APPENDIX A

THE ARPABET PHONE SET

The ARPAbet phone set was developed as part of the ARPA Speech Understanding project (1971-1976), and is included with the TIMIT speech corpus [87].

Table A.1: *ARPAbet phone set [87]*

no		example	no		example	no		example
1	iy	beat	22	r	red	43	zh	measure
2	ih	bit	23	y	yet	44	sh	shoe
3	eh	bet	24	w	wet	45	v	very
4	ae	bat	25	m	mom	46	f	fief
5	ix	roses	26	em	buttom	47	dh	they
6	ax	the	27	n	non	48	th	thief
7	ah	butt	28	nx	flapped n	49	hh	hay
8	uw	boot	29	en	button	50	hv	Leheigh
9	uh	book	30	ng	sing	51	dcl	d closure
10	ao	about	31	eng	Washington	52	bcl	b closure
11	aa	cot	32	ch	church	53	gcl	g closure
12	er	bird	33	jh	judge	54	tcl	t closure
13	axr	diner	34	b	bob	55	pcl	p closure
14	ey	bait	35	p	pop	56	kcl	k closure
15	ay	bite	36	d	dad	57	q	glottal stop
16	oy	boy	37	dx	butter	58	epi	epinthetic closure
17	aw	bought	38	t	tot	59	qcl	d closure
18	ow	boat	39	g	gag	60	h#	begin silence
19	ux	beauty	40	k	kick	61	#h	end silence
20	l	led	41	z	zoo	62	pau	between silence
21	el	bottle	42	s	sis			

APPENDIX B

SOME THEOREMS REGARDING MINIMAL REPRESENTATION GRAPHS

This appendix contains a number of proofs supporting the arguments in Chapter 5.

B.1 WORD SETS

Statement 1 (context_implies_matchwords)

$$\begin{aligned} &\forall r, s \in Z', Z' \subseteq Z_{combined} : \\ &context(r) \supset context(s) \implies \\ &matchwords(r) \subseteq matchwords(s). \end{aligned} \tag{B.1}$$

Consider any word $w \in matchwords(r)$, then $match(w, r) = 1$ (eq. 5.34), and then $context(w) \supseteq context(r)$ (eq. 5.11). Now also $context(w) \supseteq context(r) \supset context(s)$, so $match(w, s) = 1$ (eq. 5.34), and then $w \in matchwords(s)$. Since this holds for all $w \in matchwords(r)$, $matchwords(r) \subseteq matchwords(s)$.

Statement 2 (subset_transitive)

$$\begin{aligned} &\forall r, s \in Z', v \in Z_e, Z_e \subseteq Z' \subseteq Z_{combined}, \forall oset(Z') \subseteq allset(Z') : \\ &path(subset(Z', Z_e, oset(Z'), v, r, s)) = 1 \implies \\ &subset(Z', Z_e, oset(Z'), v, r, s) = 1. \end{aligned} \tag{B.2}$$

If $path(subset(Z', Z_e, oset(Z'), v, r, s)) = 1$, then there exists $n \geq 2$ rules $t_1 = r, t_2, ..., t_n = s$ such that for each t_i, t_{i+1} pair it holds that $subset(Z', Z_e, oset(Z'), v, t_i, t_{i+1}) = 1$. Then $possible\_words(Z', Z_e, oset(Z'), v, t_i = r) \subset ... \subset possible\_words(Z', Z_e, oset(Z'), v, t_i) \subset possible\_words(Z', Z_e, oset(Z'), v, t_{i+1}) \subset ... \subset possible\_words(Z', Z_e, oset(Z'), v, t_n = s)$, and then $subset(Z', Z_e, oset(Z'), v, r, s) = 1$ (from eq, 5.51).

Statement 3 (possible_words_rulewords)

$$\begin{aligned} \forall r, s \in Z_e, Z_e \subseteq Z_{combined}, \forall oset(Z_e) \subseteq allset(Z_e) : \\ w \in possible\_words(Z_e, Z_e, oset(Z_e), r, r) \iff \\ w \in rulewords(Z_e, oset(Z_e), r). \end{aligned} \tag{B.3}$$

If $w \in possible\_words(Z_e, Z_e, oset(Z_e), r, r)$, then $match(w, r) = 1$ and there exists no rule $s \in Z_e$ such that $match(w, s) = 1$ and $(s, r) \in oset(Z_e)$ (eq. 5.36). Then $r \in winningrule(Z', oset(Z'), w)$ (eq. 5.12), and then $w \in rulewords(Z_e, oset(Z_e), r)$ (eq. 5.35); and vice versa.

Statement 4 (words_relations)

$$\begin{aligned} \forall r \in Z', Z_e \subseteq Z' \subseteq Z_{combined}, \forall oset(Z') \subseteq allset(Z'), \\ \forall v \in Z_e, v = r \text{ or } (v, r) \in oset(Z') : \\ rulewords(Z', oset(Z'), r) \subseteq \\ possible\_words(Z', Z_e, oset(Z'), v, r) \subseteq \\ matchwords(r). \end{aligned} \tag{B.4}$$

If $w \in rulewords(Z', oset(Z'), r)$, then $match(w, r) = 1$ and there exists no $s \in Z'$ such that $match(w, s) = 1$ and $(s, r) \in oset(Z')$ (eq. 5.35 and eq. 5.12). Then, since $Z_e \subseteq Z'$, there also exists no such $s \in Z_e$, and then $w \in possible\_words(Z', Z_e, oset(Z'), v, r)$ with $v = r$ the only valid value for v (eq. 5.36). For any w' in $possible\_words(Z', Z_e, oset(Z'), v, r)$ it also holds by definition that $match(w', r) = 1$ (eq. 5.36), so w' in $matchwords(r)$ (eq. 5.34).

Statement 5 (complement_directpath)

$$\begin{aligned} \forall r, s \in Z', Z_e \subseteq Z' \subseteq Z_{combined}, \\ \forall oset(Z') \subseteq allset(Z') : \\ complement(Z', Z_e, oset(Z'), r, s) = 1 \implies \\ mincomp(Z', Z_e, oset(Z'), r, s)) = 1 \\ \text{or } path(containpat(Z', r, s)) = \pm 1. \end{aligned} \tag{B.5}$$

Let $r, s \in Z'$ be any two rules such that $complement(Z', Z_e, oset(Z'), r, s) = 1$; and consider all the options for a $containpat$ path between r and s. If $path(containpat(Z', r, s)) = \pm 1$ the statement holds. If neither $path(containpat(Z', r, s)) = 1$ nor $path(containpat(Z', r, s)) = -1$, then, since $complement(Z', Z_e, oset(Z'), r, s) = 1$, it follows that $mincomp(Z', Z_e, oset(Z'), r, s) = 1$ by definition (eq. 5.49).

Statement 6 (rulewords_sub_rulewords)

$$\begin{aligned} \forall r \in Z', Z' \subseteq Z_{combined}, \\ \forall oset(Z') \subseteq oset'(Z') \subseteq allset(Z') : \\ rulewords(Z', oset'(Z'), r) \subseteq rulewords(Z', oset(Z'), r). \end{aligned} \tag{B.6}$$

Let w be any word such that $w \in rulewords(Z', oset'(Z'), r)$. By definition (eq 5.35 and eq. 5.12) it follows that $match(w, r) = 1$ and there exists no s such that $match(w, s) = 1$ and $(s, r) \in oset'(Z')$. Now $oset(Z') \subseteq oset'(Z')$, which means that $oset(Z')$ has fewer restrictions than $oset'(Z')$ and if $(s, r) \notin oset'(Z')$ for an s as above, then also $(s, r) \notin oset(Z')$, and then $w \in rulewords(Z', oset(Z'), r)$. Since this holds for any $w \in rulewords(Z', oset'(Z'), r)$, $rulewords(Z', oset'(Z'), r) \subseteq rulewords(Z', oset(Z'), r)$.

