Finite-state morphology for Kwak’wala: A phonological approach

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Abstract

This paper presents the phonological layer of a Kwak’wala finite-state morphological transducer, using the phonological hypotheses of Lincoln and Rath (1986) and the “lenient composition” operation of Karttunen (1998) to mediate the complicated relationship between underlying and surface forms. The resulting system decomposes the wide variety of surface forms in such a way that the morphological layer can be specified using unique and largely concatenative morphemes.

1 Introduction

Kwak’wala1 (ISO 639-3: kwk) is a Northern Wakashan language of British Columbia, spoken primarily on the northern part of Vancouver Island, the adjacent mainland, and the islands in between. Kwak’wala morphology and morphophonology is famously complex; words are frequently made up of many morphemes, and these morphemes can cause dramatic changes in the surface realizations of words.

As a basic example, the root for “man” can occur in various forms depending on the suffixes with which it occurs, and in some of these words (the three ending in -\@m) the identity of the suffix can only be distinguished by the effects (lenition, fortition, vowel lengthening, or reduplication) that it has on the root:

\begin{verbatim}
 bag\@m an\@m “man”
 bag\@s ans “visitor” (literally, “unexpected man”)
 bak\@m om “without expression, sternly” (literally, “man-face”) (FirstVoices, 2009)
 bak\@s os “Wildman of the forest”
 bak\@m om “First Nations person” (literally, “genuine man”)
 babag\@m om “boy”
\end{verbatim}

This is compounded by suffixes potentially changing syllable structure as well, which further increases the apparent variety of surface forms:

\begin{verbatim}
 de “to wipe” (Boas et al., 1947)
 di\@x?id “to wipe something” (FirstVoices, 2009)
 day\@xst\@xand “to wipe one’s mouth” (FirstVoices, 2009)
 da\@x?e\@xlb\@xand “to wipe one’s nose” (FirstVoices, 2009)
\end{verbatim}

The combination of mutation and resyllabification can cause a complete restructuring of the word. For example, adding the participial suffix -\@l to the root pix\@l- (“feel”) results not in something like [*pix\@l\@l] but rather [poy\@xul], in which only the first and last letters remain intact.

\footnote{1Strictly speaking, Kwak’wala is the most-spoken variety of a larger language for which there is no completely-agreed-upon name. This language is often also called Kwak’wala, but some speakers prefer a more general term Bak’wamk’ala (Littell, 2016, pp. 29–30).}

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Given such changes, a grammar engineer has two potential avenues of approach to Kwak’wala morphology:

1. Assume that Kwak’wala has a fairly straightforward relationship between phonemes and surface phones, but that roots and suffixes fall into a large number of derivational classes that behave differently when certain suffixes are added.

2. Assume that Kwak’wala has a comparatively straightforward agglutinative morphology, with morphemes that have unique forms and are mostly separable at the phonemic level, and that the apparent diversity of surface forms is due to a complex phonological component.

The FST described in this paper leans towards the second approach, meaning that the lion’s share of the difficult work will be in the phonological component, while the morphological component should be (mostly) concatenative and assume (where possible) one unique form for each morpheme. Given this, this paper concentrates on creating the phonological component, the success or failure of which determines what form the morphological component must take. The phonological component uses the “lenient composition” technique of Karttunen (1998) to express Kwak’wala phonology in an Optimality-Theoretic way, while maintaining the linear-time efficiency of a finite-state system. This is, to our knowledge, the first attempt at computationalizing Kwak’wala morphophonology.

The downside of the phonological approach here is that there are few people who have a mastery of this particular style of Northern Wakashan phonological analysis, and thus while the resulting system is simpler, it can be difficult even for someone familiar with Kwak’wala to look at the resulting grammar and understand what is going on. To try to mitigate this, we are attempting to write this grammar in a “literate” (in the sense of Knuth (1992) and Maxwell (2012)) style, with a greater proportion of human-readable prose accompanied by relatively short snippets of executable code.

2 Motivation

Figure 1: An excerpt from Boas and Hunt (1902). The stories, songs, history, and oratory collected by Boas and Hunt constitute a substantial body of text—still the largest corpus of Kwak’wala—and contain much that is of cultural and linguistic interest to this day. However, few modern readers can read this orthography.

