A Linguistic Theory of Robustness *

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1 Introduction

Syntactical robustness is a desired design property of natural language parsers. Within the past decade, several developmental robustness approaches have been forwarded: Syntax-free semantic parsing [1] constraint relaxation after parse failure in a pattern matching [2] or ATN framework [3,4], parse tree fitting [5] and several non-formalized case frame approaches (e.g. the parser series in [6,7]). Three approaches [5,8,9] account for special defectivities by extending grammatical coverage. This paper reformulates the so-called weakness approach, first published in [10], which extends robustness to declarative parsing formalisms.

There are serious shortcomings in robustness research, emerging from the common view of robustness as a parsing and not as a representation problem. Typically, two distinct representation levels for grammatical and non-grammatical language are assumed. The former is given by the basic framework, the latter by relaxed pattern slots [2] or ATN arc tests [3], by "non-grammatical" meta-rules [4], by some construction specific strategies [6,7] or by the schema mechanism [11]. While formalism syntax is sometimes specified (e.g. [4,10]), a semantics of robust grammar formalisms, being necessary to define these two representation levels, has not been given yet. Without a well-defined formalism semantics, it is impossible to predict the behaviour of a (robust) grammar fragment when applied to non-grammatical language. Therefore, no robustness methodology has been available until now.

2 The WACSG approach

WACSG (Weak ACSG) is an experimental formalism for defining robust grammars. ACSG (Annotated Constituent Structure Grammar) is a class of two-level grammar formalisms such as LFG [11], DCG [12] and PATR-II [13]. Nevertheless, WACSG weakness concepts may also be implemented in monostratal formalisms as e.g. HPSG [14]. WACSG is dedicated to syntactical robustness, and not to morphosyntactic (spelling correction), semantic or pragmatic robustness. This does not preclude semantics and/or pragmatics from resolving robustness conflicts.

For a WACSG-grammar fragment to be robust, its formalism's weakness is necessary but not sufficient and its adequacy w.r.t. defective language is necessary but not sufficient. Robustness theory is to show that defective language is *exactly* the language described by "weak" description methods. Any less metaphorical construction of the notion of weakness needs a considerable formal apparatus.

3 The WACSG Formalism

A WACSG grammar rule is a context free production annotated with an attribute-value- (av-) formula. The following two subsections deal with weakness relations for context free grammars and av-languages. Section 3.3, then, specifies the WACSG formalism semantics.

3.1 Partial String Languages

Below
(1), three partial string languages of a context-free grammar $G =< Cat, Lex, Pr, Sset >$ are defined, where Cat and Lex are sets of nonterminal and terminal symbols, respectively, Pr a set of productions and $Sset$ a set of start symbols. Now let P_w a set of substrings of w and PP_w a set of power-substrings of w with any $w' \in PP_w$ resulting from deletion of arbitrary substrings in w. If $|w| > 0$, then P_w and PP_w must not contain ϵ. Z_w and ZZ_w are partition functions in P_w and PP_w respectively. More simply, $SET(G)$ equals $L(G)^+$. $SUB(G)$ allows an undefined leftside and/or rightside substring and $PAR(G)$ even undefined infix substrings for every element from $L(G)$.

(1)

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$SET(G) = \{w \in Lex^\star \mid \exists n \in \aleph\ \exists z \in Z_w \cap L(G)^n\}$
$SUB(G) = \{w \in Lex^\star \mid \exists \hat{w} \in P_w \cap L(G)\ \}$
$PAR(G) = \{w \in Lex^\star \mid \exists \hat{w} \in PP_w \cap L(G)\ \}$

Partial string languages have appealing formal properties: $\phi(G)$ for $\phi \in \{SET, SUB, PAR\}$ is context-free, contains ϵ iff $L(G)$ contains ϵ and there is an order $L(G) \subseteq SET(G) \subseteq SUB(G) \subseteq PAR(G)$. Nesting partial string languages introduces a set $\Phi(G)$ of languages such as e.g. $SET(SUB(G))$,$SET(PAR(G))$. We have $|\Phi_\phi(G)| = 1$, i.e. alle languages with maximal operator ϕ are weakly equivalent, though not pairwise strongly equivalent.