Statement 7 (rulewords_redundant)

$$\begin{aligned} \forall r \in Z', Z' \subseteq Z_{combined}, \forall oset'(Z') \subseteq allset(Z') : \\ \exists oset(Z') \subseteq oset'(Z') : rulewords(Z', oset(Z'), r) = \phi \iff \\ \text{r is a redundant rule in } Z', oset'(Z'). \end{aligned} \tag{B.7}$$

For any $oset'(Z') \supseteq oset(Z')$, it follows directly from statement 6 that if $rulewords(Z', oset(Z'), r) = \phi$ also $rulewords(Z', oset'(Z'), r) = \phi$ (since $rulewords(Z', oset'(Z'), r) \subseteq rulewords(Z', oset'(Z'), r)$). In all orderings that include $oset(Z')$, rule r will never be invoked to predict a word. Also, if r is a redundant rule in $oset'(Z')$ then $rulewords(Z', oset'(Z'), r) = \phi$. For at least $oset(Z') = oset'(Z')$, but possibly also for other sets of orderings, it then holds that $rulewords(Z', oset(Z'), r) = \phi$.

B.2 CHARACTERISTICS OF Z_M

Statement 8 (possibly_minimal_single)

$$\forall r \in Z_m, Z_m \subseteq Z_{combined}: \\ possibly\_minimal(Z_m) = 1 \implies r \in Z_{single} \tag{B.8}$$

Consider any $r \in Z_m \subseteq Z_{combined}$. Then $r \in Z_{conflict-resolved} \cup Z_{no-conflict} \cup Z_{conflict-combined}$ (eq. 5.21). Since $possibly\_minimal(Z_m) = 1$, there exists an ordering $oset(Z_m)$ such that $minimal(Z_m, oset(Z_m)) = 1$ (eq. 5.26). According to this ordering, rule r will be invoked by at least one word w in TD, otherwise r would be a redundant rule in a $minimal$ rule set, which is impossible. If $r \in Z_{conflict-combined}$, r would predict w with at least two different outcomes depending on which of the specific alternative outcomes are selected (eq. 5.19). Since this is not possible in an $accurate$ set of rule orderings, $minimal(Z_m, oset(Z_m)) \neq 1$, and then it is not possible to find the required $oset(Z_m)$, and Z_m cannot be a $possibly\_minimal$ rule set. For $possibly\_minimal(Z_m) = 1$ to hold, $r \notin Z_{conflict-combined}$, and then $r \in Z_{conflict-resolved} \cup Z_{no-conflict}$, which is the same as stating that $r \in Z_{single}$ (eq. 5.22). Note that any $possibly\_minimal$ rule set Z_m can therefore be assumed to be a subset of Z_{single}.

Statement 9 (rulewords_eq_invalid)

$$\forall r, s \in Z_m, Z_m \subseteq Z_{single}, possibly\_minimal(Z_m) = 1, \\ \forall oset(Z_m) \subseteq allset(Z_m): valid(oset(Z_m)) = 1 \implies \\ rulewords(Z_m, oset(Z_m), r) \neq rulewords(Z_m, oset(Z_m), s). \tag{B.9}$$

Consider any rules r and s ordered according to the $valid$ ordering $oset(Z_m)$, and let $oset'(Z_m)$ be the final ordering used during word prediction, where $oset'(Z_m) \supseteq oset(Z_m)$. Irrespective of whether there is a $rule\_order(.)$ relation between rules r and s or not, or the existence of any additional rules; in the final rule numbering assignment based on $oset'(Z_m)$, either $rulenum(r) < rulenum(s)$ or $rulenum(s) < rulenum(r)$. Choose r to be the rule such that $rulenum(r) < rulenum(s)$, and let $rulewords(Z_m, oset(Z_m), r) = rulewords(Z_m, oset(Z_m), s)$. Let w be any word pattern in TD such that $w \in rulewords(Z_m, oset'(Z_m), s)$. At least one such a word pattern must exist, otherwise (from statement 7) s is a redundant rule in a $possibly\_minimal$ rule set. Since, from statement 6, $rulewords(Z_m, oset'(Z_m), s) \subseteq rulewords(Z_m, oset(Z_m), s) = rulewords(Z_m, oset(Z_m), r)$, it follows that $match(w, r) = 1 = match(w, s)$ (eq. 5.35). For any additional t such that $match(w, t) = 1$, one of the following situations can occur: (1) no such t exists, (2) $(t, r) \notin oset'(Z_m), (t, s) \notin oset'(Z_m)$, (3) $\{(t, r), (t, s)\} \in oset'(Z_m)$, (4) $(t, r) \in oset'(Z_m)), (t, s) \notin oset(Z_m)$, or (5) $(t, r) \notin oset(Z_m), (t, s) \in oset(Z_m)$. If (1) or (2) occurs, then $w \in rulewords(Z_m, oset'(Z_m), r)$ and $w \in rulewords(Z_m, oset'(Z_m), s)$ (eq.

5.35), but since $rulenum(r) < rulenum(s)$, rule s will never be invoked to predict word pattern w. If (3) occurs, then rule t will always be invoked to predict word pattern w, and neither rule r or s will be invoked for this purpose. If (4) occurs, then either t or s can be invoked, but since $rulenum(t) < rulenum(r) < rulenum(s)$ only t will be invoked. If (5) occurs, either rule t or r can be invoked, but again rule s will not be invoked to predict word pattern w. Rule s will therefore never be invoked to predict word pattern w, irrespective of the option that occurs. Since this holds for all $w \in rulewords(Z_m, oset'(Z_m), s)$, rule s is a redundant rule in a $possibly\_minimal$ rule set, so $valid(oset'(Z_m)) \neq 1$. But $oset'(Z_m)$ was not restricted in any other way than by requiring that $oset'(Z_m) \supseteq oset(Z_m)$ where $rulewords(Z_m, oset(Z_m), r) = rulewords(Z_m, oset(Z_m), s)$. It is therefore not possible that $rulewords(Z_m, oset(Z_m), r) = rulewords(Z_m, oset(Z_m), s)$. If $rulewords(Z_m, oset(Z_m), r) \neq rulewords(Z_m, oset(Z_m), s)$ then it is possible that a word $w' \in rulewords(Z_m, oset(Z_m), s)$ exists such that $match(w', s) = 1, match(w', r) \neq 1$, and that s can be invoked to predict w' irrespective of whether $rulenum(r) < rulenum(s)$; and a similar contradiction does not occur. Exactly the same argument holds if s is chosen to be the rule such that $rulenum(s) < rulenum(r)$.

Statement 10 (poswords_redundant)

$$\begin{aligned}\forall r, s \in Z_m, r \neq s, Z_m \subseteq Z_{combined}, \forall oset(Z_m) \subseteq allset(Z_m) :\\ minimal(Z_m, oset_m(Z_m)) = 1 \implies\\ \forall s \in Z_m : possible\_words(Z_m, Z_m, oset_m(Z_m), r, r) \not\equiv\\ possible\_words(Z_m, Z_m, oset_m(Z_m), r, s).\end{aligned} \tag{B.10}$$

From statement 3 and 7 it follows that if $minimal(Z_m, oset_m(Z_m)) = 1$, then $possible\_words(Z_m, Z_m, oset_m(Z_m), r, r) = rulewords(Z_m, oset_m(Z_m), r) \neq \phi$. If $(r, s) \notin oset_m(Z_m)$, then (since $r \neq s$) $possible\_words(Z_m, Z_m, oset_m(Z_m), r, s) = \phi$ (eq. 5.36), and then the statement holds. Now consider the situation if $(r, s) \in oset_m(Z_m)$: $possible\_words(Z_m, Z_m, oset_m(Z_m), r, r) \equiv possible\_words(Z_m, Z_m, oset_m(Z_m), r, s)$ implies that for each word pattern $w \in possible\_words(Z_m, Z_m, oset_m(Z_m), r, s)$ also $match(w, r) = 1$. Then, if $(r, s) \in oset_m(Z_m)$, $possible\_words(Z_m, Z_m, oset_m(Z_m), s, s) = \phi$ (eq. 5.36). But then $rulewords(Z_m, oset_m(Z_m), s) = \phi$ (statement 3) and then s becomes a redundant rule (statement 7), which is impossible since $s \in Z_m$. Then $possible\_words(Z_m, Z_m, oset_m(Z_m), r, r) \not\equiv possible\_words(Z_m, Z_m, oset_m(Z_m), r, s)$, and the statement again holds.

