff) factors out four more primitive component constraints which can be manipulated independently: 1) Layeredness (a node of given layer cannot dominate a node of any higher layer, i.e. a syllable cannot dominate a foot), 2) Headedness (each node of layer n must dominate at least one unit of layer n-1), 3) Exhaustivity (association lines may not bypass any layer: no association of two units that belong to non-adjacent layers is allowed) and 4) Nonrecursivity (nested structures are prohibited: no node may dominate a node of the same label). Selkirk holds that the two former are always true in language and hence universally undominated (which is another means of saying that they are hard), while the latter two may be violated.

Free ranking of constraints (characteristic 3) is abandoned in response to empirical pressure where a given pattern predicted by some specific ranking either never occurs cross-linguistically (e.g. Pater & Werle 2001), or never occurs as a repair although it could (the to-many-repairs problem, see section 12). One way to go about this are fixed rankings, i.e. where some constraints have a universal order.

It was already mentioned in section 3 that Harmonic Grammar, a closely related theory, implements a connectionist essential that OT has not taken over: connection weight. In Harmonic grammar, the relationship of constraints is not defined by dominance (characteristic 4) but by weight, i.e. a number associated with each constraint whereby lower ranked constraints can gang up and outrank a higher ranked constraint if their cumulated weight is higher than the weight of this constraint. This is also a perspective explored in OT (e.g. by Pater (2008, 2009); Stochastic OT (Boersma 1998) is specific implementation of this perspective.

Finally, derivational models of OT do evaluate intermediate forms, not just surface forms (characteristic 5). This is true for both approaches where phonology and morphology are derivationally related (DOT, Stratal OT, see section 9) and those where derivational elements occur within phonological computation itself (OT-CC, see section 10).

The only characteristic that seems to be obeyed by all work in OT up to the present day is the bipartition of computational instructions into faithfulness and markedness constraints (characteristic 6, no third category has been proposed).

In sum, the face of OT in 2013 is quite different from what it was upon inception twenty years ago.

7. The nature of constraints

Constraints are statements in prose, and there is no constraint on the formulation of constraints: anything that can be formulated is a possible constraint. Constraints may refer to grammatical categories (e.g. NoCoda), to (non-grammatical) properties of the phonetic signal (e.g. formant values, Flemming 2002), to extra-linguistic properties e.g. of psycholinguistic kind (e.g. positional faithfulness to the "prominence" of first positions: in a string, in a word, in a morpheme, in a root etc., Beckman 1997), to broad behavioural categories (e.g. Lazy "be lazy!", Kirchner 1998), or to any other content.

There are no guidelines in the theory that marshal what kind of categories constraints should or should not refer to (but see van Oostendorp & van de Weijer's 2005 attempt to define what they call a universe of discourse for the expression of instructions in OT). The choice made by different approaches, then, is indicative of their orientation: referring to formant values (Flemming 2002) makes phonology and phonetics one single computational system (i.e. one single constraint hierarchy), and referring only to extra-grammatical categories (phonetic, psycholinguistic etc.) promotes a phonetically-based view of phonology. The latter is the approach of Hayes *et al.* (2004), phonetically-based phonology (also called inductive grounding), whereby there is no or little grammatical content left, and the only thing that remains under grammatical control is the constraint hierarchy itself: systems are different because their constraint ranking is defined arbitrarily, i.e. does not reflect any extra-grammatical logic.

8. Rules vs. constraints

Rules are made of a structural change (the part on the lefthand side of the slash in A → B / C__D) and a structural description (the part on the righthand side). The latter defines a string, CAD, that is in need of modification. This is also the case of constraints, which issue a general requirement or prohibition, in our case for example *CAD. However, they do not specify what should be done in order to satisfy the requirement or prohibition at hand. This is one reason why constraint-based computation is said to be output-oriented: it specifies how things should or must not look like, but does not give any indication how the desired state of affairs should be achieved. Constraints thus divorce the structural description and the structural change of rewrite rules. Hale & Reiss (2008:195ff), Uffmann (2011: 174f) and Scheer (2011b:428ff) discuss formal differences between rules and constraints at greater length.