A recursive partial string grammar (RPSG) is obtained by indexing rightside (nonterminal) symbols of a cfg G with indices SET, SUB, or PAR. The formalism- semantics for an RPSG is given by a derivation relation (cf.[15]) for non-indexed and SET-indexed nodes of a tree graph and by a generation function gen as displayed in 2 for any other nodes. Let $\Omega(G)$ the set of derivations for a given G, $\omega \in \Omega(G)$ a derivation and t_ω its tree graph. Let l_ω be a label function with $l_\omega(0) \in Sset_{ind}$ a (possibly indexed) start symbol [1] The languages $L(G)$ (derived language) and $RPSL(G)$ (generated language) are defined in 3. $L(G)$ and $RPSL(G)$ are context-free and we have $L(G) \subseteq RPSL(G)$, $L(G)$ usually being much smaller than $RPSL(G)$.

(2)

$gen_\omega : t \times (Cat_{ind} \cup Lex)^+ \longrightarrow \{0,1\}$

(3)

Let G be a RPSG.

- $L(G) = \{w \in Lex^+ \mid \exists S_\phi \in Sset_{ind}\ S_\phi \stackrel{\star}{\Longrightarrow} w\}$
- $RTSS(G) = \{w \in Lex^+ \mid \exists \omega \in \Omega(G)\ gen_\omega(0, w) = 1\}$

3.2 Attribute-Value Languages

The av-language ∂ is a first order predicate logic including 1-ary function symbols and two 2-ary predicates "$\approx$" and "$\in$"for equality and set membership, respectively. Soundness and completeness of ∂ without $\in$ have been proven in [16]. The predicate "$\in$" introduces well-founded, distributive, recursive sets of attribute-value-structures, and is discussed in [17] . We assume the existence of a reduction algorithm RNF with $RNF(A) \in \partial$, iff is A satisfiable and $RNF(A) = \perp$ otherwise (for any formula $A \in \partial$) [2].

[1] By notational convention, it is $Cat_{ind} \subseteq Cat \times \{SET, SUB, PAR\}$ and by definition of RPSG, it is $Sset_{ind} \subseteq Cat_{ind}$.

[2] $RNF(A)$ is in disjunctive normal form, such that $DNF(RNF(A)) = RNF(A)$

Robustness in the area of av-languages is the ability to cope with inconsistent (i.e. overspecified) formulae. Two different methods for maintaining consistency will be considered, namely set weakening and default formulae.

3.2.1 Set weakening

In robustness theory, the purpose of av-sets is to weaken the function condition on av-structures. Set weakening may be used e.g. for the transition from an inconsistent formula $A = x(\text{syn})(\text{case}) \approx$ nom $\wedge\ x(\text{syn})(\text{case}) \approx$ akk to a consistent (therefore non-equivalent) formula $A^{x(\text{syn})(\text{case})} = x_1 \approx$ nom $\wedge\ x_2 \approx$ akk $\wedge\ x_1 \in x(\text{syn})(\text{case}) \wedge x_2 \in x(\text{syn})(\text{case})$. This transition preserves case information, but not inconsistency for the denotatum $[\![x]\!]$. In general, set weakening is defined as follows:

(4)

Let $A \in \partial$ a formula in disjunctive normal form and t a non-constant term. Let $L^t_A = \{A_{i,j}.k \mid t \text{ occurs } k-\text{times in a literal} A_{i,j}\}$ a set of indices. For any $r \in L^t_A$, z_r is a variable not occuring in A. The set weakening of A for a term t is

$A^t = (A[t^r/z_r] \wedge \bigwedge_r z_r \in t)_{r \in L^t_A}$

For any $A \in \partial$ and non-constant term t it has been shown (see [17]) that, if $RNF(A) = A \neq \perp$, then also $DNF(A^t) = RNF(A^t) \neq \perp$. Therefore, if A is satisfiable, then A^t is also satisfiable. Since satisfiability of A does not follow from satisfiability of A^t (see above), A^t is weaker-or-equivalent to A. However, the theoretically motivated A^t-notation has not been integrated into WACSG formalism, since set weakening can be achieved by using the predicate "$\in$".

