When segmentation helps: Implicative structure and morph boundaries in the Navajo verb

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Labex EFL, opération Morph1

ISMo, dec. 2017
“...the Na-Dene languages are not one-third as synthetic as they look....What Swanton calls affixes are all independent stems entering into composition, or even little verbs...
It all crumbles into pieces at the least touch....”

Edward Sapir (1921)
excerpts from a letter to A. L. Kroeber
The Athabaskan / Dene

migrated over a huge section of northern geography

small hunter gather communities inaccessible areas (even today)
Figure 4. Dene-Yeniseian Out-of-Beringia.

http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0091722
The Athabaskan / Dene

- closely related languages
  common morphological structure
- ‘morphologically complex’
  (complex rich exponence)
- ‘polysynthetic’ (opaque)

- resistant to change
  - despite time depth over 2000yrs
Edward Sapir (1884 - 1939)

“The languages of the Athabaskan group are singularly conservative in form as well as in phonetics and vocabulary in spite of their enormous and irregular spread.”

“They are singularly resistant to exotic influence”
The Athabaskan / Dene language family

5 groups

*non tone:*
Alaska, Yukon, Pacific Northwest

*tone:*
interior
Mackenzie River Basin across to Hudson Bay
Apachean - American Southwest
- Navajo and Apache
The Athabaskan / Dene

Navajo

- in American SW
- New Mexico and Arizona
The Navajo Language:
A Grammar and Colloquial Dictionary

Robert Young and William Morgan

World-class grammar and dictionary
60 years of work
extensive paradigm charts
organization of a complex aspectual system
dictionary of fully inflected word forms

The mental lexicon of a polysynthetic language
Dene language family

Primarily verbal, **noun poor**

Nouns and verbal elements are **closed class**

Complex ‘**polysynthetic**’ morphology
Word (verb) structure
The Dene template – Navajo

Classic example of position class template
Comparative device - not descriptive
The **Dene** template – Navajo

Prosthetic - maintains order
Govern order of stipulated morphs
highly abstract
involving opaque UR – SR
requiring ad-hoc rewrite rule

it doesn’t produce well-formed words
works nicely as comparative device
<table>
<thead>
<tr>
<th>Object &amp; Possessive Pronoun</th>
<th>Derivational &amp; Themeless</th>
<th>Indirect Object Pronoun</th>
<th>Reflexive Pronoun</th>
<th>Reversive</th>
<th>Iterative</th>
<th>Plural Marker</th>
<th>Distinctive Object Pronoun</th>
<th>Inceptive</th>
<th>Derivative &amp; Themeless</th>
<th>Modal &amp; Aspectival</th>
<th>Subject Pronoun</th>
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<tbody>
<tr>
<td>1. shi-</td>
<td>-i,-i',</td>
<td>-a, -a'</td>
<td>away</td>
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</table>
Dimensionality parameters are enormous.
Position class template for Navajo verb
(Hoijer 1967; Young and Morgan 1987)

<table>
<thead>
<tr>
<th>Key</th>
<th>Description</th>
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<tr>
<td>Ia</td>
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**KEY (from left to right):**

- **Disjunct**
  - Ia
  - Ib
  - Ic
  - Id
  - Ie
  - II
  - III

- **Conjunct**
  - IV
  - V
  - VIa
  - VIb
  - VIc
  - VII
  - VIII
  - IX

- **Stem**
  - X
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Position class template for Navajo verb
(Hoijer 1967; Young and Morgan 1987)

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Problems

- ill-defined terms ‘morpheme’
- derived from & dependent on fully inflected forms for reconstruction
- heavily supported by rewrite rules
- cannot predict forms
- does not address relations among words
- does not address organization of lexicon
  - conjugation classes
  - learnability
$\sigma \left[ \begin{array}{c} af - BASE_x \\ \text{MODE/person} \end{array} \right] \mid \sigma \left[ \begin{array}{c} BASE_y \\ \text{VL.STEM.MODE} \end{array} \right]^{\text{VCOMPLEX}}$

<table>
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<tr>
<th>Disjunct</th>
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<tbody>
<tr>
<td>0 1b 1a 1c 1d 2 3</td>
<td>4 5 6a 6b 6c 7 8 9</td>
<td>X</td>
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<tr>
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*Core verb*