Another difference between constraints and rules is the vocabulary in which they are stated: wile rules can only refer to the specific vocabulary items that phonology is made of (features or other items of autosegmental representations), constraints are made of prose statements and can express anything that prose can express. This includes very broad instructions such as "be lazy!", which is the formulation of the constraint LAZY that Kirchner (1998) holds to be the motor for lenition (*STRUCTURE is another case in point). The loss of reference to a specifically phonological vocabulary is meaningful in terms of Cognitive Science: while so-called domain-specificity is a defining property of cognitive modules (which operate over a specific and proprietary vocabulary), it is denied by connectionism, where computation is content-free (or colourless) (e.g. Segal 1996, Gerrans 2002).

9. Anti-derivationalism among modules: anti-cyclicity

In the 90s, anti-derivationalism was strictly enforced and included the relationship of phonology with other grammatical modules: cyclic derivation was prohibited. That is, the basic modular and syntactico-centristic architecture of generative grammar was abandoned: according to the inverted T model (Chomsky 1965:15ff), morpho-syntax first concatenates lexical items that are stored in long-term memory (this is where the discrete infinity and creativity are located), and the resulting string is then sent to two interpretative modules, phonology (or PF, where it is assigned a pronunciation) and semantics (or LF, where it is assigned a meaning). Since Chomsky et al. (1956:75), the communication between morpho-syntax and phonology is cyclic: the Transformational Cycle (SPE) encodes morpho-syntactic information piecemeal, from the most to the least embedded item. This embedded structure, e.g. [D[C[AB]]], is then interpreted by phonology from inside-out, that is cyclically. Since these workings involve operations that are carried out in a (chrono)logical order, they are rejected from a (connectionist) viewpoint where nothing in the cognitive system can be derivational (e.g. Lakoff 1993). Therefore OT has developed a body of anti-cyclicity literature (e.g. Kager 1999:277, see also the section 16).

Alternatives to unbeloved cyclicity that have been developed in OT include parallel mini-grammars (co-phonologies, indexed constraints, e.g. Itô & Mester 1995, Pater 2009), interface constraints (e.g. Anttila 2002), analogy (which is called Output-Output faithfulness in OT, e.g. Benua 1995) and Orgun's HPSG-based perspective (Orgun 1996).

At the same time there were voices which argued that the parallel ambition of OT applies only to phonology proper: it does not extend to interface operations. Orgun (1999:250f) for example writes that OT and other approaches which reject cyclicity "have taken it for granted that cyclic phonology, like rule ordering, is derivational and that this is sufficient reason to look for alternatives to cyclicity. […] [W]hether or not there is a derivational residue in phonology is entirely a question for phonological theory proper. Phonology-morphology interleaving is not a source of derivationalism."

This point of view was exploited by revitalized incarnations of Lexical Phonology in the general OT environment: Rubach (1997) introduced Derivational OT (DOT), and Stratal OT was put on the agenda by Bermúdez-Otero (1999) and Kiparsky (2000). In these approaches, phonological computation itself is strictly parallel, but communication among modules is serial: first the phonology of a stratum is computed, then the output is assessed by the phonology of another stratum, which has a different morphological identity and therefore a different phonology (i.e. a different constraint ranking).

10. Anti-derivationalism within phonological computation: opacity

One advantage advertised by stratal implementations of OT is that they can get to grips with some cases of opacity. Opacity is a situation where a generalization is true and necessary for the workings of grammar, but invisible on the surface. OT with strictly enforced holistic parallelism is unable to produce these patterns, which are traditionally analyzed in terms of extrinsically ordered rules. The treatment of opacity was the major issue in the development of OT since the late 90s, and its failure eventually led to the implosion of the theory into the current scattered landscape. Various parallel solutions for opaque interactions have been proposed, but none has proven successful: Output-Output (OO) correspondence (e.g. Benua 1995, 1997), sympathy (various versions, e.g. McCarthy 1999, 2003b), Comparative Markedness (McCarthy 2003a), targeted constraints (Wilson 2000, 2001), enriched inputs (Sprouse 1997) and a couple of others. Gussenhoven & Jacobs (2011:111ff) provide an informed overview of the question.