The FST described in this paper is intended as part of a spell-checking system, initially intended to help guide the optical character recognition (OCR) of historical texts (e.g. Boas and Hunt (1902)). There
are extensive high-quality scans of documents from the early 20th century, but they are written in an orthography that most modern readers find impenetrable. OCR is the first step to unlocking this content for modern readers. It may also be the case that the resulting spellchecker can be useful for end-users (e.g. in a word processor) and other downstream tasks.

Since we do not have a complete lexicon of Kwak’wala, we cannot at this point design a system that divides actual Kwak’wala words from non-actual ones. Rather, this system has to divide possible Kwak’wala words from impossible ones.

This is, however, probably much of what we want a low-resource spell-checker to do. We do not want to limit an OCR system for historical texts, for example, to words known in the modern era; part of the reason for engaging with these texts is to rediscover words that are no longer commonly used. We do, however, want to avoid hypothesizing forms that could not be Kwak’wala words.

The morphophonological complexity of Kwak’wala presents an opportunity here, and not just a challenge. Because the morphophonology shapes words in particular ways, given an unknown word we can, with some degree of confidence, (1) guess that it is a Kwak’wala word and (2) have some idea of its structure, even if its meaning, and the meaning of its components, are unclear. For example, even if we do not know that the following word means “school”, we can determine from its shape that it probably is a Kwak’wala word (not a loanword, or a sequence of random characters, or an OCR error) and that it has four or five component morphemes (because it contains three or four phoneme sequences that we associate with changes that happen across morpheme boundaries).

(4) qaʔiʔaʔci
qa-qa\w\-a-as-si
try-know-try-LOC-NOMINAL

“school” (literally: “building where one learns”)

3 A phonological approach to the complexity of Kwak’wala morphology

Kwak’wala is noted for its highly complex morphology and morphophonology, and is, by the definition of polysynthesis in Anderson (1985), the prototypical polysynthetic language. There are roughly 400–500 suffixal or enclitic elements that can be added to roots, many of which (the “lexical suffixes”) have quite concrete meanings of the sort that few languages (outside of the Wakashan and some neighboring languages) express in suffixes. These suffixes express body parts, different sorts of ground the action is done on (e.g. on the beach, on manmade surfaces, in a forest, in a boat, etc.), shapes, paths of motion, and even different kinds of physical technology (e.g. tools vs. containers vs. work surfaces vs. headgear). In addition to this, there is also a layer of inflectional morphology, and beyond this a tendency for all small particle-like words that follow the word to encliticize to the previous word.

On top of this, Kwak’wala phonology and morphophonology is also highly complex, with suffixes causing a variety of mutations (particularly fortition and lenition) in the bases to which they attach. These mutations can then interact with the syllabification, stress, and vowel derivation systems to cause surprising alternations, as in (3).

In order to compartmentalize this complexity, we assume a phonology roughly equivalent to that of Lincoln and Rath (1980) and Lincoln and Rath (1986), which posited that Northern Wakashan words consist underlyingly of sequences of consonants (e.g. /py\w\/ for [p\w\y\] and /kn\w\/ for [k\w\n\w]), although this component will probably also undergo further development with the flood of new historical text that will become available due to OCR.

It depends, however, on which definition of polysynthesis one uses. Anderson’s definition (which comes out of his own research on Kwak’wala) only requires that the language typically expresses within words what other languages require whole sentences for. On the other hand, if we take the definition of polysynthesis in Baker (1996), which requires verbal inflection for particular structural arguments, Kwak’wala is probably not polysynthetic; much of the complexity of Kwak’wala morphology is probably not inflectional per se and does not necessarily involve the arguments intended by Baker.

Kwak’wala also has famously complex reduplication patterns (Struijke, 1998; Struijke, 2000), but this system does not yet attempt to account for them.

2The second step, conversion between historical and modern orthographies, is already available at orth.nfshost.com, although this component will probably also undergo further development with the flood of new historical text that will become available due to OCR.

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which are vocalized by the epenthesis of schwas and the realization of particular consonants as syllabic nuclei (here, the lenition of /ˈkw/ to /w/ and /s/ to /y/, respectively, and their subsequent vocalization to [u] and [i]). Since suffixes affect syllabification and can mutate consonants (and thus change their potential vocalizations), different root+suffix combinations can appear to have dramatically different surface forms.