*bídish’ne*
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*Core verb*

\[ \sigma \quad \sigma \]
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\[ \text{Core verb} \]

The verb is **bídish’ne**.
### bíni’séľ tsih

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- **Disjunct**
- **Conjunct**
- **Stem**

- **Core verb**
- **ό**
- **MODE.1s**
- **VL.STEM.MODE**
Two inflected LEXEMES AS BASES

\[
[\text{Core verb}] = [\text{BASE}]_x \text{ MODE/1s} \quad [\text{BASE}]_y \text{ VC\textsc{OMPLEX}} \\
(af-) VL.\text{STEM.IPV}
\]
Two inflected LEXEMES AS Bases

\[
\begin{align*}
\text{bíni'} & \quad \text{cé} & \quad \text{łtsih} \\
\sigma & \quad 7.8 & \quad \sigma \\
af- & \quad \text{MODE/1s} & \quad 9.\text{stem} \\
[af\ldots \text{BASE }]_x & \quad [ \text{BASE }]_y \nu^{\text{COMPLEX}}
\end{align*}
\]
Two inflected LEXEMES AS BASES

\[ bíni' - sé \]

\([af\ldots \text{BASE}]_x\]

(af-) MODE/1s

\[ Ł.tsih \]

\([\text{BASE}]_y \text{\textsuperscript{\text{VCOMPLEX}}}]\]

VL.STEM.IPV
Two inflected **LEXEMES AS BASES**

\[ \sigma \left[ \text{af...} \right] \]
\( \text{BASE} \)
\( \text{MODE/1s} \)
\( (\text{af-}) \)

\[ \sigma \left[ \text{BASE} \right] \]
\( \text{VCOMPLEX} \)
\( \text{VL.STEM.IPV} \)

**Pre-stem**
\( (\text{af-})\text{BASE} \)

**Stem**
\( \text{BASE} \)
Two inflected **LEXEMES AS BASES**

- **yishcha**  
  ‘cry’

- **‘adiishbááh**  
  ‘make oneself grey’

- **diish’eeł**  
  ‘sail a boat’

- **yiishjjíh**  
  ‘throw Ob with force’

- **distsoós**  
  ‘begin carrying SRO’

- **‘iishkááh**  
  ‘trail away’
Two inflected **LEXEMES** as **BASES**

\[
\begin{align*}
\sigma & \text{ [ af BASE ]}_x \\
\sigma & \text{ [ BASE ]}_y \quad \text{VCOMPLEX}
\end{align*}
\]

yishcha

bíni’séltsih

‘adiishbááh

diish’eeł

dishjíįsh

distsóós

’iishkááh
**Two inflected LEXEMES AS BASES**

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<td>$[\text{af…-}\times\text{BASE}]$</td>
<td>$[\text{BASE}]_{\text{VCOMPLEX}}$</td>
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<table>
<thead>
<tr>
<th>$x$</th>
<th>$y$</th>
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<tr>
<td>yish</td>
<td>$\emptyset$.cha</td>
</tr>
<tr>
<td>‘adiish</td>
<td>d.bááh</td>
</tr>
<tr>
<td>diish</td>
<td>‘l.‘eeł</td>
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<tr>
<td>yiish</td>
<td>$\emptyset$.jíjísh</td>
</tr>
<tr>
<td>dis</td>
<td>$\emptyset$.tsóós</td>
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<td>’iish</td>
<td>‘l.kááh</td>
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Two inflected LEXEMES AS Bases

\[
\begin{array}{c|c}
\sigma & \sigma \\
\text{[ af...- BASE ]}_x & \text{[ BASE ]}_y \text{ VCOMPLEX} \\
\hline
(y)ish & \emptyset.cha \\
‘adi - ish & d.bááh \\
di- ish & \ddot{l}.’eeł \\
yi- ish & \emptyset.jjįsh \\
d(i)- is & \emptyset.tsóós \\
’a- ish & \ddot{l}.kááh \\
\end{array}
\]
Two inflected LEXEMES AS BASES

\[
\begin{array}{c|c}
\sigma & \sigma \\
[ \text{af…-} & [ \text{BASE} ]_x \\
\text{BASE} & [ \text{BASE} ]_y ]_{\text{VCOMPLEX}} \\
\end{array}
\]