John McCarthy was a major driving force in the development of parallel opacity killers. He gave up in the mid-00s, admitting that opacity is a true property of language, and that it cannot be solved without serial elements in the computational system. He therefore revived Harmonic Serialism, an option already discussed in Prince & Smolensky (1993), which McCarthy 2007a adapted into OT-CC (OT Candidate Chains). In this theory, candidate chains (rather than simple candidates) are evaluated, and the output of a pass through EVAL is fed back into GEN. This looping continues until the constraint ranking cannot produce any harmonic improvement anymore. Equivalent to intermediate forms in a derivation by ordered rules are intermediate forms in a candidate chain in OT-CC.

As a result of this evolution, the founding statement of OT, connectionist-inspired parallel computation, appears to be abandoned, at least in its absolute (holistic) ambition: most offsprings of Prince & Smolensky (1993) today implement serial elements either at the interface of phonology with other modules, or in phonological computation itself, or in both (but see section 15 on representations).

11. Giving up on the universality of the constraint set

Regarding the generative heritage of OT, a recent trend is to give up on the universality of the constraint set: rather than being part of UG and hence given at birth, constraints are supposed to be figured out by children based on environmental data during first language acquisition.

This direction follows two distinct logics. One is called online constraint induction (e.g. Albright & Hayes 2002, Heinz 2007, Hayes & Wilson 2008) and relates to machine-based modelling of artificial and/or natural language learning (where constraints are formulated by the machine in order to improve the result). The other is less radical since only markedness constraints are negotiable on a language-specific basis. Bermúdez-Otero & Börjars (2006) argue that if it turns out that there is no universal markedness, i.e. that the melodic properties of phonological processes are arbitrary (see so-called crazy rules that turn p into r etc., Bach & Harms 1972), the entire justification of universal markedness constraints disappears. Responding to this issue, Boersma (1998) and Bermúdez-Otero & Börjars (2006) propose that markedness constraints are acquired/constructed on the basis of available data, rather than innate.

As a result, different speakers may arrive at different grammars according to the environmental data available and the choices made during acquisition (while a standard assumption in acquisition is that learning paths may be distinct, but adult grammars are not, e.g. Fikkert 2007). Another consequence is that grammar is emptied of everything that is universal and specifically linguistic (at least with online constraint induction).

Giving up on the universality of CON may therefore look like a minimalist move in phonology: syntactic minimalism holds that the best grammar is one where UG is the smallest possible, i.e. where its functions are taken over by more general cognitive capacities, of which the grammatical effects observed are only the consequence in one specific area of cognition (third factor explanations, e.g. Chomsky 2005). In the case of online constraint induction, though, specifically linguistic universals are not interpreted as reflections of more general cognitive abilities. Rather, they are exchanged against purely environmental factors that are grammaticalized upon acquisition: nothing is universal or more generally cognitive.

Another issue is the notion of impossible grammars: if grammar exclusively depends on environmental data, any grammar and its reverse should be able to be learned, and hence should be able to exist. If anything and its reverse is possible, there should be no universals. The absence of, say, closed syllable lengthening or compensatory shortening from the record must then be attributed to the fact that children are never exposed to the relevant input (if they were, they would acquire such processes). This, however, only moves the question to diachronics: why should it be the case that languages can innovate new patterns in all possible directions, but never end up evolving in such a way that the outlandish processes mentioned occur?

Eliminating universality from grammar and allowing for anything and its reverse to exist moves the theory away from the basic generative idea that grammar should generate all *and only* those expressions that are well-formed.