3.2.2 Defaults

The classical subsumption $\sqsubseteq$ gives a partial ordering within the set of av-models. There are, however, no inconsistent models. Therefore, a partiality notion with inconsistency must be based upon descriptions i.e. av-formulae. The relation 3-partial $\subseteq \partial^2$ is a subsumption-isomorphism into a (canonical) subset of ∂. The relation 0-partial defined below is still weaker in allowing inconsistency of one formula B and can be shown to be a superset of 3-partial, i.e. 3-partial $\subseteq$ 0-partial.

(5)

Let $I \in \partial$ a conjunction of literals, and $A, B \in \partial$. Then A 0-partial B iff:

1. $RNF(A \wedge I) \neq RNF(A)$
2. $RNF(A \wedge I) = RNF(B)$, if $RNF(B) \neq \perp$
   $DNF(A \wedge I) = DNF(B)$ otherwise

3. $RNF(A) \neq \bot$

The formula $I \in \partial$ may be restricted to be a conjunction of default literals, whose predicate is marked with a subscript $_d$. This gives a default relation, which is a subset of a superset of subsumption between formulae. A relation of default-satisfiability "$\models_d$" may be based upon this default relation. It is easy to demonstrate that a default-relation like this has some desired disambiguation properties: a disjunctive formula $A = A_1 \vee A_2$ is reduced to $RNF(A_1 \wedge I)$ by conjoining it with a default formula $I \in \partial$ such that $RNF(A_2 \wedge I) = \bot$.

4 WACSG formalism semantics

For any WACSG-Grammar G, a domain $D(G)$ and its subset $SDDE(G)$ of strictly derivable domain elements is defined as follows. Any domain element not in $SDDE(G)$ bears weakness relations to a derivation $\omega \in \Omega(G)$, where $\omega(0)(1) \in Sset_{ind}$. Any formula $\omega(i)(2)$ $(0 \leq i \leq |\omega)$ may be inconsistent. Now, a grammar G is called weak iff $D(G) - SDDE(G) \neq \emptyset$.

(6)

Let G be a WACSG grammar, G^k the cf base of G and ω^k the cf part of a derivation $\omega \in \Omega(G)$. Let $\mathbf{M}$ be the set of av-models.

- $D(G) = \{< w, M > \in Lex^+ \times \mathbf{M} \mid \exists \omega \in \Omega(G)$
    1. $w \in RPSL_{\omega^k}(G^k)$
    2. $M \models_d \omega(|\omega)(2)\}$
- $SDDE(G) = \{< w, M > \in Lex^+ \times \mathbf{M} \mid \exists \omega \in \Omega(G)$
    1. $w = \omega(|\omega)(1)$
    2. $M \models \omega(|\omega)(2)\}$

Default-formulae and set membership formulae cannot be simulated by anything else in WACSG formalism. For every WACSG grammar G, however, there is an equivalent WACSG grammar G' without any partial string indices within it. This grammar G' shows an extreme complexity already for a few indices in G. This fact challenges the view (see e.g. [8]) that robustness can be achieved by coverage extension of any nonweakeable ACSG.

5 A WACSG-treatment of restarts

In this section, the WACSG formalism is applied to restarts, a class of spoken language constructions, which is often referred to in robustness literature [2,3,4]. A grammatical explanation, however, is still lacking. The German restart data in 7 are given with transliteration and segmentation. Constructions in 7,8 are ungrammatical, but not inacceptable.

(7) die [Umschaltung $\mathcal{A}$ Einstellung] des Fonts
the [switching $\mathcal{A}$ adjustment]of the font
α β β' γ

(8) Peter [versuchte dann $\mathcal{A}$ konnte] kommen
Peter [tried then $\mathcal{A}$ could] come
α β β' γ

From the viewpoint of robustness theory, a restart $< \alpha\beta$ A $\beta'\gamma, M > \in D(G)$ should not be in $SDDE(G)$ exactly if it is defect, where G is a realistic WACSG fragment of the language in question. Roughly, restarts are a kind of phrasal coordination not allowing for deletion phenomena such as ellipsis, gapping or left deletion. Additionally, the β-substring (i) does not contribute to (extensional) meaning [3] of the construction and, (ii), may show recursive defectivenesses such as contamination and constituent break (examples 9,10).