B.3 Z_M AS A SUBSET OF $Z_{COMBINED}$

Statement 11 (poswords_sub_poswords)

$$\begin{aligned}
\forall r \in Z_B, v \in Z_b, \forall Z_a \subseteq Z_b \subseteq Z_B \subseteq Z_A \subseteq Z_{combined}, \\
\forall oset_A(Z_A) \subseteq allset(Z_A), \forall oset_B(Z_B) \subseteq allset(Z_B), \\
order_subset(oset_A(Z_A), oset_B(Z_B)) = 1 : \\
possible_words(Z_B, Z_b, oset_B(Z_B), v, r) \subseteq \\
possible_words(Z_A, Z_a, oset_A(Z_A), v, r).
\end{aligned} \tag{B.11}$$

Let w be any word such that $w \in possible\_words(Z_B, Z_b, oset_B(Z_B), v, r)$. By definition (eq 5.36) it follows that $match(w, r) = 1$ and that there exists no $s \in Z_b$ such that $match(w, s) = 1$ and $\{(s, r), (s, v)\} \in oset_B(Z_B)$. Now $order\_subset(oset_A(Z_A), oset_B(Z_B)) = 1$, which means that $oset_A(Z_A)$ has fewer restrictions than $oset_B(Z_B)$ and, if for no such matching $s \in Z_b$ it holds that $(s, r) \in oset_B(Z_B)$, there also exists no such $s \in Z_b$ such that $\{(s, r), (s, v)\} \in oset_A(Z_A)$ (eq. 5.27). And since $Z_a \subseteq Z_b$, there also exists no such $s \in Z_a$, and then $w \in possible\_words(Z_A, Z_a, oset_A(Z_A), v, r)$ (eq. 5.36). Since this holds for all w in $possible\_words(Z_B, Z_b, oset_B(Z_B), v, r)$, it follows that $possible\_words(Z_B, Z_b, oset_B(Z_B), v, r) \subseteq possible\_words(Z_A, Z_a, oset_A(Z_A), v, r)$.

Statement 12 (sharedwords_sub_sharedwords)

$$\begin{aligned}
\forall r \in Z_B, v \in Z_b, \forall Z_a \subseteq Z_b \subseteq Z_B \subseteq Z_A \subseteq Z_{combined}, \\
\forall oset_A(Z_A) \subseteq allset(Z_A), \forall oset_B(Z_B) \subseteq allset(Z_B), \\
order_subset(oset_A(Z_A), oset_B(Z_B)) = 1 : \\
shared_words(Z_B, Z_b, oset_B(Z_B), v, r, s) \subseteq \\
shared_words(Z_A, Z_a, oset_A(Z_A), v, r, s).
\end{aligned} \tag{B.12}$$

Let w be any word pattern such that $w \in shared\_words(Z_B, Z_b, oset_B(Z_B), v, r, s)$. Then $w \in possible\_words(Z_B, Z_b, oset_B(Z_B), v, r)$ and $w \in possible\_words(Z_B, Z_b, oset_B(Z_B), v, s)$ (eq. 5.42). Since $order\_subset(oset_A(Z_A), oset_B(Z_B)) = 1$, it follows from statement 11 that also $w \in possible\_words(Z_A, Z_a, oset_A(Z_A), v, r)$ and $w \in possible\_words(Z_A, Z_a, oset_A(Z_A), v, s)$, and then $w \in shared\_words(Z_A, Z_a, oset_A(Z_A), v, r, s)$ (eq. 5.42). As this holds for all $w \in shared\_words(Z_B, Z_b, oset_B(Z_B), v, r, s)$, $shared\_words(Z_B, Z_b, oset_B(Z_B), v, r, s) \subseteq shared\_words(Z_A, Z_a, oset_A(Z_A), v, r, s)$.

Statement 13 (poswords_sub_poswords_later_v)

$$\begin{aligned}\forall r \in Z', Z_a \subseteq Z_b \subseteq Z' \subseteq Z_{combined}, \forall oset(Z') \subseteq allset(Z'),\\ \forall v \in Z_a, v = r \text{ or } (v,r) \in oset(Z'),\\ \forall t \in Z_b, t = v \text{ or } \{(v,t),(t,r)\} \in oset'(Z'):\\ possible\_words(Z', Z_b, oset(Z'), t, r) \subseteq\\ possible\_words(Z', Z_a, oset(Z'), v, r).\end{aligned} \tag{B.13}$$

Consider any word pattern $w \in possible\_words(Z', Z_b, oset(Z'), t, r)$. Then $match(w,r) = 1$ and there exists no $q \in Z_b$ such that $match(w,q) = 1$ and $q = t$ or $(q,t) \in oset(Z')$. Since $t = v$ or $(v,t) \in oset(Z')$, there therefore also exists no such matching $q \in Z_b$ such that $q = v$ or $(q,v) \in oset(Z')$. Since $Z_a \subseteq Z_b$, there also exists no such $q \in Z_a$. By definition then $w \in possible\_words(Z', Z_a, oset(Z'), v, r)$ (eq. 5.36). Since this holds for all word patterns $w \in possible\_words(Z', Z_b, oset(Z'), t, r)$, it follows that $possible\_words(Z', Z_a, oset(Z'), t, r) \subseteq possible\_words(Z', Z_b, oset'(Z'), v, r)$.

Statement 14 (poswords_sub_poswords_later_all)

$$\begin{aligned}\forall r \in Z_B, v \in Z_b, \forall Z_a \subseteq Z_b \subseteq Z_B \subseteq Z_A \subseteq Z_{combined},\\ \forall oset_A(Z_A) \subseteq allset(Z_A), \forall oset_B(Z_B) \subseteq allset(Z_B),\\ order\_subset(oset_A(Z_A), oset_B(Z_B)) = 1,\\ \forall v \in Z_a, v = r \text{ or } (v,r) \in oset(Z'),\\ \forall t \in Z_b, t = v \text{ or } \{(v,t),(t,r)\} \in oset'(Z'):\\ possible\_words(Z_B, Z_b, oset_B(Z_B), t, r) \subseteq\\ possible\_words(Z_A, Z_a, oset_A(Z_A), v, r).\end{aligned} \tag{B.14}$$

Since $possible\_words(Z_B, Z_b, oset_B(Z_B), t, r) \subseteq possible\_words(Z_A, Z_a, oset_A(Z_A), t, r)$ (statement 11), and $possible\_words(Z_A, Z_a, oset_A(Z_A), t, r) \subseteq possible\_words(Z_A, Z_a, oset_A(Z_A), v, r)$ (statement 13, choosing $Z_a \equiv Z_b$), it follows that $possible\_words(Z_B, Z_b, oset_B(Z_B), t, r) \subseteq possible\_words(Z_A, Z_a, oset_A(Z_A), v, r)$.

Statement 15 (relations_superset_minset)

$$\forall r, s, v \in Z_m, Z_e \subseteq Z_m \subseteq Z' \subseteq Z_{combined},$$
$$\forall oset(Z') \subseteq allset(Z'), oset_m(Z_m) \subseteq allset(Z_m),$$
$$allowed\_state(Z', Z_e, oset(Z')) = 1$$
$$\forall (Z_m, oset_m(Z_m)) \in minrules(Z', Z_e, oset(Z')) :$$
$$containpat(Z', r, s) = 1 \implies containpat(Z_m, r, s) = 1. \quad (B.15)$$
$$containpat(Z', r, s) = -1 \implies containpat(Z_m, r, s) = -1. \quad (B.16)$$
$$path(containpat(Z_m, r, s)) = 1 \iff path(containpat(Z', r, s)) = 1. \quad (B.17)$$
$$complement(Z_m, Z_m, oset(Z_m), v, r, s) = 1 \implies$$
$$complement(Z', Z_e, oset(Z'), v, r, s) = 1. \quad (B.18)$$
$$mincomp(Z_m, Z_m, oset(Z_m), v, r, s) = 1 \implies$$
$$mincomp(Z', Z_e, oset(Z'), v, r, s) = 1. \quad (B.19)$$

Consider each relationship separately, and note that this relates specifically to $r, s, v \in Z_m$:

- Eq. B.15: If $containpat(Z', r, s) = 1$, then $context(r) \supset context(s)$ and no $t \in Z'$ exists such that $context(r) \supset context(t) \supset context(s)$ (eq. 5.47). Since $Z_e \subseteq Z_m \subseteq Z'$, no such t can exist in Z_m either, and then $containpat(Z_m, r, s) = 1$.

