A computational approach to the abstraction of morphopholonogical alternations

Sacha Beniamine
Laboratoire de Linguistique Formelle, Université Paris Diderot

Typologie et modélisation des systèmes morphologiques
Jeudi 12 Janvier 2017

A computational abstractive approach

- Item and Pattern Morphology : Morphology is modeled directly in terms of surface alternations between wordforms.
  - Term due to **Blevins2016**; preferable to the ambiguous 'Word and Paradigm'
  - Abstractive in Blevins, 2006's sense.
- Items are wordforms rather than subword units.
- The **alternation patterns** allow us to classify lexemes' behavior.
- Extracting patterns automatically without prior knowledge on the language's profile is a fundamental step for instrumented typology

Finding alternation patterns

- We describe an automated way to find morphopholonogical alternations cross-linguistically from surface forms.
- These take the form of bidirectionnal alternation patterns : *X alternates with Y in the context Z* written "X $\rightleftharpoons$ Y / Z"
- They can be used to study various alternations

Inflection: English past

'acted' /aktɪd/ $\rightleftharpoons$ 'act' /akt/ ➡ ɪd $\rightleftharpoons$ / X+[bdpt]_

Finding alternation patterns

- We describe an automated way to find morphopholonogical alternations cross-linguistically from surface forms.
- These take the form of bidirectionnal alternation patterns : *X alternates with Y in the context Z* written "X ⇌ Y / Z"
- They can be used to study various alternations

Derivation: French nouns

'gloire' /glwaʁ/ ⇌ 'glorieux' /gloʁjø/ ➡ wa_ ⇌ o_jø / X+_ʁ_

Finding alternation patterns

- We describe an automated way to find morpholonogical alternations cross-linguistically from surface forms.
- These take the form of bidirectionnal alternation patterns : *X alternates with Y in the context Z* written ”X ⇌ Y / Z”
- They can be used to study various alternations

Variation and Change: French and Morisien

’judiciaire’ /ʒydisjɛʁ/ ⇌ ’zidisier’ /zidisjɛɚ/ → ʒy_ʁ ⇌ zi_ɚ / X*_X+_

- This work was developped with inflectional morphology in mind.
  - Investigations on Inflection Classes (my PhD topic)
  - Studying the Paradigm Cell Filling Problem
- For this purpose, we were considering all possible pairwise alternations in large inflectional paradigms
  - Here: 7 cells, 42 relations.
- We needed a system able to find patterns in a reasonable time for a large number of alternations.

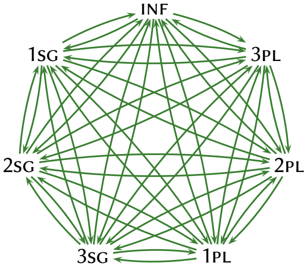

Table of Contents

Abstracting patterns from pairs of forms

- Input :
  - Pairs of forms involved in some morphopholonogical alternation
    ex: /amɛn/ $\rightleftharpoons$ /amøne/
  - A definition of phonemes in distinctive features
    ex: m = [+son -syl +cons +cont +nas -haut -arr +ant -cor +vois]

Abstracting patterns from pairs of forms

- Input :
  - Pairs of forms involved in some morphopholonogical alternation
    ex: **/amɛn/ ⇌ /amøne/**
  - A definition of phonemes in distinctive features
    ex: m = [+son -syl +cons +cont +nas -haut -arr +ant -cor +vois]

Abstracting patterns from pairs of forms

- Input :
  - Pairs of forms involved in some morphopholonogical alternation
    ex: /amɛn/ $\rightleftharpoons$ /amøne/
  - A definition of phonemes in distinctive features
    ex: **m = [+son -syl +cons +cont +nas -haut -arr +ant -cor +vois]**

Abstracting patterns from pairs of forms

- Input :
  - Pairs of forms involved in some morphopholonogical alternation
    ex: /amɛn/ ⇌ /amøne/
  - A definition of phonemes in distinctive features
    ex: m = [+son -syl +cons +cont +nas -haut -arr +ant -cor +vois]
- Output: a list of alternation patterns

_ɛ_ ⇌ _ø_e / X+_[-syl]_

ex:	/amɛn/ 1.SG 'bring'	/amøne/ 2.PL 'bring'

Patterns can be deduced from alignments

A pattern is a representation of alternating and constant material in a pair of forms.