(9) daß er [dieses Meinung $\mathcal{A}$ dieser Meinung] ist
that he [this-neuter opinion-fem $\mathcal{A}$ this-fem opinion-fem] has

(10) Peter ist [ins in das $\mathcal{A}$ dann Vater gewesen]
Peter is [in-the in the $\mathcal{A}$ then father been]

5.1 NP-restarts

The following WACSG rules 11-14 deal with openly coordinated NP restarts and are easily generalized to prepositional, adverbial or adjectival phrase restarts. Under the coordination hypothesis, a parallelism between defective and non-defective restarts is assumed. Right-recursive coordination of defective and nondefective conjuncts is unrestricted. In 11, equations simulating semantic *and* syntactic projections (see [18]) "control up" the syntactic but not the semantic description of a β conjunct in a restart construction.

In rules 13,14, partial string indices $_{SUBR}$ und $_{PAR}$ allow a defect conjunct to cover a prefix substring (if no phonological restart marker of category AC is present) or every substring (if there is a restart marker).

[3] However, it does contribute to meaning in an intensional sense: β-substrings are not absurd.

Rule 11 applies set weakening to the syntactic av structures of both conjuncts, resulting in a well-known coordination treatment [19]. Default equations provide disambiguation to syntactic features $[\![x_1(\text{syn})(\text{case})]\!]$ and $[\![x_1(\text{syn})(\text{gender})]\!]$, since defectivity may render the first conjunct ambiguous [4]. Furthermore, rule 15 shows default weakening of the syntactic description of NP's.

(11) NP $\longrightarrow$ NPC NP
$$\begin{array}{l} x_1(\text{syn}) \in x(\text{syn}) \wedge \\ x_1(\text{syn})(\text{gender}) \approx_d \text{ mas } \wedge \\ x_1(\text{syn})(\text{case}) \approx_d \text{ nom } \wedge \\ x_2(\text{syn}) \in x(\text{syn}) \wedge \\ [\quad x_1(\text{syn})(\text{koord})(\text{syn})(\text{defec}) \approx + \wedge \\ \quad x_2(\text{sem}) \approx x(\text{sem}) \\ \vee \; x_1(\text{syn})(\text{koord})(\text{syn})(\text{defec}) \approx - \wedge \\ \quad x(\text{sem}) \approx x_1(\text{syn})(\text{koord})(\text{sem}) \wedge \\ \quad x_2(\text{sem}) \approx x(\text{sem})(\text{arg5})] \end{array}$$

(12) NPC $\longrightarrow$ NP CO
$$\begin{array}{l} x_1(\text{syn}) \approx x(\text{syn}) \wedge \\ x_1(\text{sem}) \approx x(\text{sem})(\text{arg4}) \wedge \\ x_2 \approx x(\text{syn})(\text{koord}) \end{array}$$

(13) $NPC_{SUBR} \longrightarrow$ Det
$$\begin{array}{l} x_1 \approx x \wedge \\ x(\text{syn})(\text{koord})(\text{syn})(\text{defec}) = + \end{array}$$

(14) $NPC_{PAR} \longrightarrow$ Det AC
$$\begin{array}{l} x_1 \approx x \wedge \\ x_2 \approx x(\text{syn})(\text{koord}) \end{array}$$

(15) NP $\longrightarrow$ Det N
$$\begin{array}{l} x_1(\text{syn}) \approx_d x(\text{syn}) \wedge \\ x_1(\text{sem}) \approx x(\text{sem}) \wedge \\ x_2 \approx x \end{array}$$

Example C1 (appendix) shows a complex NP-coordination of defective and non-defective conjuncts. The conjunct NP *des Peter* shows a contaminated case feature, since *des* has genitive and *Peter* has nominative, accusative or dative morphological case marking. Nevertheless, remark that $[\![0.2.1(\text{syn})(\text{case})]\!]$ is disambiguated to nominative in the av-structure in C1.