- Eq. B.16: If $containpat(Z', r, s) = -1$, then $containpat(Z', s, r) = 1$. Then $containpat(Z_m, s, r) = 1$ (from eq. B.15), and then $containpat(Z_m, r, s) = -1$.

- Eq. B.17: If $path(containpat(Z_m, r, s)) = 1$, then $context(r) \supset context(s)$ (eq. 5.48) and then $path(containpat(Z', r, s)) = 1$; and vice versa.

- Eq. B.18: If $complement(Z_m, Z_m, oset(Z_m), v, r, s) = 1$ then there exists a rule $v \in Z_m$ and word w such that $w \in shared\_words(Z_m, Z_m, oset(Z_m), v, r, s)$ (eq 5.43). Since $order\_subset(oset(Z'), oset(Z_m)) = 1$ and $Z_e \subseteq Z_m \subseteq Z'$ by definition (eq. 5.29), it follows from statement 12 that also $w \in shared\_words(Z', Z_e, oset(Z'), v, r, s)$, and then $complement(Z', Z_e, oset(Z'), v, r, s) = 1$ (eq 5.43).

- Eq. B.19: If $mincomp(Z_m, Z_m, oset(Z_m), v, r, s) = 1$ then $complement(Z_m, Z_m, oset(Z_m), v, r, s) = 1$ and $path(containpat(Z_m, r, s)) = 0$ (eq. 5.49). Then also $complement(Z', Z_e, oset(Z'), v, r, s) = 1$ (eq. B.18) and $path(containpat(Z', r, s)) = 0$ (eq. B.17), and then $mincomp(Z', Z_e, oset(Z'), r, s) = 1$.

B.4 RULE ORDERING IN Z_M

Statement 16 (red_implies_acc)

$$\begin{aligned} \forall r, s \in Z_m, Z_m \subseteq Z_{combined}, possibly\_minimal(Z_m) = 1, \\ \forall oset(Z_m) \subseteq allset(Z_m), valid(oset(Z_m)) = 1 : \\ order_{red}(Z_m, oset(Z_m), r, s) = 1 \implies order_{acc}(Z_m, oset(Z_m), r, s) = 1. \end{aligned} \tag{B.20}$$

If $order_{red}(Z_m, oset(Z_m), r, s) = 1$ then requiring s to occur before r causes some rule t to become redundant given any state $(Z_m, Z_m, oset'(Z_m))$, where $oset'(Z_m) \supseteq oset(Z_m) \cup (s, r)$ (eq. 5.55). If it were possible that for any such $oset'(Z_m)$ it could hold that $accurate(Z_m, oset'(Z_m)) = 1$, then rule t could be removed from the rule set and the new rule set would still be accurate. However, then the new rule set would have fewer rules than Z_m, which is impossible, given that Z_m is a $possibly\_minimal$ rule set (eq. 5.26 and eq. 5.25). This means that if both r and s are in Z_m and $order_{red}(Z_m, oset(Z_m), r, s) = 1$, then also $order_{acc}(Z_m, oset(Z_m), r, s) = 1$.

Statement 17 (order_implies_acc)

$$\begin{aligned} \forall r, s \in Z_m, Z_m \subseteq Z_{combined}, possibly\_minimal(Z_m) = 1, \\ \forall oset(Z_m) \subseteq allset(Z_m), valid(oset(Z_m)) = 1 : \\ order(Z_m, oset(Z_m), r, s) = 1 \implies order_{acc}(Z_m, oset(Z_m), r, s) = 1. \end{aligned} \tag{B.21}$$

This follows directly from statement 16 and eq. 5.56.

Statement 18 (direct_order_implies_complement)

$$\begin{aligned} \forall r, s \in Z_m, Z_m, \subseteq Z_{combined}, possibly\_minimal(Z_m) = 1, \\ \forall oset(Z_m) \subseteq allset(Z_m), valid(oset(Z_m)) = 1 : \\ direct\_order(Z_m, oset(Z_m), r, s)) = 1 \implies \\ \forall v \in Z_m, (v, r), (v, s) \in oset(Z_m) : complement(Z_m, Z_m, oset(Z_m), v, r, s) = 1. \end{aligned} \tag{B.22}$$

Since Z_m is a $possibly\_minimal$ rule set, $order(Z_m, oset(Z_m), r, s) = 1$ implies that $order_{acc}(Z_m, oset(Z_m), r, s) = 1$ (statement 17). The accuracy ordering between any two rules r and s can be caused in two ways: (1) A direct ordering requirement arises from one or more word patterns that each create the need for such an ordering independently. (2) An indirect ordering requirement is caused by a set of word patterns in TD predicted one after the other, each prediction an independent event. Such a set of word patterns may require rule r to occur earlier than another rule v, and again require rule v to to occur earlier than rule s, creating an indirect ordering requirement from rule r to rule s. If $direct\_order(Z_m,\ oset'(Z_m), r, s) = 1$, then by definition there exists no rule t such that $order(Z_m, oset'(Z_m), r, t) = 1$ and $order(Z_m, oset'(Z_m), t, s) = 1$, even though $order(Z_m, oset'(Z_m), r, s) = 1$. It therefore follows that the ordering between r and s is a direct ordering (as in (1) above) caused by at least one (single) word pattern w. Such a word pattern w will be predicted incorrectly if $rulenum(s) < rulenum(r)$ (since $order_{acc}(Z_m, oset(Z_m), r, s) = 1$) and predicted correctly for at least one ordering which requires that $rulenum(r) < rulenum(s)$ (since $valid(oset(Z_m)) = 1$). This is only possible if the word pattern w is predicted accurately by rule r and incorrectly by rule s. Then $match(w, r) = 1$ and $match(w, s) = 1$, and no $v \in Z_m$ exists earlier in the rule set than r such that $match(w, v) = 1$. Since such a w exists, it follows that $complement(Z_m, Z_m, oset(Z_m), v, r, s) = 1$ for all v such that $\{(v, r), (v, s)\} \in oset(Z_m)$.

Statement 19 (order_complement_order)

$$\begin{aligned} &\forall r, s \in Z_m, Z_m \subseteq Z_{single}, possibly\_minimal(Z_m) = 1, \\ &\forall oset(Z_m) \subseteq allset(Z_m) : \\ &order_{acc}(Z_m, Z_m, oset(Z_m), r, s) = 1 \implies \forall v : \{(v, r), (v, s)\} \in oset(Z_m) : \\ &path(complement\&direct\_order(Z_m, Z_m, oset(Z_m), v, r, s)) = 1. \end{aligned} \tag{B.23}$$

If $order_{acc}(Z_m, oset(Z_m), r, s) = 1$ then by definition, $order(Z_m, oset(Z_m), r, s) = 1$ (eq. 5.56) and $path(direct\_order(Z_m, oset(Z_m), r, s)) = 1$ (eq. 5.57). Now consider any rules t_i, t_{i+1} along the path from r to s. Since for each t_i, t_{i+1} pair it holds that $direct\_order(Z_m, oset(Z_m), t_i, t_{i+1}) = 1$, it follows from statement 18 that $complement(Z_m, oset(Z_m), v, t_i, t_{i+1}) = 1$ for a valid v. Since this holds for all t_i along this path, it follows that $path(complement\&direct\_order(Z_m, Z_m, oset(Z_m), v, r, s)) = 1$.