PRS.1SG 'I bring'	a	m	ɛ	n	
	|	|	|	|	|
PRS.2PL 'you bring'	a	m	ø	n	e

Patterns can be deduced from alignments

A pattern is a representation of alternating and constant material in a pair of forms. It can be deduced from an alignment of the forms

PRS.1SG 'I bring'	a	m	ɛ	n	
	|	|	|	|	|
PRS.2PL 'you bring'	a	m	ø	n	e

↓

_ɛ_ ⇌ _ø_e / am_n_

Finding the optimal local alignment

- Suffixal alternations require left alignment (French):

PRS.1SG 'I bring'	a	m	ɛ	n	
	|	|	|	|	|
PRS.2PL 'you bring'	a	m	ø	n	e

Finding the optimal local alignment

- Suffixal alternations require left alignment (French):

PRS.1SG 'I bring'	a	m	ɛ	n	
	|	|	|	|	|
PRS.2PL 'you bring'	a	m	ø	n	e

- Prefixal alternations require a right alignment (Swahili):

FUT.1SG 'I will want'	n	i	t	a	t	a	k	a
	|	|	|	|	|	|	|	|
PRS.2PL 'you want'		m	n	a	t	a	k	a

Finding the optimal local alignment

- Suffixal alternations require left alignment (French):

PRS.1SG ‘I bring’	a	m	ɛ	n	
	|	|	|	|	|
PRS.2PL ‘you bring’	a	m	ø	n	e

- Prefixal alternations require a right alignment (Swahili):

FUT.1SG ‘I will want’	n	i	t	a	t	a	k	a
	|	|	|	|	|	|	|	|
PRS.2PL ‘you want’		m	n	a	t	a	k	a

- More complex alternations can require arbitrary alignments :

(Persian)

PRS.1SG ‘I buy’	m	i	x	a	r			a	n
	|	|	|	|	|	|	|	|	|
PAS.PERF.1SG ‘I bought’			x	a	r	i	d	a	n

(Arabic)

PFV.3SG ‘he wrote’			k	aː	t	a	b	aː
	|	|	|	|	|	|	|	|
IPF.3SG ‘he writes’	j	u	k	aː	t	i	b	u

Finding the optimal global alignment

- There can be several optimal local alignments

Alignments for ‘baba’ and ‘ba’

Alignment					Pattern
	b	a	b	a	
(i) Prefix	_	_	b	a	$\epsilon \rightleftharpoons$ ba / _ba
(ii) Suffix	b	a	_	_	$\epsilon \rightleftharpoons$ ba / ba_
(iii) Infix	b	_	_	a	$\epsilon \rightleftharpoons$ ab / b_a

Finding the optimal global alignment

- There can be several optimal local alignments
- Choosing the most appropriate alignment requires cross-lexeme comparisons

Three imaginary languages.

A.Infix -ab-		B. Prefix ba-		C. Suffix -ba	
SG	PL	SG	PL	SG	PL
ba	baba	ba	baba	ba	baba
to	tabo	to	bato	to	toba
ri	rabi	ri	bari	ri	riba
su	sabu	su	basu	su	suba
ne	nabe	ne	bane	ne	neba

Morphology beyond affixes

- We saw that non concatenative processes can require complex alignments,
- So do multidimentional alternations, e.g. in Zenzontepec Chatino
  - In the following example, inflection relies on both segmental and tonal alternations.
  - It is important to be able to capture both with the same system.

	'break'	'drench'	'slide'	
POT	ku^{0}ki^{0}tę^{1}ʔ	ku^{0}ki^{0}li^{0}	ki^{0}ki^{0}li^{0}	...
CPL	nka^{0}ki^{1}tę^{2}ʔ	nka^{0}ki^{0}li^{0}	nku^{0}ki^{0}ti^{0}	...

Table of Contents

The PCFP as a NLP problem

- When constructing lexical resources, the paradigms extracted from corpora are usually sparse
- The Paradigm Cell Filling Problem arises in this context
  Finding alternation rules provides a way to fill-in the missing forms.
- In NLP, this is called reinflection Cotterell et al., 2016.
- Symbolic solutions have various contributions to the alignment problem.
- Neural networks perform best (Kann and Schütze, 2016).
- Because of distinct goals, none provide the type of generalisations we need.