(j)ʔʃ  \quad \emptyset.ʧʰa
‘ati - ʔʃ  \quad d.ʔpááh
ti- ʔʃ  \quad ɬ.‘eːɬ
ji- ʔʃ  \quad \emptyset.ʧʃʃʃh
t(i)- is  \quad \emptyset.tsóós
’a- ʔʃ  \quad ɬ.kʰááh
Two inflected LEXEMES AS Bases

\[
\begin{align*}
\sigma & \quad [\text{MODE/1s}]_x \\
\text{BASE} & \\
\sigma & \quad [\text{VCOMPplex}]_y \\
\text{BASE} & \\
\text{VL.STEM.IPV} & 
\end{align*}
\]

Bases represent two common types of inflection: exponence and stem alternations.
VC\text{OMPLEX}

\begin{align*}
\sigma \\
\left[ \begin{array}{c}
af \\
- BASE
\end{array} \right]_x
\end{align*}

MODE/person

\begin{align*}
\sigma \\
\left[ \begin{array}{c}
BASE
\end{array} \right]_y
\end{align*}

_{VC\text{OMPLEX}}

\text{VL.STEM.MODE}
BASES

PRESTEM mode inflected Person & Number

STEM  VL.STEM

‘STEM SETS’

valence (‘classifiers’).stem shape
I arrive flying it for the purpose of getting it.
fly it to go after it (a plane)
Pre-stem **BASE** EXPONENCE = **InflP**

4 primary **MODE** conjugations (16 classes)

Conjugation marking of person

1-3 (3a,3i,3s)

number

**singular** - **dual**

*Base and Extended Paradigms*

Young & Morgan 1987:200ff
## Pre-stem BASE EXPONENCE = InflP

4 primary MODE conjugations (16 patterns)

### I. IMPERFECTIVE

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Base and Extended Paradigms

Y&M 1987:200
STEMS ⇒ vl.stemshape

500 ROOTS - CLOSED CLASS = STEM SHAPES

(mainly) monosyllabic
CV(V)(C)
classificatory meaning
Stem shapes combined w vl into stem sets

Valence
’classifiers’ \{ ø ₁ ₃ ₄ \}

stems sets = vl.stem shapes
“...constitute a fundamental resource on which native speakers draw subconsciously to elicit the multiple stem shapes required by various modes and aspects in which a given verbal root is expressed.”

Y&M 1987:g302

stems conjugate in the same 5 modes of the full words

imperfective (I)  repetitive (R)  perfective (P)  future (F)  optative (O)
IPV  REP  PFV  FUT  OPT

but ‘stem sets’ for any word require VL (‘classifiers’) affixes
**STems sets = vl.stem shape**

**Root:** **taał**  act w feet move quickly

6 stem sets

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<tr>
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shapes of stems: tał  táał  taał  taal  tał
**STEMS SETS = VL.STEM SHAPE**

**ROOT:** **TAAŁ**  act w feet move quickly
6 stem sets

### ASP - of full word form

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**word aspect**
The **aspect** of a verb can be determined by the conjugation patterns of the **MODE** elements by differences in the **STEM SET** alone or by a combination of the above

understand the pattern of interdependencies of the elements in the verbal complex
**Root:** yi.ıh  eat

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**Aspect:**

*Mom:* eating

*Transitional, mom/term:* begin to eat, finished eating, finish eating a meal,

*Durative/Continuative:* eat all over (like a termite), eating around (town)

*Distributive:* sample foods
STEMS are marked for mode

’AAH learn

ø.’aah (I) ø.’ááh (R) ø.’áá (P) ø.’áál (F) ø.’áál (O)

bihoo’aaah_{ipv} it was learned

STEM alternation patterns are not understood
Morphosyntax

- strong interdependencies between the two Base lexemes
  inflection classes in Pre-stem inflections - shapes of Stem = Stem shapes
Navajo