Statement 20 (subset_implies_red_min)

$$\begin{aligned} &\forall r, s, v \in Z_m, Z_m \subseteq Z_{single}, possibly\_minimal(Z_m) = 1, \\ &\forall oset(Z_m) \subseteq allset(Z_m), \\ &subset(Z_m, oset(Z_m), r, r, s) = 1 \implies \\ &order_{red}(Z_m, oset(Z_m), r, s) = 1. \end{aligned} \tag{B.24}$$

If $subset(Z_m, oset(Z_m), r, r, s) = 1$ it follows by definition that $possible\_words(Z_m, Z_m, oset(Z_m), r, r) \subset possible\_words(Z_m, Z_m, oset(Z_m), r, s)$ (eq. 5.51), and then it will hold for any word pattern $w \in possible\_words(Z_m, Z_m, oset(Z_m), r, r)$ that also $match(w, s) = 1$ (eq. 5.36). Since $possible\_words(Z_m, Z_m, oset(Z_m), r, r) = rulewords(Z_m, oset(Z_m), r)$ (statement 3), this set provides a list of all the words in TD that may possibly invoke rule r during pronunciation prediction (eq. 5.35). It therefore follows that, if s occurred before r, all words that could possibly match r would first be matched against s and r would never be invoked. Rule r will then be a redundant rule within a $possibly\_minimal$ rule set, which contradicts the definition of a $possibly\_minimal$ rule set. Since rule r becomes redundant if rule s occurs before rule r when enforcing all the restrictions required by $oset(Z_m)$, it follows that $order_{red}(Z_m, oset(Z_m), r, s) = 1$ (eq. 5.55).

Statement 21 (subset_implies_red)

$$\begin{aligned}\forall r, s \in Z_m, v \in Z_e, Z_e \subseteq Z_m \subseteq Z' \subseteq Z_{combined}, \forall oset(Z') \subseteq allset(Z'),\\ \forall (Z_m, oset_m(Z_m) \in minrules(Z', Z_e, oset(Z')) :\\ subset(Z', Z_e, oset(Z'), v, r, s) = 1 \implies\\ order_{red}(Z_m, oset(Z_m), r, s) = 1.\end{aligned} \tag{B.25}$$

Choose any $v \in Z_e$ and $r, s \in Z_m$ such that $subset(Z', Z_e, oset(Z'), v, r, s) = 1$. Then $v = r$ or $\{(v, r), (v, s)\} \in oset(Z')$ and $possible\_words(Z', Z_e, oset(Z'), v, r) \subset possible\_words(Z', Z_e, oset(Z'), v, s)$ (eq. 5.51). Now consider any word pattern $w \in possible\_words(Z_m, Z_m, oset(Z_m), r, r)$. Since $order\_subset(oset(Z'), oset_m(Z_m)) = 1$ and $Z_e \subseteq Z_m$ (eq. 5.29) it follows from statement 14 that also $w \in possible\_words(Z', Z_e, oset(Z'), v, r)$. Since $possible\_words(Z', Z_e, oset(Z'), v, r) \subset possible\_words(Z', Z_e, oset(Z'), v, s)$ (as given above), it follows that also $w \in possible\_words(Z', Z_e, oset(Z'), v, s)$. This implies that $match(w, s) = 1$ and no $q \in Z_e$ exists such that $match(w, q) = 1$ and $q = v$ or $(q, v) \in oset(Z')$. Now since $v = r$ or $\{(v, r), (v, s)\} \in oset(Z')$ this means no such matching $q \in Z_e$ exists such that $q = r$ or $\{(q, r), (q, s)\} \in oset(Z')$. Then no $q \in Z_m$ exists such that $q = r$ or $\{(q, r), (q, s)\} \in oset_m(Z_m)$ (since $Z_e \subseteq Z_m$ and $order\_subset(oset(Z'), oset_m(Z_m)) = 1$), and then $w \in possible\_words(Z_m, Z_m, oset_m(Z_m), r, s)$. Since this holds for all $w \in possible\_words(Z_m, Z_m, oset(Z_m), r, r)$, it follows that $possible\_words(Z_m, Z_m, oset_m(Z_m), r, r) \subseteq possible\_words(Z_m, Z_m, oset_m(Z_m), r, s)$. But from statement 10 it is not possible that $possible\_words(Z_m, Z_m, oset_m(Z_m), r, r) \equiv possible\_words(Z_m, Z_m, oset_m(Z_m), r, s)$, so $possible\_words(Z_m, Z_m, oset_m(Z_m), r, r) \subset possible\_words(Z_m, Z_m, oset_m(Z_m), r, s)$, and then $subset(Z_m, Z_m, oset_m(Z_m), r, r, s) = 1$ (eq. 5.51). Then it follows from statement 20 that $order_{red}(Z_m, oset(Z_m), r, s) = 1$.

Statement 22 (containpat_implies_order_min)

$$\begin{aligned}\forall r, s \in Z_m, Z_m \subseteq Z_{combined}, possibly\_minimal(Z_m) = 1, valid(oset(Z_m)) = 1\\ path(containpat(Z_m, r, s)) = 1 \implies order_{red}(Z_m, oset(Z_m), r, s) = 1.\end{aligned} \tag{B.26}$$

If $path(containpat(Z_m, r, s)) = 1$ then $context(r) \supset context(s)$ (eq. 5.47) and then $matchwords(r) \subseteq matchwords(s)$ (statement 1). Let $oset'(Z_m)$ be any ordering that includes $(s, r) \cup oset(Z_m)$. Then for every word pattern w such that $match(w, r) = 1$ also $match(w, s) = 1$, and since $(s, r) \in oset'(Z_m)$ and both s and r in Z_m, $possible\_words(Z_m, Z_m, oset'(Z_m), s, r) = \phi$

(eq. 5.36). Since $rulewords(Z_m, oset'(Z_m), r) \subseteq possible\_words(Z_m, Z_m, oset'(Z_m), s, r)$ (statement 4) also $rulewords(Z_m, oset'(Z_m), r) = \phi$, which means that r has become a redundant rule (statement 7). Since this holds for any $oset'(Z_m) \supseteq oset(Z_m) \cup (s, r)$ it follows that $order_{red}(Z_m, oset(Z_m), r, s) = 1$ (eq. 5.55).

B.5 RULE ORDERING IN Z_M AS A SUBSET OF $Z_{COMBINED}$

Statement 23 (path_order_min)

$$\begin{aligned}
&\forall r, s \in Z_m, Z_e \subseteq Z_m \subseteq Z' \subseteq Z_{combined},\\
&\forall oset(Z') \subseteq allset(Z'), allowed_state(Z', Z_e, oset(Z')) = 1,\\
&\forall (Z_m, oset_m(Z_m) \in minrules(Z', Z_e, oset(Z')) :\\
&containpat/supercomp/rule_order(Z', Z_e, oset(Z'), r, s) = 1 \implies\\
&(r, s) \in oset_m(Z_m).
\end{aligned} \tag{B.27}$$

Choose any $r, s \in Z_m$:

- If $rule\_order(Z', Z_e, oset(Z'), r, s) = 1$, then $(r, s) \in oset(Z')$ (eq. 5.7). Since $allowed\_state(Z', Z_e, oset(Z')) = 1$, $order\_subset(oset(Z'), oset_m(Z_m)) = 1$ (eq. 5.29) and then $(r, s) \in oset_m(Z_m)$.
- If $supercomp(Z', Z_e, oset(Z'), r, s) = 1$, then $subset(Z', Z_e, oset(Z'), r, s) = 1$ by definition (eq. 5.52) and then, from statement 21 it follows that $order_{red}(Z_m, oset_m(Z_m), r, s) = 1$, and again $(r, s) \in oset_m(Z_m)$.
- If $containpat(Z', r, s) = 1$ then $containpat(Z_m, r, s) = 1$ (eq. B.15) and then it follows from statement 22 that $order_{red}(Z_m, oset_m(Z_m), r, s) = 1$. Again $(r, s) \in oset_m(Z_m)$.