Studies of inflectional morphology

- Much previous studies of Inflectional structure (e.g. Ackerman and Malouf 2013; Stump and Finkel 2013) works from hand-designed classifications.
- Neural networks have been used too as a model of the PCFP (Malouf, 2016).
- The main contribution to automated inference of patterns is the Minimal Generalization Learner
    - Simulate the behavior of speakers in a wug test (Albright and Hayes, 2002, 2003, 2006)
    - Generalize patterns incrementally and retain all intermediate generalizations.
    - This is both too slow to be applied to large inflection systems and contrary to our need to find one pattern per pair of forms.
- Following Albright & Hayes, several studies infer alternation patterns with strategies devised for specific datasets (Sims, 2015; Albright and Hayes, 2002; Bonami and Boyé, 2014; Bonami and Beniamine, 2015)

Alignment strategies in previous work

- Transducer intersection (Ahlberg, Forsberg, and Hulden, 2014)
- Hard coded linguistically motivated alignment
  - Sims (2015): Suffixation
  - Albright and Hayes (2002): A single change, with a bias:
    Suffixation > Prefixation > Stem-internal alternation (ablaut/infixation)
  - Bonami and Boyé (2014) : No stem-internal alternation, with a bias:
    Suffixation > Prefixation > Circumfixation
  - Bonami and Beniamine (2015):Suffixation with a potential stem-internal alternation
- Alignment that minimizes edit distance:
  - Durrett and DeNero, 2013 : weighted according to cross-lexeme comparisons.
  - Albright and Hayes, 2006 : weighted according to phonological similarity.

Table of Contents

General strategy

Strategy in 3 steps:

1. Align forms locally to find patterns.
2. Generalize by merging patterns with the same structural alternation.
3. Select the patterns which perform best across lexemes.

Alignment with simple edit distances (I)

- For any pair of forms, find the set of alignments that minimize a weighted edit distance
- We define three operations with costs :

PRS.1SG 'I bring'	a	m	ɛ	n	
	|	|	|	|	|
PRS.2PL 'you bring'	a	m	ø	n	e

Alignment with simple edit distances (I)

- For any pair of forms, find the set of alignments that minimize a weighted edit distance
- We define three operations with costs :
  - `COPY` is free

PRS.1SG 'I bring'	a	m	ɛ	n	
	|	|	|	|	|
PRS.2PL 'you bring'	a	m	ø	n	e
Operation	C	C		C	
Cost	0	0		0	

Alignment with simple edit distances (I)

- For any pair of forms, find the set of alignments that minimize a weighted edit distance
- We define three operations with costs :
  - `COPY` is free
  - `INSERTION/DELETION` costs 1

PRS.1SG 'I bring'	a	m	ɛ	n	
	|	|	|	|	|
PRS.2PL 'you bring'	a	m	ø	n	e
Operation	C	C		C	I
Cost	0	0		0	1

Alignment with simple edit distances (I)

- For any pair of forms, find the set of alignments that minimize a weighted edit distance
- We define three operations with costs :
  - COPY is free
  - INSERTION/DELETION costs 1
  - SUBSTITUTION costs 2 (equivalent to insert + delete)

PRS.1SG 'I bring'	a	m	ɛ	n	
	|	|	|	|	|
PRS.2PL 'you bring'	a	m	ø	n	e
Operation	C	C	S	C	I
Cost	0	0	2	0	1

From alignment to patterns

- Find all best alignments and deduce alternation patterns (back to an imaginary language) :

Alignment					Distance	Pattern
	b	a	b	a		
(i) Prefix	_	_	b	a	2	$\epsilon \rightleftharpoons$ ba / _ba
(ii) Suffix	b	a	_	_	2	$\epsilon \rightleftharpoons$ ba / ba_
(iii) Infix	b	_	_	a	2	$\epsilon \rightleftharpoons$ ab / b_a

- List the set of patterns for each alternation:

SG	PL	Patterns
ba	baba	{$\epsilon \rightleftharpoons$ ba / _ba, $\epsilon \rightleftharpoons$ ba / ba_, $\epsilon \rightleftharpoons$ ab / b_a}
to	tabo	{$\epsilon \rightleftharpoons$ ab / t_o}
ri	rabi	{$\epsilon \rightleftharpoons$ ab / r_i}
su	sabu	{$\epsilon \rightleftharpoons$ ab / s_u}

Merging patterns generalizes the context

- Fuse patterns with identical structural alternations
- This step attempts to find phonological restrictions on contexts by generalizing sets of phonemes to their smallest natural classes.