12. Conspiracy, anti-conspiracy and output-orientation

de Lacy (2007b:14ff) reviews the advantages of parallel over serial computation: a better way of handling ordering paradoxes, global conditions and conspiracy. The latter is certainly the most prominent analytical achievement of OT: McCarthy (2002:54) says that "the conspiracy problem constitutes the single biggest phonological influence on the emergence of OT" (see also Uffmann 2011:176f). The issue was brought up early on by Charles Kisseberth (1970), and the rule-based environment reacted by proposing "transderivational" devices: output filters, global rules (e.g. Dinnsen 1974), persistent rules (Myers 1991).

The empirical situation called conspiracy is one where different processes appear to have a common goal, i.e. converge to achieve the same result. For example, changes that individuated Common Slavic in the realm of Indo-European dialects conspire to eliminate all closed syllables (law of open syllables, e.g. Bethin 1998:12ff). This is the result of a series of seemingly individual processes such as monophthongization, loss of final consonants, simplification of word-internal clusters by deletion or epenthesis, emergence of nasal vowels and liquid metathesis. Rule-based computation will have to posit as many rules are there are processes, and cannot capture the insight that there is an "invisible hand" that drives the events. These thus turn out not to be independent, and the only way to unify them is to issue a computational instruction that bears on their *result*. This is exactly what constraints do (see section 8): a constraint, but not a rule, can be formulated so to prohibit a certain output of phonological computation, in our case closed syllables. There are many different ways, though, to achieve this goal. Conspiracies such as the Common Slavic law of open syllables implement a number of them.

This is why constraint-based computation (connectionist PDP) in general, and OT in particular, are said to be output-oriented. Output-orientation, however, also has a backlash when it comes to the reverse empirical pattern. This is when language does not work in the interest of a specific surface result, but on the contrary makes relevant generalizations about processes that are surface-untrue. This pattern is known as opacity, which had an important impact on the development of OT because it cannot be described by the theory (see section 10).

Another backlash is what may be called anti-conspiracy: constraint interaction defines what the surface must or must not look like, but does not provide any clue how input structures that do not conform to the desirable surface pattern should be repaired (see section 8). In the case of the empirical pattern known as conspiracy, this openness for how to achieve a predefined goal is precisely what is required and makes the analytical success of OT. There are other empirical situations, however, where the reverse is required: sometimes there is a clear goal, but the cross-linguistic record offers only one single path. This is what is known as the too-many-repairs problem of OT (e.g. Bakovic 2007, van Oostendorp 2007b): different languages should be able to put different means to use in order to enforce for example the absence of word-final voiced obstruents in final devoicing systems. These could be deleted, there could be a vowel epenthesized to their right, they could become a sonorant etc. The only repair that language seems to practice, though, is final devoicing.

13. Variation, Factorial Typology, overgeneration

The question how many constraints there are in the universal constraint set, how many there ought to be or it is reasonable to admit, was debated in the 90s, but today is hardly pursued anymore. What is a reasonable number? A hundred, a couple of hundreds, a thousand, or does the number not really matter?

The question is closely related to the issues of overgeneration (and computational complexity, see section 14): the more constraints there are, the more grammars, i.e. languages, are predicted to exist. Given free ranking and n constraints, the number of distinct rankings, i.e. different grammars generated, is n!. This immediately produces astronomic numbers that for sure have no echo in the empirical record: 10 constraints generate 10!=3.628.800 grammars, and McCarthy's (2002:305f) index of constraints quoted in his book contains 103 items. Nobody has counted the number of constraints proposed in the literature, but their number for sure is much higher than a hundred. Also, it needs to be taken into account that the non-constrained formulation of constraints adds to the possible diversity, and hence to overgeneration (not to speak of machine-created constraints in online constraint induction).

Overgeneration was also a major issue for SPE and in post-SPE times: Noam Chomsky and Morris Halle were aware of the fact that (ordered) rules can describe all phenomena which occur in natural language, but also all others, and that this situation conflicts with the foundational generative ambition to generate *all* well-formed items, and *no others*. Their response was to plug markedness statements into rules (the famous ninth chapter of SPE). During the 70s and the early 80s, though, an unexpected overgeneration-killer appeared: autosegmental representations. Much hope was put into this new tool for fighting back overgeneration, and it is certainly true that it efficiently constrained the expressive power of grammar. But not all overgeneration could be eliminated this way (see Scheer 2011b for discussion).