5.2 VP-restarts

Although VP-restarts follow the same lines as NP-restarts, open coordination of defective conjuncts imposes additional problems [5]:

- Within a simulated projection theory, controlling down a verbal argument into a vcomp-embedded element of an av-set requires a complex regular term $x(\text{ syn })^+[\text{ (vcomp)(syn) }^+]^\star$, which is expensive to compute. Therefore, rules 16,18 introduce an additional term $x(\text{kosem})$, such that $[\![x(\text{kosem})]\!]$ is the semantic structure of a set $[\![x]\!]$ of openly coordinated av-structures. By default satisfiability of $x(\text{sem}) \approx_d x(\text{kosem})$, $[\![x(\text{sem})]\!]$ equals $[\![x(\text{kosem})]\!]$ except if $[\![x]\!]$ is the av set of a non-restart coordination.
- Since defectivity, e.g. a constituent break, may render incomplete the β verbal phrase incomplete, rule 17 provides semantic default values for every possible semantic argument.
- Distributed av formulae may be necessary for one conjunct but inconsistent with (the description of) the other. This situation may arise due to contamination of the first (β-) conjunct. Independently it can be shown that contaminations almost exclusively affect syntactic (as opposed to semantic) features. Now, if the conditions coherence and completeness (see [11]) are defined on semantic structure, syntactic coherence can be inforced by lexicalized formulae as shown in 19 that depend on a syntactic defectivity feature $[\![x(\text{syn})(\text{defec})]\!]$

(16) VP $\longrightarrow$ VP1 VP
$$\begin{array}{l} x_1 \in x \wedge \\ x_2 \in x \wedge \\ [\quad x_1(\text{syn})(\text{koord})(\text{syn})(\text{defec}) \approx + \wedge \\ \quad x_2(\text{sem}) \approx x(\text{kosem}) \\ \vee \; x_1(\text{syn})(\text{koord})(\text{syn})(\text{defec}) \approx - \wedge \\ \quad x(\text{kosem}) \approx x_1(\text{syn})(\text{koord})(\text{sem}) \wedge \\ \quad x_2(\text{sem}) \approx x(\text{kosem})(\text{arg5})] \end{array}$$

(17) $VP1_{PAR} \longrightarrow$ V AC
$$\begin{array}{l} x_1(\text{syn}) \approx x(\text{syn}) \wedge \\ x_1(\text{syn})(\text{defec}) \approx + \wedge \\ x(\text{sem})(y)(\text{pred}) \approx_d \text{ unfilled } \wedge \\ x_1(\text{sem})(\text{tense}) \approx_d \text{ pres } \wedge \\ x_2 \approx x(\text{syn})(\text{koord}) \end{array}$$ [6]

(18) VP $\longrightarrow$ V AC
$$\begin{array}{l} x_1 \approx x \wedge \\ x_2 \approx x \wedge \\ x(\text{sem}) \approx_d x(\text{kosem}) \end{array}$$

(19) V $\longrightarrow$ gefällt
$$\begin{array}{l} x_1 \approx x \wedge \\ [\quad x(\text{syn})(\text{defec}) \approx + \\ \vee \; x(\text{syn})(\text{defec}) \approx - \wedge \\ \quad x(\text{syn})(\text{obj}) \approx - \wedge \\ \quad x(\text{syn})(\text{vcomp}) \approx - \wedge \\ \quad x(\text{syn})(\text{acomp}) \approx -] \end{array}$$

[4] For any av-term t, $[\![t]\!]$ is the denotation of t (in the model in question).

[5] A coordination construction is called open iff there is a constituent whose av structure is distributed over the syntactic av-set assigned to this construction.

The example C2 (appendix) involves a distributed av-structure, whose description is inconsistent with respect to syntactic case subcategorization of β's finite verb *gefällt*.

6 Conclusion

The reformulation of robustness theory as a theory of weak grammars (and, consequently, of robust parsing as parsing of weak grammars) has enabled both the specification of working parsers [17] and a substantial explanation of non-grammatical language. Further study has to be done. Cross-linguistic research on defective constructions (e.g. non-grammatical ellipses) and a default logic matching methodological standards of AI theory remain important desiderata. Our prediction that there is no strong theory of defectiveness, however, invites for falsification.