$$\left.\begin{array}{l} \epsilon \rightleftharpoons \text{ ab / b\_a} \\ \epsilon \rightleftharpoons \text{ ab / t\_o} \\ \epsilon \rightleftharpoons \text{ ab / r\_i} \\ \epsilon \rightleftharpoons \text{ ab / s\_u} \end{array}\right\} \epsilon \rightleftharpoons \text{ ab / } C\_V$$

Merging patterns captures phonological operations

- A structural alternation can be a phonological operation such as lengthening

$$\left.\begin{array}{l} \text{a} \rightleftharpoons \text{aː} / \ldots \\ \text{i} \rightleftharpoons \text{iː} / \ldots \end{array}\right\} \text{[aiu]} \rightleftharpoons \text{[aːiːuː]} / \ldots$$

Merging patterns captures phonological operations

- A structural alternation can be a phonological operation such as lengthening

A real example (Arabic verbs)
[aiu]_na ⇌ [aːiːuː]_iː
imp.act.2p.f ⇌ imp.act.2s.f

Merging patterns captures phonological operations

- A structural alternation can be a phonological operation such as lengthening
- However, this only works if there is a true phonological naturality

Irish: broadening and attenuation, from Carnie, 2008

(25) Broadening

Spelling	Sound change	Example
ói → ó	[oː] (no change)	*cóir → córa*
ei → ea	[ɛ] → [a]	*greim → greama*
éi → éa	[eː] (no change)	*tincéir → tincéara*
i→ ea	[ɪ] → [a]	*rith→ reatha*
(a)í → (a)ío	[iː] (no change)	*feadaíl → feadaíola*
ui → o	[ɪ] →[ɔ]	*cuid → coda*
io → ea	[ɪ] → [a]	*lios → leas*

Merging patterns captures phonological operations

- A structural alternation can be a phonological operation such as lengthening
- However, this only works if there is a true phonological naturality

Irish: broadening and attenuation, from Carnie, 2008

(24) Attenuation

Spelling	Sound change	Example
ea → i	[a] → [ɪ]	*fear → fir*
ea → ei	[a] → [ɛ]	*sceach → sceiche*
éa → éi	[eː] (no change)	*éan → éin*
ia → éi	[iə] → [eː]	*iasc → éisc*
ío → í	[iː] (no change)	*íol → íl*
io → i	[iː]/[ɪ]/[ʊ] →[ɪ]	*fionn → finn*
iu → i	[ʊ] → [ɪ]	*fliuch → fliche*

Scoring and choosing

- Score patterns using the harmonic mean of their coverage and accuracy

Scoring and choosing

- Score patterns using the harmonic mean of their coverage and accuracy
  - coverage: proportion of lexemes which are candidate for this pattern.

$$\frac{\text{lexemes to which the pattern is applicable}}{\text{total lexemes}}$$

Scoring and choosing

- Score patterns using the harmonic mean of their coverage and accuracy
  - coverage: proportion of lexemes which are candidate for this pattern.

$$\frac{\text{lexemes to which the pattern is applicable}}{\text{total lexemes}}$$

  - accuracy: proportion of candidates actually instantiating the pattern.

$$\frac{\text{lexemes derived correctly}}{\text{lexemes to which the pattern is applicable}}$$

Scoring and choosing

- Score patterns using the harmonic mean of their coverage and accuracy
  - coverage: proportion of lexemes which are candidate for this pattern.

$$\frac{\text{lexemes to which the pattern is applicable}}{\text{total lexemes}}$$

  - accuracy: proportion of candidates actually instantiating the pattern.

$$\frac{\text{lexemes derived correctly}}{\text{lexemes to which the pattern is applicable}}$$

- For each lexeme, decide on the pattern with the highest score

Alignment					Pattern	Coverage	Accuracy	Score
	b	a	b	a				
(i) Prefix	_	_	b	a	$\epsilon \rightleftharpoons$ ba / _ba	1/4	1/1	0.4
(ii) Suffix	b	a	_	_	$\epsilon \rightleftharpoons$ ba / ba_	1/4	1/1	0.4
(iii) Infix	b	_	_	a	$\epsilon \rightleftharpoons$ ab / C_V	4/4	4/4	1.0

More subtle alignments

- Simple edit distances are not always enough to choose the best alignment :