**áhodidiniishtłóóh**

áhodidini – ish ] [ l.tłóoh ] ] \( \text{VCOMPLEX} \)

\( \phi \text{IPV.1} \) [ ‘cause to slaken’ ] IPV ]

I’m relaxed (nervous tension), I’m overcoming anxiety

**áhodishchah**

áhodi – ish ] [ d.chah ] ] \( \text{VCOMPLEX} \)

reflexive [ \( \phi \text{IPV.1} \) [ d.’cry’ ] IPV ]

I’m pretending to cry

**bidádi’nish’aaah**

bidádi’ – nish ] [ \( \phi .’aah \) ] ] \( \text{VCOMPLEX} \)

‘blocking’ [ nIPV.1 ] [ handle (sro) ] IPV ]

I close it with it, to block the entranceway or hole with it (a rock)
Whole word inflection

\[
\begin{align*}
\text{bits’a’nísht’ááh} & \quad \text{NIPFV.1s} \\
\text{bi-ts’a-’a-nísh} & \quad \text{Ł.t’ááh} \\
\text{[ nipfv.1s } & \quad \text{fly ]}
\end{align*}
\]

I flew in and left it behind

The Navajo Language
Young and Morgan 1987:d247
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<td><em>bits’a’níiit’ááh</em></td>
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<td><em>I (fly away) leave it</em></td>
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**contrast sets n-imperfective**

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<td>3a</td>
<td><em>bits’a’</em> - <em>jí</em></td>
<td><em>bits’a’dá’</em> - <em>jí</em></td>
<td>plural</td>
</tr>
<tr>
<td>3</td>
<td><em>yits’a’</em> - <em>ní’</em></td>
<td><em>yits’a’dá’</em> - <em>as</em></td>
<td>PFV</td>
</tr>
<tr>
<td></td>
<td>sing</td>
<td>dual</td>
<td>mode</td>
</tr>
<tr>
<td>-----</td>
<td>---------------</td>
<td>-----------------------</td>
<td>--------</td>
</tr>
<tr>
<td>1</td>
<td><strong>bits’anísht’ááh</strong></td>
<td><strong>bits’a’niit’ááh</strong></td>
<td>IPV</td>
</tr>
<tr>
<td></td>
<td><em>I (fly away) leave it</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td><strong>bits’a’nít’ááh</strong></td>
<td><strong>bits’a’nóht’ááh</strong></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td><strong>yits’a’nít’ááh</strong></td>
<td></td>
<td>****</td>
</tr>
<tr>
<td>3a</td>
<td><strong>bits’a’jít’ááh</strong></td>
<td><strong>bits’a’da’jít’ááh</strong></td>
<td>plural</td>
</tr>
<tr>
<td>3</td>
<td><strong>yits’a’nít’a’</strong></td>
<td><strong>yits’a’da’ast’a’</strong></td>
<td>PFV</td>
</tr>
</tbody>
</table>
Young and Morgan 1987:d256

bits’a’nísh kǫ́ǫh  swim away from it
bits’a’nísh’eeł  sail away from it
bits’a’nísh dlq̓qsəh  move away ‘on all fours’
bits’a’níshbáás    drive away from it
bits’a’níshbáás drive away from it
bits’a’níshkọ́qh  swim away from it
bits’a’nísheeɁ  sail away from it
bits’a’níshdlq̓q̓sh  move away ‘on all fours’
bits’a’níshbááɬ  drive away from it
‘iisdziis pull or drag O out of sight
‘adaas ‘iisdzįįs pull down from a height
‘ałts’ásdziís pull apart
bíis ʻiisdzī̂s pull and add to a pile
bikiisdzījs cover O
‘adah ch’ésdzíis  drag O over the edge
haas dzijs pull O out (like a splinter)
Verb: DZIÍS ‘pull’ InfCl

‘iisdzíís pull or drag O out of sight
‘adaas ‘iisdzíís pull down from a height
‘ałts’ásdzíís pull apart
bíís ‘iisdzíís pull and add to a pile
bikiisdzíís cover O
‘adah ch’é dzíís drag O over the edge
haasdzíís pull O out (like a splinter)
**bits’a’nísh ḥbáás**  
I drive away from it  