Although OT in its initial state, and also in a minoritarian strand today (see section 15), was representationally oriented (in Prince & Smolensky 1993, constraint interaction was supposed to be the mediating computation between autosegmental representations), the evolution of OT has progressively demoted (autosegmental) representations to decoration and sometimes prides itself of having eliminated them altogether (e.g. de Lacy 2007b, see section 15). Therefore the situation is a little different when compared to the post-SPE period where overgeneration was considered a serious problem, and devices were sought for fighting it back.

Rather than being considered a challenge, the almost unmarshalled generative power of OT is advertised as a trump for modelling parametric, typological and dialectal variation. Since Prince & Smolensky (1993), the typological orientation of the theory is known as Factorial Typology, and was later supplemented with the Emergence of the Unmarked (TETU, McCarthy & Prince 1994). McCarthy puts it this way:

"Universal constraints and language-specific ranking yield a *factorial typology*. […] Every permutation of the constraints in CON is predicted to be a possible human language, and the grammar of every observed human language must be one of those permutations." McCarthy (2002:12, emphasis in original)

OT may thus be rightfully said to be typologically oriented, and to be particularly suited for the description of variation. This, however, comes at the cost of heavy overgeneration.

14. Computational complexity, competence and performance

OT has often been challenged for its computational complexity: in principle GEN produces an infinite set of candidates (see section 5) that cannot even be stored, let alone computed, and the number of grammars that a set of, say, two- or three hundred universal constraints produces given free ranking is astronomical (even when logically impossible rankings and those that produce identical patterns are counted out, see section 13). Overgeneration was discussed in the previous section, but the architectural setup of OT also prompts an issue regarding computation itself, especially when recalling that parallel computation was imported from connectionism precisely in order to replace biologically unrealistic serial computation with an alternative that can be executed in real time by a real brain (brain-style computation is a connectionist slogan, see section 1).

Right from the beginning, the answer of OT to criticisms regarding computational complexity was to call on the competence-performance distinction:

> "It is not incumbent upon a grammar to compute, as Chomsky has emphasized repeatedly over the years. A grammar is a function that assigns structural descriptions to sentences; what matters formally is that the function is well-defined. […] Grammatical theorists are free to contemplate any kind of formal device in pursuit of these goals; indeed, they *must* allow themselves to range freely if there is to be any hope of discovering decent theories. Concomitantly, one is not free to impose arbitrary additional metaconstraints (*e.g*. computational plausibility) which could conflict with the well-defined basic goals of the enterprise." Prince & Smolensky (1993:215f, emphasis in original)

McCarthy (2002:9f) makes the same point: "OT shares with the rest of generative grammar a commitment to *well-definition* but not to *efficient computation*" (emphasis in original). He then provides a number of quotes from Chomsky's work that illustrate this idea:

"[w]hen we say that a sentence has a certain derivation with respect to a particular generative grammar, we say nothing about how the speaker or hearer might proceed, in some practical or efficient way, to construct such a derivation" Chomsky (1965:9)

"although we may describe the grammar *G* as a system of processes and rules that apply in a certain order to relate sound and meaning, we are not entitled to take this as a description of the successive acts of a performance model such as *PM* - in fact, it would be quite absurd to do so" Chomsky (1968:117, emphasis in original).

McCarthy endorses this view for OT:

"That confusion has sometimes led to skepticism about OT: how can EVAL sort an infinite set of candidates in finite time (cf. Bromberger & Halle 1997)? The error lies in asking how long EVAL takes to execute. It is entirely appropriate to ask whether EVAL, like Chomsky's *G,* is well defined, captures linguistically significant generalizations, and so on. But questions about execution time or other aspects of (neural) computation are properly part of the performance model *PM* and must be addressed as such." McCarthy (2002:10)

OT thus hides behind the firewall that Chomsky has established between competence and performance since the inception of generative grammar in the 50s: performance cannot have any bearing on the discovery or the properties of competence, and grammar is only about competence.