NOM.SG 'chihuahua' (čivav)	t	ʃ	ɪ	v	a	f		(Czech)
	|	|	|	|	|	|	|	
GEN.PL 'chihuahua' (čivava)	t	ʃ	ɪ	v	a	v	a	
Operation	C	C	C	C	C	S	I	
Cost	0	0	0	0	0	2	1	=3

More subtle alignments

- Simple edit distances are not always enough to choose the best alignment :

NOM.SG 'chihuahua' (čivav)	t	ʃ	ɪ	v			a	f	(Czech)
	|	|	|	|	|	|	|	|	
GEN.PL 'chihuahua' (čivava)	t	ʃ	ɪ	v	a	v	a		
Operation	C	C	C	C	I	I	C	I	
Cost	0	0	0	0	1	1	0	1	=3

Alignment with phonologically weighted edit distances

- We use phonological similarity as a weight (Frisch, Pierrehumbert, and Broe, 2004; Albright and Hayes, 2003)
  - `SUBSTITUTION` of segments costs $1-$ phonological similarity.

$$\text{sim}(a, b) = \frac{|\text{classes}(a) \cap \text{classes}(b)|}{|\text{classes}(a) \cup \text{classes}(b))}$$

Copy is a substitution and costs 0, as $sim(a, a) = 1$.

Alignment with phonologically weighted edit distances

- We use phonological similarity as a weight (Frisch, Pierrehumbert, and Broe, 2004; Albright and Hayes, 2003)
  - `SUBSTITUTION` of segments costs 1− phonological similarity.

t	ʃ	ɪ	v	a	f	
|	|	|	|	|	|	|
t	ʃ	ɪ	v	a	v	a
S	S	S	S	S	S	
0	0	0	0	0	0.1	

t	ʃ	ɪ	v			a	f
|	|	|	|	|	|	|	|
t	ʃ	ɪ	v	a	v	a	
S	S	S	S			S	
0	0	0	0			0	

Czech, ‘chihuahua’, NOM.SG čivav ⇌ GEN.PL čivava

Alignment with phonologically weighted edit distances

- We use phonological similarity as a weight (Frisch, Pierrehumbert, and Broe, 2004; Albright and Hayes, 2003)
  - `SUBSTITUTION` of segments costs 1− phonological similarity.
  - `INSERTION` is a parameter (here 0.5)

t	ʃ	ɪ	v	a	f	
|	|	|	|	|	|	|
t	ʃ	ɪ	v	a	v	a
S	S	S	S	S	S	I
0	0	0	0	0	0.1	0.5

t	ʃ	ɪ	v			a	f
|	|	|	|	|	|	|	|
t	ʃ	ɪ	v	a	v	a	
S	S	S	S	I	I	S	I
0	0	0	0	0.5	0.5	0	0.5

Czech, ‘chihuahua’, NOM.SG čivav ⇌ GEN.PL čivava

Alignment with phonologically weighted edit distances

- We use phonological similarity as a weight (Frisch, Pierrehumbert, and Broe, 2004; Albright and Hayes, 2003)
  - `SUBSTITUTION` of segments costs 1− phonological similarity.
  - `INSERTION` is a parameter (here 0.5)

t	ʃ	ɪ	v	a	f	
|	|	|	|	|	|	|
t	ʃ	ɪ	v	a	v	a
S	S	S	S	S	S	I
0	0	0	0	0	0.1	0.5

=0.6

t	ʃ	ɪ	v			a	f
|	|	|	|	|	|	|	|
t	ʃ	ɪ	v	a	v	a	
S	S	S	S	I	I	S	I
0	0	0	0	0.5	0.5	0	0.5

=1.5

Czech, ‘chihuahua’, NOM.SG čivav ⇌ GEN.PL čivava

Table of Contents

Evaluation: Qualitative

The algorithm does infer transfixation patterns

$$\_a\_a \rightleftharpoons \mathrm{ju\_i\_u} / \_X + \_C\_$$

ka:taba:	juka:tibu
PFV 'he wrote'	IPF 'he writes'

$$\mathrm{n\_a\_}^{1}\_^{2} \rightleftharpoons \mathrm{\_u\_}^{0}\_^{1} / \mathrm{\_k\_}^{0}\texttt{[+con,-lat,-nas]}\,V\_X\_\text{ʔ}$$

nka^{0}ki^{1}tę^{2}ʔ	ku^{0}ki^{0}tę^{1}ʔ
CPL 'she/he broke'	POT 'she/he will break'

Evaluation: Quantitative (I)

- Can the patterns be used for prediction ?
- 10-fold cross-validation
- Training :
  - Learn patterns on 90% of pairs.
  - Define a form's **class** as the set of patterns applicable to it.
  - Compute probabilities of the form $P(\text{pattern}|\text{class})$.
- Test :
  - Look at single forms for the other 10%.
  - Find the class for each form.
  - Predict by maximizing $P(\text{pattern}|\text{class})$.
  - If the class is unknown, or the predicted form is false, fail.