1  2

Whole word paradigms are necessary  
what kinds of combinations are well-formed  
stem shapes for the pre-stem elements
## Athabaskan consonant phoneme inventory:

<table>
<thead>
<tr>
<th></th>
<th>bilabial</th>
<th>interdental</th>
<th>alveolar</th>
<th>alveolar affricate</th>
<th>lateral</th>
<th>palato-alveolar</th>
<th>velar</th>
<th>labialized velar</th>
<th>glottal</th>
</tr>
</thead>
<tbody>
<tr>
<td>stops and affricates</td>
<td>b</td>
<td>ddh</td>
<td>d</td>
<td>dz</td>
<td>dl</td>
<td>j</td>
<td>g</td>
<td></td>
<td>′</td>
</tr>
<tr>
<td></td>
<td>tth</td>
<td>t</td>
<td>ts</td>
<td>tɬ</td>
<td>ch</td>
<td>k</td>
<td>kw</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ejectives</td>
<td>tth’</td>
<td>t’</td>
<td>ts’</td>
<td>tɬ’</td>
<td>ch’</td>
<td>k’</td>
<td>kw’</td>
<td></td>
<td></td>
</tr>
<tr>
<td>voiceless fricatives</td>
<td>th</td>
<td>s</td>
<td>ɬ</td>
<td>sh</td>
<td>x / h</td>
<td>h</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>voiced fricatives</td>
<td>dh</td>
<td>z</td>
<td>l</td>
<td>zh</td>
<td>gh</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>nasals</td>
<td>m</td>
<td>n</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>glides, rhotics</td>
<td>r</td>
<td></td>
<td></td>
<td></td>
<td>y</td>
<td>w</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Vowel quality contrasts: 4 vowel system

\[ \text{i} \]
\[ \text{e} \quad \text{o} \]
\[ \text{a} \]

plus length, tone (H,L), nasality
= 16 vowel contrasts
Phonological and phonetic evidence for this structure

**Phonotactics**
asymmetric distribution of contrasts – stems severely reduced in Prestem domain (McDonough 1990, 2003)

**Phonological processes**
consonant harmony (core verb) (McDonough 2003)
‘classifier’ effects (d-effects) (McDonough 2001)

**Phonetic**
internal boundary effects (McDonough 2000a, 200b, 2003)
tone resetting (McDonough 2000)
vowel coalescence ~ quality (McDonough 2003)
interim summary

- Navajo verb forms have two bases: Pre-stems and Stems.
- The boundary between these two parts is phonologically and morphologically salient.
- This contrasts with the typical situation in inflection
  - Inflected forms usually have a single base.
  - Morph boundaries are usually less predictable.
- In the following section, we investigate the consequences of this for predictability in paradigms.
Item and Pattern Morphology

We take on an Item and Pattern approach:

- Term due to Blevins, (2016); preferable to the ambiguous ‘Word and Paradigm’
- Surface alternations between forms lead to opacities that are problematic for speakers
  - Classical phonological and morphological analyses try to reduce them (Blevins, 2006).
  - Item and Pattern Morphology quantifies them instead. (PCFP, Ackerman, Blevins, and Malouf, 2009).

- Morphology is modeled directly in terms of surface alternations
The argument against segmentation

Why word-based morphology?

▶ Segmenting forms into constitutive morphemes
  1. Reduces opacities by assuming underlying forms, which prevents us from studying these opacities.
The argument against segmentation

Why word-based morphology?

▶ Segmenting forms into constitutive morphemes

1. Reduces opacities by assuming underlying forms, which prevents us from studying these opacities.
2. Discards the implicative structure in paradigms, which has to be compensated in grammars by building instructions (Blevins, 2016).
The argument against segmentation

Why word-based morphology?

- Segmenting forms into constitutive morphemes
  1. Reduces opacities by assuming underlying forms, which prevents us from studying these opacities.
  2. Discards the implicative structure in paradigms, which has to be compensated in grammars by building instructions (Blevins, 2016).

- When considering predictability in paradigms, words are the relevant unit. (Robins, 1959).
The argument against segmentation

Why word-based morphology?