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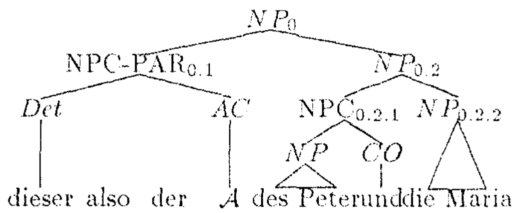
Appendix

(C1)

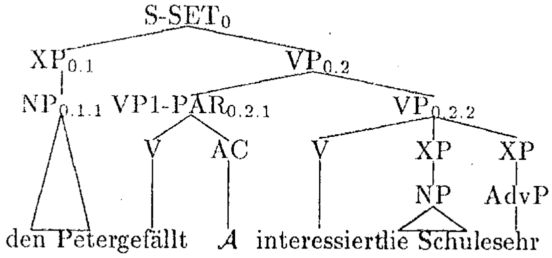
dieser also des $\mathcal{A}$ des Peter und die Maria
this therefore the-gen $\mathcal{A}$ the-gen Peter and the Mary



$$
0\begin{bmatrix}
\text{syn} & \left\{\begin{array}{l}
0.1\begin{bmatrix}\text{case} & \text{nom}\\ \text{gender} & \text{mas}\\ \text{koord} & \begin{bmatrix}\text{syn} & \begin{bmatrix}\text{defec} & +\end{bmatrix}\\ \text{sem} & [1]\end{bmatrix}\end{bmatrix}\\
\left\{\begin{array}{l}\begin{bmatrix}\text{case} & \text{nom}\\ \text{gender} & \text{mas}\end{bmatrix}\\ \begin{bmatrix}\text{case} & \text{nom/akk}\\ \text{gender} & \text{fem}\end{bmatrix}\end{array}\right\}
\end{array}\right\}\\
\text{sem} & [1]\begin{bmatrix}\text{pred} & \text{und'(arg4,arg5)}\\ \text{arg4} & \begin{bmatrix}\text{pred} & \text{peter'}\end{bmatrix}\\ \text{arg5} & \begin{bmatrix}\text{pred} & \text{maria'}\end{bmatrix}\end{bmatrix}
\end{bmatrix}
$$

(C2)

den Peter [gefällt $\mathcal{A}$ interessiert die Schule sehr]
the-akk Peter [likes (with no akk argument) $\mathcal{A}$
is-interested-in the-akk school very]



$$
0\left\{\begin{array}{l}
0.2.1\begin{bmatrix}
\text{syn} & \begin{bmatrix}
\text{defec} & +\\
\text{koord} & \text{[syn[defec+]]}\\
\text{obj} & 0.1.1\begin{bmatrix}\text{syn} & \begin{bmatrix}\text{case} & \text{akk}\\ \text{spec} & \text{def}\end{bmatrix}\\ \text{sem} & \begin{bmatrix}\text{pred} & \text{peter'}\\ \text{class} & \text{human}\end{bmatrix}\end{bmatrix}\\
\text{subj} & \begin{bmatrix}\text{syn}\ldots & \\ \text{sem} & \begin{bmatrix}\text{pred} & \text{unfilled}\end{bmatrix}\end{bmatrix}\\
\text{obj2} & \begin{bmatrix}\text{syn}\ldots & \\ \text{sem} & \begin{bmatrix}\text{pred} & \text{unfilled}\end{bmatrix}\end{bmatrix}
\end{bmatrix}\\
\text{kosem} & [3]
\end{bmatrix}\\
0.2.2\begin{bmatrix}
\text{syn} & \begin{bmatrix}
\text{defec} & -\\
\text{obj2} & -\\
\text{obj} & 0.1.1\begin{bmatrix}\text{syn} & \begin{bmatrix}\text{case} & \text{akk}\\ \text{spec} & \text{def}\end{bmatrix}\\ \text{sem} & [1]\begin{bmatrix}\text{pred} & \text{peter'}\\ \text{class} & \text{human}\end{bmatrix}\end{bmatrix}\\
\text{subj} & \begin{bmatrix}\text{syn} & \begin{bmatrix}\text{case} & \text{nom}\\ \text{gender} & \text{fem}\end{bmatrix}\\ \text{sem} & [2]\begin{bmatrix}\text{pred} & \text{schule'}\end{bmatrix}\end{bmatrix}
\end{bmatrix}\\
\text{sem} & [3]\begin{bmatrix}\text{pred} & \text{interessieren'(arg3,arg2)}\\ \text{arg3} & [1]\\ \text{arg2} & [2]\end{bmatrix}\\
\text{kosem} & [3]
\end{bmatrix}
\end{array}\right\}
$$