Evaluation: Quantitative (II)

	Chatino	French	Portuguese	Arabic
train size	351	4689	1791	855
test size	39	521	199	95
Left aligned (suffix)	24	93	92	48
Right aligned (prefix)	54	22	17	0.4
Albright and Hayes, 2002	55	93	94	49
Simple edit distances	58	93	-	87
Similarity based edit distances	58	93	93	87

Conclusion

- We presented a fully implemented algorithm to automatise the inference of alternation patterns.
  - it's open source: http://drehu.linguist.univ-paris-diderot.fr/qumin/
- Crucial properties :
  - Generalizes from fully specified form pairs to alternation patterns, with a phonologically constrained context.
  - Fast enough to perform on numerous series of pairs (cf. inflection).
  - Not limited to affixal material.
  - Does not require prior knowledge on the language's profile.
  - Optimizes the patterns globally across lexemes as well as locally.
  - Known patterns can be applied to unknown forms to predict new forms.
- It has already been used in previous works Beniamine and Bonami, 2016; Bonami and Beniamine, 2016.

Thank You !

References I

Ackerman, Farrell and Robert Malouf (2013). "Morphological organization: The low conditional entropy conjecture." In: *Language* 89.3, pp. 429–464. DOI: 10.1353/lan.2013.0054.

Ahlberg, Malin, Markus Forsberg, and Manstio Hulden (2014). "Semi-supervised learning of morphological paradigms and lexicons". In: *Proceedings of the 14th Conference of the European Chapter of the Association for Computational Linguistics, Gothenburg, Sweden 26–30 April 2014*, pp. 569–578. ISBN: 978-1-937284-78-7. DOI: 10.3115/v1/E14-1060.

Albright, Adam and Bruce Hayes (2002). "Modeling English Past Tense Intuitions with Minimal Generalization". In: *Proceedings of the ACL-02 Workshop on Morphological and Phonological Learning - Volume 6*. MPL '02. Stroudsburg, PA, USA: Association for Computational Linguistics, pp. 58–69. DOI: 10.3115/1118647.1118654.

— (2003). "Rules vs. analogy in English past tenses: A computational/experimental study". In: *Cognition* 90, pp. 119–161. DOI: 10.1016/S0010-0277(03)00146-X.

— (2006). "Modeling productivity with the gradual learning algorithm: The problem of accidentally exceptionless generalizations". In: *Gradience in grammar: Generative perspectives*, pp. 185–204.

Beniamine, Sarah and Olivier Bonami (2016). *A comprehensive view on inflectional classification*. Annual Meeting of the Linguistics Association of Great Britain (LAGB). York.

Blevins, James P. (2006). "Word-based morphology". In: *Journal of Linguistics* 42 (03), pp. 531–573. ISSN: 1469-7742. DOI: 10.1017/S0022226706004191.

Bonami, Olivier and Sarah Beniamine (2015). "Implicative structure and joint predictiveness". In: *Word Structure and Word Usage. Proceedings of the NetWordS Final Conference*. Ed. by Vito Pirelli, Claudia Marzi, and Marcello Ferro.

References II

Bonami, Olivier and Sarah Beniamine (2016). "Joint predictiveness in inflectional paradigms". In: *Word Structure* 9. Ed. by Farrell Ackerman and Robert Malouf, pp. 156–182. DOI: 10.3366/word.2016.0092.

Bonami, Olivier and Gilles Boyé (2014). "De formes en thèmes". In: *Foisonnements morphologiques. Etudes en hommage à Françoise Kerleroux*. Ed. by Florence Villoing, Sarah Leroy, and Sophie David. Presses Universitaires de Paris Ouest, pp. 17–45.

Carnie, Andrew (2008). *Irish nouns: a reference guide*. Oxford University Press.