▶ Segmenting forms into constitutive morphemes
  1. Reduces opacities by assuming underlying forms, which prevents us from studying these opacities.
  2. Discards the implicative structure in paradigms, which has to be compensated in grammars by building instructions (Blevins, 2016).

▶ When considering predictability in paradigms, words are the relevant unit. (Robins, 1959).

▶ In the following, we rely on alternations between wordforms.
We study all alternations between paradigm cells, here, we focus on 5 cells (1st person, principal parts).
Alternation patterns

- We study all alternations between paradigm cells, here, we focus on 5 cells (1st person, principal parts).
- through binary patterns between phonological forms

```
/pitiʃneʔ/  /pititeʃniːɬ/  /pitóʃneʔ/  /pitíːɬneʔ/  /pińtíʃniːh/
“bidííłne’”  “bidideeshniil”  “bidóshne’”  “bidííłne’”  “bińdíshniih”
PFV.1       FUT.1            ITER.1     IPFV.1           OPT.1
```

*BIDISHNE’, “to pound off something (as ice, rock, hard candy)”*
Alternation patterns

- We study all alternations between paradigm cells, here, we focus on 5 cells (1st person, principal parts).
- through binary patterns between phonological forms
- Patterns are written similarly to SPE (Chomsky and Halle, 1968) phonological rules, with a context expressing phonological constraints.

\[ \_i:\_ \Leftrightarrow _o:\_ / XC\_CVC \]

\[
\text{/pitíːɬneʔ/} \\
\text{PFV.1}
\]

\[
\text{/pitóʃneʔ/} \\
\text{OPT.1}
\]

BIDISHNE’, “to pound off something (as ice, rock, hard candy)”
From words to patterns

- **Input data:**
  - principal parts from Young and Morgan, 1987 = 1st person forms
  - Automatically transcribed to IPA
  - Semi automatic validation led to many corrections
  - Without defective lexemes
  - Final dataset: 1741 lexemes

- We infer alternation patterns using Beniamine’s (2017) algorithm
  - Does not presuppose a pre-existing inflectional classification
  - Does not need to know the type of alternations in advance
  - Requires large paradigms
Inference of alternation patterns

For each pair of forms:

1. Find local alternation patterns

PFV.1 /pitíːɬneʔ/

OPT.1 /pitóʃneʔ/
Inference of alternation patterns

For each pair of forms:

1. Find local alternation patterns
   - Align two forms automatically

PFV.1 \( \text{p\ i\ t\ i:\ n\ e\ ?} \)

OPT.1 \( \text{p\ i\ t\ o\ f\ n\ e\ ?} \)
Inference of alternation patterns

For each pair of forms:

1. Find local alternation patterns
   - Align two forms automatically
   - Separate what is constant vs alternating material

PFV.1 /pitíːɬneʔ/

OPT.1 /pitóʃneʔ/
Inference of alternation patterns

For each pair of forms:

1. Find local alternation patterns
   ▶ Align two forms automatically
   ▶ Separate what is constant vs alternating material
   ▶ Deduce a pattern

\[
\text{PFV.1} \quad \begin{array}{c}
\text{OPT.1} \\
\text{constant}
\end{array}
\]

\[
\text{BIDISHNE’} \quad \begin{array}{c}
_\text{íːɬ}_ \\
\Rightarrow \\
_\text{óʃ}_ \\
/ \quad \text{pit_neʔ}
\end{array}
\]
Inference of alternation patterns

For each pair of forms:

1. Find local alternation patterns
   ▶ Align two forms automatically
   ▶ Separate what is constant vs alternating material
   ▶ Deduce a pattern

2. Generalize patterns with identical structural alternation by merging contexts.

\[
\begin{array}{ccc}
\text{PFV.1} & \text{OPT.1} & \text{constant} \\
\hline
\text{BIDISHNE’} & _íːɬ_ & _óʃ_ / \text{pit_neʔ} \\
\text{HANISHCHAAD} & _íːɬ_ & _óʃ_ / \text{hanʃʰaːt} \\
\ldots & \ldots & \ldots \\
\text{= } & _íːɬ_ & _óʃ_ / \text{XC_CVC}
\end{array}
\]
Microclasses