Statement 24 (order_not_order)

$$\begin{aligned}
&\forall r, s \in Z', Z_e \subseteq Z' \subseteq Z_{combined},\\
&\forall oset(Z') \subseteq allset(Z'), allowed_state(Z', Z_e, oset(Z')) = 1 :\\
&order(Z', Z_e, oset(Z'), r, s) = 1 \implies order(Z', Z_e, oset(Z'), s, r) \neq 1.
\end{aligned} \tag{B.28}$$

Consider any $r, s \in Z'$ and first consider the $order_{acc}$ relation specifically. If $order_{acc}(Z', Z_e, oset(Z'), r, s) = 1$, then no $oset'(Z') \supseteq oset(Z') \cup (s, r)$ exists such that $allowed\_state(Z', Z_e, oset'(Z')) = 1$ (eq. 5.54). But since $allowed\_state(Z', Z_e, oset(Z')) = 1$, at least one $Z_m, oset_m(Z_m)$ pair exists such that $(Z_m, oset_m(Z_m)) \in minrules(Z', Z_e, oset(Z'))$ (eq. 5.29), such that $minimal(Z_m, oset_m(Z_m)) = 1$ (eq. 5.28). Clearly $(s, r) \notin oset_m(Z_m)$, which means that either (1) $(r, s) \in oset_m(Z_m)$ or (2) that the relationship between r and s is indeterminate, that is, that either $rulenum(r) < rulenum(s)$ or $rulenum(s) < rulenum(r)$ is allowed without affecting the value of $accurate(Z_m, oset_m(Z_m))$, or that (3) either or both of r and s are not in Z_m. In all the above cases, (r, s) can be added to $oset_m(Z_m)$, and it will still hold that $minimal(Z_m, oset_m(Z_m)) = 1$. Then $order_{acc}(Z', Z_e, oset(Z'), s, r) \neq 1$. The same can be shown to hold with regard to $order_{red}(Z', Z_e, oset(Z'), r, s)$ using eq. 5.55 in the same way as above, and therefore this statement also holds with regard to the $order$ relation in general.

Statement 25 (order_complement_options)

$$\begin{aligned}
&\forall r, s \in Z', Z_e \subseteq Z' \subseteq Z_{combined}, \forall oset(Z') \subseteq allset(Z) : \\
&complement\&order(Z', Z_e, oset(Z'), r, s) = 1 \implies \\
&path(containpat(Z', Z_e, oset(Z'), r, s))) = 1 \\
&\text{or } mincomp(Z', Z_e, oset(Z'), r, s) = 1.
\end{aligned} \tag{B.29}$$

If $complement\&order(Z', Z_e, oset(Z'), r, s) = 1$ then both $complement(Z', Z_e, oset(Z'), r, s) = 1$ and $order(Z', Z_e, oset(Z'), r, s) = 1$ (eq. 5.44). Since $complement(Z', Z_e, oset(Z'), r, s) = 1$ it follows from statement 5 that either $mincomp(Z', Z_e, oset(Z'), r, s)) = 1$ or that $path(containpat(Z', r, s)) = \pm 1$. However, if $path(containpat(Z', r, s)) = -1$, then $path(containpat(Z', s, r)) = 1$ (eq. 5.47 and eq. 5.44) and then $order_{red}(Z', Z_e, oset(Z'), s, r) = 1$ (statement 22). Since it is not possible that both $order(Z', Z_e, oset(Z'), s, r) = 1$ and $order(Z', Z_e, oset(Z'), r, s) = 1$ (statement 24), it is therefore impossible that $path(containpat(Z', r, s)) = -1$. So either $mincomp(Z', Z_e, oset(Z'), r, s)) = 1$ or $path(containpat(Z', r, s)) = 1$.

Statement 26 (oreq_implies_acc)

$$\begin{aligned}
&\forall r, s \in Z', Z_e \subseteq Z' \subseteq Z_{combined}, \\
&\forall oset(Z') \subseteq allset(Z'), allowed_state(Z', Z_e, oset(Z')) = 1 : \\
&\exists v \in Z_e : order_req(Z', Z_e, oset(Z'), v, r, s) = 1, \\
&order_{red}(Z', Z_e, oset(Z'), r, s) = 0 \implies \\
&direct_order(Z', Z_e, oset(Z'), r, s) \neq -1.
\end{aligned} \tag{B.30}$$

If $order\_req(Z', Z_e, oset(Z'), v, r, s) = 1$, then by definition (eq. 5.58) it follows that $direct\_order(Z', Z_e, oset(Z'), r, s) = 1$, $shared\_words(Z', Z_e, oset(Z'), v, r, s) \neq \phi$, and for all $w_i \in shared\_words(Z', Z_e, oset(Z'), v, r, s)$ it holds that $outcome(w_i) = outcome(r)$. Furthermore, there exists at least one w' in $shared\_words(Z', Z_e, oset(Z'), v, r, s)$ such that $outcome(w') \notin outcome(s)$. The value of $direct\_order(Z', Z_e, oset(Z'), r, s)$ can be $0, 1$ or -1. Since $order_{red}(Z', Z_e, oset(Z'), r, s) = 0$ the value of $direct\_order(Z', Z_e, oset(Z'), r, s)$

depends on the value of $order_{acc}(Z', Z_e, oset(Z'), r, s)$, which also can be $0, 1$ or -1 (eq. 5.57). Now consider any $(Z_m, oset_m(Z_m)) \in minrules(Z', Z_e, oset(Z'))$. Since $allowed\_state(Z', Z_e, oset(Z')) = 1$, at least one such a $Z_m, oset_m(Z_m)$ pair exists. Since $shared\_words(Z_m, Z_m, oset_m(Z_m), v, r, s) \subseteq shared\_words(Z', Z_e, oset(Z'), v, r, s)$ (statement 12) it still holds that for all the $x_i \in shared\_words(Z_m, Z_m, oset_m(Z_m), v, r, s)$ $outcome(x_i) = outcome(r)$. If it were possible that $direct\_order/order_{acc}(Z', Z_e, oset(Z'), s, r) = 1$, then there would exist at least one word pattern y such that s would predict y accurately, and r would predict y incorrectly. But since for all the x_i above $outcome(x_i) = outcome(r)$, no such y can exist, and therefore $direct\_order/order_{acc}(Z', Z_e, oset(Z'), s, r) \neq 1$ which implies that $direct\_order(Z', Z_e, oset(Z'), r, s) \neq -1$.

B.6 CHARACTERISTICS OF AN ALLOWED STATE

Statement 27 (allowed_state_decided)

$$\begin{aligned} \forall Z_e \subseteq Z' \subseteq Z_{combined}, \forall oset(Z') \subseteq allset(Z'), \\ allowed\_state(Z', Z_e, oset(Z')) = 1, \\ \forall (Z_m, oset_m(Z_m)) \in minrules(Z', Z_e, oset(Z')) : \\ order\_subset(decided\_set(Z', Z_e, oset(Z')), oset_m(Z_m)) = 1. \end{aligned} \tag{B.31}$$