Cotterell, Ryan et al. (2016). "The SIGMORPHON 2016 shared task—morphological reinflection". In: *Proceedings of the 14th Annual SIGMORPHON Workshop on Computational Research in Phonetics, Phonology, and Morphology*. Association for Computational Linguistics. Berlin, Germany, pp. 10–22.

Durrett, Greg and John DeNero (2013). "Supervised Learning of Complete Morphological Paradigms". In: *Proceedings of the 2013 Conference of the North American Chapter of the Association for Computational Linguistics: Human Language Technologies*. Atlanta, Georgia: Association for Computational Linguistics, pp. 1185–1195.

Frisch, Stefan A, Janet B Pierrehumbert, and Michael B Broe (2004). "Similarity avoidance and the OCP". In: *Natural Language & Linguistic Theory* 22.1, pp. 179–228. DOI: 10.1023/B:NALA.0000005557.78535.3c.

Kann, Katharina and Hinrich Schütze (2016). "MED: The LMU system for the SIGMORPHON 2016 shared task on morphological reinflection". In: *ACL 2016*, p. 62.

Malouf, Robert (2016). "Deep learning for abstractive morphology". In: *Computational methods for descriptive and theoretical morphology, 17th International Morphology Meeting*. Vienna, Austria.

References III

Sims, Andrea (2015). *Inflectional Defectiveness.* Cambridge University Press. DOI: 10.1017/CBO9781107053854.

Stump, G. and R.A. Finkel (2013). *Morphological Typology: From Word to Paradigm.* Cambridge Studies in Linguistics. Cambridge University Press. ISBN: 9781107029248. DOI: 10.1017/CBO9781139248860.

Evaluation: Quantitative

	Chatino	French	Portuguese	Arabic
train size	351	4689	1791	855
test size	39	521	199	95
Left aligned (suffix)	24	93	92	48
(num. of patterns)	229	26	17	409
Right aligned (prefix)	54	22	17	0.4
(num. of patterns)	54	3612	1467	464
Albright and Hayes, 2002	55	93	94	49
(num. of patterns)	73	26	17	397
Simple edit distances	58	93	-	87
(num. of patterns)	55	26	-	22
Similarity based edit distances	58	93	93	87
(num. of patterns)	54	26	16	23

A few patterns for English verbs

lexeme	PAST⇌PPART	PAST⇌PRES3S	PRES3S⇌PRESNOT3S	PPART⇌PRESNOT3S	PPART⇌PRESPART
DRIVE	XəʊC ⇌ XɪCn̩	XəʊC_ ⇌ XaɪCz	Xz ⇌ X	XɪCn̩ ⇌ XaɪC	XɪCn̩ ⇌ XaɪCɪŋ
RIDE	XəʊC ⇌ XɪCn̩	XəʊC ⇌ XaɪCz	Xz ⇌ X	XɪCn̩ ⇌ XaɪC	XɪCn̩ ⇌ XaɪCɪŋ
BITE	X⇌ Xn̩	XɪC ⇌ XaɪCs	Xs ⇌ X	XɪCn̩ ⇌ XaɪC	XɪCn̩ ⇌ XaɪCɪŋ
FORGET	X ⇌ Xn̩	XɒC ⇌ XɛCs	Xs ⇌ X	XɒCn̩ ⇌ XɛC	XɒCn̩ ⇌ XɛCɪŋ

lexeme	PAST⇌PRESNOT3S	PPART⇌PRES3S	PRESNOT3S⇌PRESPART	PAST⇌PRESPART	PRES3S⇌PRESPART
DRIVE	XəʊC ⇌ XaɪC	XɪCn̩ ⇌ XaɪCz	X ⇌ Xɪŋ	XəʊC ⇌ XaɪCɪŋ	Xz ⇌ Xɪŋ
RIDE	Xəʊ ⇌ Xaɪ	XɪCn̩ ⇌ XaɪCz	X ⇌ Xɪŋ	XəʊC ⇌ XaɪCɪŋ	Xz ⇌ Xɪŋ
BITE	XɪC ⇌ XaɪC	XɪCn̩ ⇌ XaɪCs	X ⇌ Xɪŋ	XVt ⇌ XaɪtVŋ	Xs ⇌ Xɪŋ
FORGET	XɒC ⇌ XɛC	XɒCn̩ ⇌ XɛCs	X ⇌ Xɪŋ	XɒC ⇌ XɛCɪŋ	Xs ⇌ Xɪŋ