- **Microclass**: group of lexemes with exactly the same inflectional behavior (patterns).
- If we apply the patterns algorithm to full forms, we find 1240 microclasses
  - Almost one class per lexeme!
  - unlikely to reflect useful generalizations
- The quality of patterns is critical if we want to evaluate the system’s complexity
K-fold evaluation on Navajo verbs

- **K-fold**: to evaluate the predictive power of the patterns
  - learn patterns on 90% of the data,
  - use the remaining 10% for evaluation,
  - cycle the 10%/90% split. Beniamine, 2017

- We reach only a mean **accuracy of 33%**.
  - way below what we find for other languages (60%–95%).
Two dimensions of variation

- The Mode and the Stem constitute distinct dimensions of variation in the Navajo verb
- **Combinatory explosion:** Attested verbs display a large number of patterns corresponding to various combinations of Mode and Stem classes.
- The test set in our evaluation is bound to contain patterns unseen in the train set.
**Illustration of the issue**

<table>
<thead>
<tr>
<th>/jiːʃʧį́ːh/</th>
<th>/jiteːʃʧį́ːɬ/</th>
</tr>
</thead>
<tbody>
<tr>
<td>/tistsʰóːs/</td>
<td>/ʔátisːpáːh/</td>
</tr>
<tr>
<td>/titeːstsʰos/</td>
<td>/ʔátiteːspah/</td>
</tr>
<tr>
<td>/tiːʃʔeːɬ/</td>
<td>/titeːʃʔoɬ/</td>
</tr>
</tbody>
</table>

Illustration of the issue

'/jiːʃʧį́ːh/ ⇌ '/jiteːʃʧį́ːɬ/
/tiːʃʔeːɬ/ ⇌ /titeːʃʔoɬ/
/tisʦʰóːs/ ⇌ /titeːstʦʰos/
/ʔátʃpáːh/ ⇌ /ʔátiteʃpah/
/ʔiːʃk͡xáːh/ ⇌ /ʔateːʃkəxah/

Illustration of the issue

/jiʃʧɨːh/ \(\Rightarrow\) /jiteʃʧɨːɬ/

/tïʃʰóːs/ \(\Rightarrow\) /ʔátïʃpáːh/ \(\Rightarrow\) /ʔiʃkˣáːh/

/tïteʃtsʰos/ \(\Rightarrow\) /ʔátïteʃpah/ \(\Rightarrow\) /ʔateʃkˣah/

/tiʃʔeːɬ/ \(\Rightarrow\) /tïteʃʔoɬ/

\(\Rightarrow\)

Illustration of the issue

Patterns based on segmented forms

To assess the usefulness of the syllable based segmentation, we re-run the patterns on two datasets (pre-stems vs stem).

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Average accuracy</th>
<th>Average # of patterns</th>
</tr>
</thead>
<tbody>
<tr>
<td>full words</td>
<td>0.33</td>
<td>537</td>
</tr>
<tr>
<td>pre-stem</td>
<td>0.79</td>
<td>87</td>
</tr>
<tr>
<td>stems</td>
<td>0.75</td>
<td>102</td>
</tr>
</tbody>
</table>

From now on, we take the alternation between two forms to consist of two separate patterns.

This allows us to rely on the more accurate classifications while inquiring about full forms.
We can now measure what we originally set out to investigate: the system’s inflectional complexity
How do speakers know how to inflect full paradigms on the basis of exposure to only some forms?

(Ackerman, Blevins, and Malouf, (2009)’s Paradigm Cell Filling Problem)

- Ackerman et al. argue that the implicative structure of paradigms (Wurzel, 1984) plays a crucial role in addressing the problem:
  - Speakers are attuned to recurrent patterns of alternation between the forms filling two paradigm cells.
  - This allows them to infer implicational statements of the form:
    \[ \text{“If paradigm cell A is realised by the form } X, \text{ then paradigm cell B is likely to be realised by the form } f(X) \” \]
Mean uncertainty as conditional entropy