Interestingly, though, Chomsky has made a complete U-turn in this respect: the minimalist and biolinguistic programme (Chomsky 1995, 2000 et passim) is based to a large extent on the idea that grammar must respond to implementational requirements. The whole point of the minimalist approach is to understand grammar (in fact, morpho-syntax) as the result of a response to the interfaces (PF and LF) and extra-grammatical factors (third factors, Chomsky 2005). Computational efficiency (which Chomsky says is irrelevant in the quote above), is now held to be the central motor for defining grammar:

"[t]he minimalist program is the attempt to explore these questions. Its task is to examine every device (principle, idea, etc.) that is employed in characterizing languages to determine to what extent it can be eliminated in favor of a principled account in terms of general conditions of computational efficiency and the interface condition that the organ must satisfy for it to function at all" Chomsky (2004:106).

"As discussed in MI [Minimalist Inquiries, Chomsky 2000] and sources cited, there is mounting evidence that the design of FL [Faculty of Language] reduces computational complexity. That is no a priori requirement, but (if true) an empirical discovery, interesting and unexpected. One indication that it may be true is that principles that introduce computational complexity have repeatedly been shown to be empirically false." Chomsky 2001:15)

Another prominent example is Phase Theory, which cuts the computation of a full sentence into computationally independent pieces for reasons of computational economy regarding the limited availability of active memory, a costly cognitive resource (e.g. Chomsky 2000:101, 2001:15).

In the current minimalist and biolinguistic environment, the issue of computational complexity prompted by the basic architecture of OT thus re-emerges with new acuteness.

15. Representations and computation

The Handbook of Phonology that Paul de Lacy (2007a) has edited in general, and de Lacy's (2007b) introduction to the volume in particular, document the global trend from representation to computation in much detail.

"Of course, it is crucial for any theory of phonology to have a well-defined restrictive theory of representation. However, OT has allowed the burden of explanation to move from being almost exclusively representation-based to being substantially constraint-based." De Lacy (2007b:24)

The connectionist roots of OT are instrumental in understanding the extreme computational orientation that phonology has taken under its lead since 1993. It is sometimes rightly recalled that OT is a theory of constraint interaction, not of constraints. This means that OT does not supply any substance itself: there are genuine vocabulary items in structuralism (phonemes), SPE (segments) and autosegmental theory (autosegmental structure), but there are no OT-specific representational items. OT uses whatever representational material comes the way (if grammatical material is referred to at all, see sections 7 and 8), and may well produce the same result with entirely different vocabulary. For example, Lombardi (2001) writes with respect to melodic representation:

"the tenets of OT, regarding constraint violability and ranking, make no particular claims about phonological representations. We could, for example, do OT with any kind of feature theory: SPE feature bundles or feature geometric representations, privative or binary features, and so on." Lombardi (2001:3)

Hence OT is a purely computational theory where representations make no sovereign contribution to the definition of grammaticality: the *only* means to determine grammaticality is constraint interaction. Hence whatever items of the representational furniture of the 80s are used, they are mere decoration that do not contribute any sovereign arbitral award, and do not have anything to say regarding grammaticality (a structure with line-crossing for example may be the optimal candidate if all other candidates violate higher-ranked constraints).

This relates back to the connectionist prototype of OT where, recall (from section 8), computation is content-free (or colourless).

The current computational orientation of OT, however, does not follow from any tenet of the theory (see Scheer 2010): OT is a theory of parallel computation that uses ranked and violable constraints. This does not lay any claim on how much of the explanative pie is computational: recall that for Prince & Smolensky (1993) constraint interaction is supposed to be the mediating computation between autosegmental representations. Taking exception with mainstream computational maximalism, a small but growing body of literature develops a representationally oriented incarnation of OT (e.g. van van Oostendorp 2002, 2003, 2005, 2006, Blaho *et al.* 2007). Contributions to the latter volume challenge Freedom of Analysis. That is, you ought not to be free to do what you want with representations. In terms of the classical OT grammar, this means that there are restrictions on GEN (rather than fixed rankings for example), which produces only a subset of logically possible candidates.