Choose any $(Z_m, oset_m(Z_m)) \in minrules(Z', Z_e, oset(Z'))$. Then $minimal(Z_m, oset_m(Z_m)) = 1$, $Z_e \subseteq Z_m \subseteq Z'$ and $order\_subset(oset'(Z'), oset_m(Z_m)) = 1$, by definition (eq. 5.28). Now consider any $r, s \in Z_m \cap Z'$ such that $(r, s) \in decided\_set(Z', Z_e, oset'(Z'))$. Then $r, s \in Z_m$ and $path(order\_decided(Z', Z_e, oset'(Z'), r, s)) = 1$ (eq. 5.60). From the definition of $order\_decided$, this implies that there exists a path $v_1 = r, v_2, ..., v_n = s$, all $v_i \in Z'$, such that either (1) $containpat(Z', v_i, v_{i+1}) = 1$, or (2) $supercomp(Z', Z_e, oset(Z'), v_i, v_{i+1}) = 1$ or (3) $(v_i, v_{i+1}) \in oset(Z')$. Now let t_i be only those v_j such that $v_j \in Z_m$. Then there exists a path $t_1 = r, t_2, ..., t_n = s$ such that for each t_i, $path(containpat/supercomp/rule\_order(Z', Z_e, oset(Z'), t_i, t_{i+1})) = 1$, with all $t_i \in Z_m$. From statement 23 it then follows that for each t_i, t_{i+1} pair it holds that $order(Z', Z_e, oset(Z'), t_i, t_{i+1}) = 1$, and then $(t_i, t_{i+1}) \in oset_m(Z_m)$. Since these t_i form a path from r to s, it follows that also $(r, s) \in oset_m(Z_m)$ (eq. 5.7). Since it holds for any $r, s \in Z_m \cap Z'$ that if $(r, s) \in decided\_set(Z', Z_e, oset'(Z'))$ then also $(r, s) \in oset_m(Z_m)$, it follows (from eq. 5.27) that $order\_subset(decided\_set(Z', Z_e, oset(Z')), oset_m(Z_m)) = 1$.

Statement 28 (allowed_state_possible)

$$\forall Z_e \subseteq Z' \subseteq Z_{combined}, \forall oset(Z') \subseteq allset(Z'),$$
$$allowed\_state(Z', Z_e, oset(Z')) = 1 \implies$$
$$\forall (Z_m, oset_m) \in minrules(Z', Z_e, oset(Z')) :$$
$$order\_subset(oset_m(Z_m), possible\_set(Z', Z_e, oset(Z'))) = 1. \tag{B.32}$$

Choose any $(Z_m, oset_m) \in minrules(Z', Z_e, oset(Z'))$, and any $r, s \in Z_m$ such that $(r, s) \in oset_m(Z_m)$. Since $(r, s) \in oset_m(Z_m)$, it follows that $order_{acc}(Z_m, Z_m, oset(Z_m), r, s) = 1$ (statement 17) and then $path(direct\_order\&complement(Z_m, Z_m, oset_m(Z_m), v, r, s)) = 1$ for all v such that $\{(v, r), (v, s)\} \in oset_m(Z_m)$ (statement 19). This means that a path of $n \geq 2$ rules exist with $t_1 = r, t_2, t_3, \ldots, t_n = s$, all the $t_i \in Z_m$. For each of these t_i, t_{i+1} pairs both $direct\_order(Z_m, Z_m, oset_m(Z_m), t_i, t_{i+1}) = 1$ and $complement(Z_m, Z_m, oset_m(Z_m), v, t_i, t_{i+1}) = 1$. Since $complement(Z_m, Z_m, oset_m(Z_m), v, t_i, t_{i+1}) = 1$, it follows that $complement(Z', Z_e, oset(Z'), v, t_i, t_{i+1}) = 1$ (eq. B.18), and then either (1) $path(containpat(Z', t_i, t_{i+1}) = 1$ or (2) $mincomp(Z', Z_e, oset(Z'), v, t_i, t_{i+1}) = 1$ (statement 25). In both cases $shared\_words(Z', Z_e, oset(Z'), v, t_i, t_{i+1}) \neq \phi$ (eq. 5.43).

- If (1) $path(containpat(Z', t_i, t_{i+1})) = 1$, then $path(order\_decided(Z', Z_e, oset(Z'), t_i, t_{i+1})) = 1$ (eq. 5.59), and then $(t_i, t_{i+1}) \in possible\_set(Z', Z_e, oset(Z'))$ (eq. 5.63).

- If (2) $mincomp(Z', Z_e, oset(Z'), v, t_i, t_{i+1}) = 1$ then (since $shared\_words(Z', Z_e, oset(Z'), v, t_i, t_{i+1}) \neq \phi$) it follows that the value of $order\_possible(Z', Z_e, oset(Z'), v, t_i, t_{i+1})$, depends on the values of (a) $order\_decided(Z', Z_e, oset(Z'), t_i, t_{i+1})$, and (b) $order\_possible1(Z', Z_e, oset(Z'), t_i, t_{i+1})$ (eq. 5.62).

  First consider the possible values for (a), and assume $order\_possible1(Z', Z_e, oset(Z'), t_i, t_{i+1}) \neq -1$, the least restrictive choice. If $order\_decided(Z', Z_e, oset(Z'), t_i, t_{i+1}) = 0$, then the value of $order\_possible(Z', Z_e, oset(Z'), t_i, t_{i+1}) = 1$ (eq. 5.62), and then $(t_i, t_{i+1}) \in possible\_set(Z', Z_e, oset(Z'))$. If $order\_decided(Z', Z_e, oset(Z'), t_{i+1}, t_i) = 1$, then also $(t_i, t_{i+1}) \in possible\_set(Z', Z_e, oset(Z'))$ (eq. 5.63). Since $(t_i, t_{i+1}) \in Z_m$ and $direct\_order(Z_m, Z_m, oset_m(Z_m), t_i, t_{i+1}) = 1$ it follows from statement 27 that $direct\_order(Z', Z_e, oset'(Z'), t_i, t_{i+1}) \neq -1$. For the two valid options it then holds that $(t_i, t_{i+1}) \in possible\_set(Z', Z_e, oset(Z'))$.

  Now consider the possible values for (b), and assume that $order\_decided(Z', Z_e, oset(Z'), t_i, t_{i+1}) = 0$, again the least restrictive choice. If $order\_possible1(Z', Z_e, oset(Z'), t_i, t_{i+1}) \neq -1$, then $order\_possible(Z', Z_e, oset(Z'), t_i, t_{i+1}) = 1$. If it were possible that $order\_possible1(Z', Z_e, oset(Z'), t_i, t_{i+1}) = -1$, then $order\_possible(Z', Z_e, oset(Z'), t_{i+1}, t_i) = 1$ (eq. 5.62) and then it would hold that $order\_req(Z', Z_e, oset(Z'), v, t_{i+1}, t_i) = 1$ for a valid v (eq. 5.61), and then $direct\_order(Z', Z_e, oset(Z'), t_{i+1}, t_i) \neq -1$ (statement 26), or stated differently, $direct\_order(Z', Z_e, oset(Z'), t_i, t_{i+1}) \neq 1$. But since $direct\_order(Z_m, Z_m, oset_m(Z_m), t_i, t_{i+1}) = 1$, this causes a contradiction. Then it must hold that $order\_possible1(Z', Z_e, \ oset(Z'), t_i, t_{i+1}) \neq -1$, and then $(t_i, t_{i+1}) \in possible\_set(Z', Z_e, oset(Z'))$.

Since it holds for all (t_i, t_{i+1}) along a path from r to s that $(t_i, t_{i+1}) \in possible\_set(Z', Z_e, oset(Z'))$, it follows that $(r, s) \in possible\_set(Z', Z_e, oset(Z'))$ (eq. 5.63). Since this holds for any $(r, s) \in oset_m(Z_m)$, it follows that $order\_subset(oset_m(Z_m), possible\_set(Z', Z_e, oset(Z')) = 1$ (eq. 5.27).

B.7 INITIAL ALLOWED STATE

Statement 29

$$\forall w \in TD, r, w' \in Z', w' \text{ a word pattern matching word } w, Z' \subseteq Z_{combined} :$$
$$match(w, r) = 1 \iff path(containpat(w', r)) = 1. \qquad \text{(B.33)}$$

Let w be any word pattern in $Z_{combined}$ and w' its associated word pattern in TD. If $match(w, r) = 1$, then, $context(w) \supseteq context(r)$ by definition (eq. 5.11). Given the construction of $Z_{combined}$, the only rule s that can exist such that $context(w) = context(s)$ is that s which is the word pattern w', so $context(w) = context(w') \supset context(r)$. Since $context(w') \supset context(r)$ it follows from eq. 5.48 that $path(containpat(Z', w', r)) = 1$. Similarly, if $path(containpat(Z', w', r)) = 1$, then (again from eq. 5.48) $context(w') \supset context(r)$, and then $context(w) = context(w') \supset context(r)$, and then $match(w, r) = 1$ (eq. 5.11).