- We use Bonami and Boyé, 2014; Bonami and Luís, 2014’s method to assess mean uncertainty in solving the PFCP.
- The implicative entropy from $A$ to $B$:

$$H(A \rightarrow B)$$

quantifies how hard it is to predict $B$ from $A$
- Technically, it is the conditional entropy between two random variables:
  - One classifies pairs of forms into alternation patterns: $A \sim B$
  - The other classifies forms of $A$ on the basis of their phonological shape $A_{A \sim B}$

$$H(A \rightarrow B) = H(A \sim B | A_{A \sim B})$$

variation on Ackerman and Malouf, 2013.
Mean implicative entropy in Navajo paradigms

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Entropy</th>
</tr>
</thead>
<tbody>
<tr>
<td>pre-stem alone</td>
<td>0.53</td>
</tr>
<tr>
<td>stems alone</td>
<td>0.62</td>
</tr>
<tr>
<td>stems + pre-stem</td>
<td>0.33</td>
</tr>
</tbody>
</table>

- Mean implicative entropy ranges from 0 to infinity.
- The results are in line with findings from Ackerman, Blevins, and Malouf, 2009; Ackerman and Malouf, 2013.
- Uncertainty is lower when predicting stems and prestems together.
Conclusion

1. The system of Navajo verbs is the combination of two inflectional systems.
   ▶ The segmentation into prestems and stems is defined phonologically for the whole system and very salient
   ▶ Surface words exhibit a high number of classes
   ▶ It is necessary to consider stems and pre-stem separately to infer relevant morphological generalisations
   ▶ It follows that the segmentation is morphological

2. These two systems are not independent
   ▶ Not all combinations of stem and pre-stem classes are attested.
   ▶ There are interdependencies between stem and pre-stem selection that help solve the PCFP.
   ▶ This is shown by a lower entropy when predicting them in combination.

Reminiscent of the bidimensional organisation of Oto-Manguean conjugation systems Beniamine and Bonami, 2016
<table>
<thead>
<tr>
<th>lexeme</th>
<th>IPFV.1</th>
<th>ITER.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>’ÁDIISHBAÁH</td>
<td>?áti:f+pá:h</td>
<td>?ánti:f+pah</td>
</tr>
<tr>
<td>BIDISHNE’</td>
<td>pitif+ne?</td>
<td>píntif+ni:h</td>
</tr>
<tr>
<td>DISTSOÓS</td>
<td>tís+tsʰós</td>
<td>ntí:s+tsʰos</td>
</tr>
<tr>
<td>’IISHKÁÁH</td>
<td>?i:f+kxá:h</td>
<td>?anáʃ+kxah</td>
</tr>
<tr>
<td>YIISHJJííH</td>
<td>ji:f+ʧʃːh</td>
<td>něiʃ+ʧʃːh</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>lexeme</th>
<th>PFV.1</th>
<th>FUT.1</th>
<th>OPT.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIDISHNE’</td>
<td>pití:+ɬneʔ</td>
<td>pitite:f+ni:ɬ</td>
<td>pitóʃ+neʔ</td>
</tr>
<tr>
<td>DISTSOÓS</td>
<td>tí:+tsʰoːz</td>
<td>tite:s+tsʰos</td>
<td>tós+tsʰóːs</td>
</tr>
<tr>
<td>’IISHKÁÁH</td>
<td>?e:f+kxai</td>
<td>?ate:f+kxah</td>
<td>?o:f+kxá:h</td>
</tr>
<tr>
<td>YIISHJJííH</td>
<td>ji:f+ʧʃːʔ</td>
<td>jite:f+ʧʃːɬ</td>
<td>wo:f+ʧʃːh</td>
</tr>
</tbody>
</table>
Thank you!
References


How easy is it to segment?

A-priori straightforward: the stem is the last syllable

- We trained a simple maximum entropy model.
- Intuition: there is more paradigmatic variation at morpheme boundaries.
- More elaborate versions of this algorithm are standardly used in NLP for segmentation.
- 84.23% of accuracy to predict Navajo Mode/Stem boundary.

1. Count all phoneme trigrams $c_1, c_2, c_3$ in words.
2. For each word:
3. estimate all $H(c_{i+1}|c_{i-1}, c_i)$
4. Segment after the $c_i$ which leads to max entropy