The idea that OT is a complete theory of grammar is around since its inception. The bare existence of versions of OT that place restrictions on GEN show that this view is overstated: OT is not a theory of grammar; it is a theory of a piece of grammar, computation.

The smallest common denominator of OT is parallel computation that uses ranked and violable constraints. All the rest is free and a matter of choice of the analyst, who may or may not be a generativist, may or may not be a functionalist, may or may not assume a modular architecture, may or may not be representationally oriented, may or may not believe in the virtue of serial ordering of phonological (and/or grammatical) events, may use this or that representational system, and so forth.

16. Inbuilt tendency for scrambling

Closely related to the tendency to maximize the labour of computation (see section 15) is the pervasive bias to make distinct things indistinct; that is, to put them in the same constraint hierarchy, to intersperse them and to assess them in one go. It was mentioned in section 1 that computation in the connectionist perspective is not only parallel, but also *distributed* (PDP). What this means is that connectionist computation is all-purpose, or colourless: whatever is computed is computed by the same technology and using the same basic units. This view contrasts with domain-specific computation in a modular environment (see section 8) where modules are identified by the different vocabulary that they manipulate (e.g. labial, occlusion in phonology, against number, gender etc. in morpho-syntax).

The OT-typical scrambling concerns the relationship of phonology with both morphology and phonetics. In the former area, the most visible departure from the basic generative architecture is anti-cyclicity, i.e. the rejection of cyclic spell-out because of its serial character. Anti-cyclicity along with its consequences for the inverted T model was discussed in section 9. Other modularity-offending devices in OT include the following (see Scheer 2011a:§523). Indirect Reference is the modularity-enforcing prohibition to make direct reference to morpho-syntactic categories that was established by Prosodic Phonology in the early 80s (e.g. Selkirk 1984). This principle of intermodular communication is abandoned in OT where ALIGN and WRAP constraints make constant reference to morpho-syntactic structure and labels. Also, so-called interface constraints such as FAITH-root and FAITH-affix make reference to designated morpho-syntactic categories (even reference to individual morphemes is not a problem: Anttila 2002 provides an overview) and thereby revive the SPE-practice of supplementing rules with morphological diacritics. Another relevant issue is mapping (of morpho-syntactic into phonological prosodic categories), which is done *in* the phonological constraint hierarchy (rather than outside of the phonology as was the case in

Prosodic Phonology): ALIGN and WRAP are interspersed with purely phonological constraints. Finally, OT provides for constraints whose formulation combines phonological and morphological instructions (see Yip 1998 on this issue).

On the other end of phonology, Kingston (2007) discusses the abandon of the distinction between phonetic and phonological constraints. He points out the causal relationship between the move from serial to parallel computation on the one hand and the everything-is-the-same perspective on the other:

"[r]eplacing serial derivation by parallel evaluation removes the barrier to phonetic constraints being interspersed among and interacting with phonological constraints. […] Future research will determine whether phonological and phonetic constraint evaluation are a single, integrated process, as advocated by Steriade and Flemming or instead sequential, as advocated by Zsiga" Kingston (2007:432).

Despite this antiderivationalism-spurred tendency, though, scrambling does not follow from any principle of OT. OT is committed to parallel *computation*, and in generative grammar the unit where computation takes place is the module. Grammar is made of several modules, each with a distinct computation that works on distinct (i.e. domain specific) vocabulary. Hence nothing withstands a perspective where all linguistic computation is perfectly parallel, but distributed over distinct and serially ordered computational systems.

As was mentioned in section 9, this architecture is favoured by modern representatives of Lexical Phonology, i.e. DOT and Stratal OT. Also quite unsurprisingly, representationally oriented incarnations of OT that are discussed in section 15 maintain sharp modular contours (e.g. van Oostendorp 2006).

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