Statement 30 (only_word_patterns) *If, prior to any rule resolution, all rules in $Z_{combined}$ are ordered according to the set of relationships $decided\_set(Z_{combined}, \phi, \phi)$, then predicting any word $w \in TD$ will only invoke the word pattern $w' \in Z_{no-conflict}$.*

Since $oset(Z_{combined}) = \phi$ does not contain any orderings whatsoever, it follows directly from the definition of $rulewords$ (eq. 5.35 and eq. 5.12) and $matchwords$ (eq. 5.34) that $matchwords(r) = rulewords(Z_{combined}, \phi, r)$. Let $w \in TD$ be any word to be predicted, and $w' \in Z_{combined}$ be each associated word pattern. Given the way in which $Z_{combined}$ has been constructed, w' exists for each word w, $match(w, w') = 1$, and furthermore there may exist a set of rules $\{r_i\}$ such that also $match(w', r_i) = 1$. From statement 29 it follows that for each of these r_i there exists a $path(containpat(Z_{combined}, w', r_i)) = 1$. Since $path(containpat(Z_{combined}, w', r_i)) = 1$, then also $path(order\_decided(Z_{combined}, \phi, \phi, w', r_i)) = 1$ (eq.5.59) and even if such r_i exist, none will be invoked – only w'. Since word variants are not allowed, $w' \in Z_{no-conflict}$.

Statement 31 (complete) *The set of rules $Z_{no-conflict}$ describes the training data accurately and completely.*

Consider any training word pattern w. If any sub-patterns existed in Z that matched both this word pattern and a conflicting one, it would have been removed from $Z_{no-conflict}$. Therefore, if a rule in $Z_{no-conflict}$ is applicable, it will be accurate. There are no word variants in TD; therefore, for each grapheme in each word pattern there exists at least one sub-pattern (the word pattern itself) that describes the grapheme in a way that does not conflict with any other pattern, implying that an applicable rule will always be found.

Statement 32 (initial_superpath_implies_subset)

$$\forall r, s \in Z_m, Z_m \subseteq Z' \subseteq Z_{combined}, possibly\_minimal(Z_m) = 1 :$$
$$path(containpat/supercomp(Z', \phi, \phi, v_0, r, s)) = 1 \implies$$
$$subset(Z_m, Z_m, \phi, v_0, r, s) = 1. \quad \text{(B.34)}$$

Consider any $w \in possible\_words(Z', \phi, \phi, v_0, r)$, $Z_m \subseteq Z'$. Since ϕ contains no orderings whatsoever, then any set $possible\_words(A, B, \phi, v_0, x)$ will consist of all the words in TD matched by x, irrespective of the constitution of A or B, except that A and B should meet the requirements specified by eq. 5.36 for $possible\_words(A, B, \phi, v_0, x)$ to be defined. Then $matchwords(x) = possible\_words(A, B, \phi, v_0, x)$ for all valid values of A, B and x; and then it also holds that for all $y \in Z_m$: $matchwords(y) \equiv possible\_words(Z', \phi, \phi, v_0, y) \equiv possible\_words(Z_m, Z_m, \phi, v_0, y) \equiv rulewords(Z_m, \phi, y)$. For any $r, s \in Z_m$, if $path(containpat/supercomp(Z', \phi, \phi, r, s)) = 1$ then there exists a set of rules $v_1 = r, v_2, .., v_n = s$ such that for each (v_i, v_{i+1}), either (1) $containpat(Z', v_i, v_{i+1}) = 1$ or (2) $supercomp(Z', \phi, \phi, v_0, v_i, v_{i+1}) = 1$. If (1) $containpat(Z', v_i, v_{i+1}) = 1$ then $context(v_i) \supset context(v_{i+1})$ (eq. 5.47) and then $matchwords(v_i) \subseteq matchwords(v_{i+1})$ (statement 1); and then $rulewords(Z_m, \phi, v_i) \subseteq rulewords(Z_m, \phi, v_{i+1})$. If (2) $supercomp(Z', \phi, \phi, , v_0, v_i, v_{i+1}) = 1$, then $possible\_words(Z', \phi, \phi, v_i) \subset possible\_words(Z', \phi, \phi, v_{i+1})$ by definition (eq. 5.51), and then also $rulewords(Z_m, \phi, v_i) \subset rulewords(Z_m, \phi, v_{i+1})$. Then it holds for all v_i that $rulewords(Z_m, \phi, v_1 = r) \subseteq rulewords(Z_m, \phi, v_2) \subseteq \ldots \subseteq rulewords(Z_m, \phi, v_n = s)$; and then $rulewords(Z_m, \phi, r) \subseteq rulewords(Z_m, \phi, s)$. But since both r and s in Z_m, and since $valid(\phi) = 1$, it is not possible that $rulewords(Z_m, \phi, r) = rulewords(Z_m, \phi, s)$ (statement 9). So $rulewords(Z_m, \phi, r) \subset rulewords(Z_m, \phi, s)$, and then $possible\_words(Z', \phi, \phi, r) \subset possible\_words(Z', \phi, \phi, s)$, and then $subset(Z', \phi, \phi, r, s) = 1$ (eq. 5.51).

Statement 33 (Initial allowed state) *If the rule set $Z_{combined}$ is ordered according to the rule set orderings generated by $decided\_set(Z_{combined}, \phi, \phi)$, then the rule set is accurate, complete and in an $allowed\_state$, i.e:*

$$Z' \equiv Z_{combined}, Z_e = \phi, oset(Z') = decided\_set(Z', \phi, \phi) \implies$$
$$accurate(Z', oset(Z')) = 1, allowed\_state(Z', Z_e, oset(Z')) = 1. \quad \text{(B.35)}$$

Let w be any word in TD and w' its associated word pattern in $Z_{no-conflict}$. It follows from statement 30 that predicting word w according to $Z', oset(Z')$ will always invoke the word pattern $w' \in Z_{no-conflict}$, which always exists. Since there is always such a word pattern, the new rule set will be complete. Since only rules in $Z_{no-conflict}$ will be invoked, and the rule set $Z_{no-conflict}$ is accurate (from statement 31), the new rule set will also be accurate; and then $accurate(Z', oset(Z')) = 1$. From the definition of $minimal$ (eq. 5.25), if a rule set can be accurate and complete, at least one rule set and rule ordering set will always exist such that $minimal(Z_m, oset_m(Z_m)) = 1$. Since $Z_{combined}$ consists of all possible rules, all such Z_m will be a subset of $Z_{combined}$, and then $\phi = Z_e \subseteq Z_m \subseteq Z' \equiv Z_{combined}$. Now consider any $r, s \in Z_m$ such that also $(r, s) \in oset(Z')$, i.e. $(r, s) \in decided\_set(Z', \phi, \phi)$. Then $path(order\_decided(Z', \phi, \phi, r, s)) = 1$ (eq. 5.60), and then $path(containpat/supercomp/rule\_order(Z', \phi, \phi, v_0, r, s)) = 1$ (eq. 5.59). Since ϕ contains no orderings whatsoever, this is only possible if $path(containpat/supercomp(Z', \phi, \phi, r, s)) = 1$. Then $subset(Z', \phi, \phi, r, s) = 1$ (statement 32), $order_{red}(Z_m, Z_m, oset_m(Z_m), r, s) = 1$ (statement 21), and then $(r, s) \in oset_m(Z_m)$ (eq. 5.56 and eq. 5.7). Since this holds for all $(r, s) \in Z_m$ it follows that $order\_subset(decided\_set(Z', \phi, \phi), oset_m(Z_m)) = 1$ (eq. 5.27), and then $order\_subset(oset(Z'), oset_m(Z_m)) = 1$, and then $allowed\_state(Z', Z_e, oset(Z')) = 1$ (eq. 5.29).

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