4 Implementation

The phonological transducer is written in the Foma (Hulden, 2009) implementation of the XFST language (Beesley and Karttunen, 2003). More specifically, it is written using the Python bindings for Foma, allowing the automation of boilerplate code in Python and the use of Jupyter for “literate programming” (Knuth, 1992; Maxwell and Amith, 2005; Maxwell, 2012) (Fig. 2).

Figure 2: Example of a “literate programming” style, which conceptualizes the primary consumer of code to be human (and thus interested in understanding either the code or the phenomenon that the code purports to capture), and augments this human-consumable description with pieces of machine-interpretable code (in this case XFST regular expressions, interpreted by Foma via a Python interface).

There is not currently a lexical component (e.g. an LEXC file filled with known morphemes); rather, a “guesser” allows any well-formed underlying form. In the future, this will be filled by a devoted lexical component, but since the structure of that component depends largely on whether this phonological component is successful, it has been left to future research. In this experiment, the underlying forms are drawn from a field corpus that includes proposals of underlying forms (§6.1).

5 Phonology and morphophonology in XFST

5.1 Phonetic and phonemic inventory

Kwak’wala has a large phonetic inventory and a complex phonology that is not yet completely understood (particularly concerning the vowel inventory). There are 42 consonants, all of which are underlying5. There are approximately 10-12 distinct vowel qualities, but this system follows most modern Kwak’wala

5It is possible that [h] is epenthetic, and may historically have been so, but it is not possible to posit that both [h] and [a] are epenthetic due to words like [hominu] (“butterfly”). Assuming that [a] is always epenthetic has significant explanatory power for many otherwise-puzzling forms, so this system must assume that /h/ is underlying.
orthographies in representing six distinct surface vowels [ə, a, e, i, o, u]; the surface vowel qualities are almost entirely predictable from the orthographic form.

In a Lincoln and Rath-style (1980, 1986) Northern Wakashan phonology, underlying forms consist primarily of consonants and most vowels are derived (either epenthetic or derived from consonants). Unlike Lincoln and Rath, whose phonemicization is entirely consonantal, we allow three actual underlying vowels, /a/, /i/, and /u/, although all are marginal in some way. [i] and [u] are probably often underlyingly /y/ and /w/, but a few forms suggest that /i/~/y/ and /u/~/w/ cannot completely be unified, and we typically default to positing that surface [i] and [u] are underlyingly /i/ and /u/ unless there is specific evidence otherwise. Lincoln and Rath also posit that [a] is a realization of /h/; we instead treat it as a separate phoneme.

5.2 Orthography

Roughly six distinct Kwak’wala orthographies can be identified, in three families:

1. Two stages (early and late) of the orthography used by Boas and his collaborators, and seen in Fig. 1. Most modern readers cannot read this orthography.

2. Two similar orthographies based on Royal British Columbia Museum conventions. The more recent version of this style, called “U’mista” script after the U’mista Cultural Centre in Alert Bay, is the de facto standard for most communities, and is the orthography in which modern books are published.

3. Two variants of the Americanist Phonetic Alphabet, typically used by linguists in the region, and seen in this paper.

The example forms given in this paper are orthographic rather than phonetic, using the typical six orthographic vowels; specifically, this paper is written using the University of Victoria variant of the North American Phonetic Alphabet (NAPA). A caron indicates a uvular consonant, and an apostrophe above a letter represents glottalization; the barred lambda [Ŀ] indicates a voiceless lateral affricate.

Although it is intended to be used mostly for documents written in (1)- or (2)-type orthographies, the transducer uses a NAPA orthography internally, because NAPA-type orthographies allow the unambiguous expression of Lincoln-and-Rath-style underlying forms, and allow the differentiation of all the sounds in the test corpus (§6.1).

5.3 Syllabification

For some languages, one can dispense with a detailed syllabification when writing a practical morphological FST, since one can define environments (like “onset”) in terms of linear consonant/vowel phonotactics (e.g., “consonant before a vowel”). In Kwak’wala, it is crucial to determine the actual syllabification, because the entire word might consist of consonant phonemes; a phoneme will be realized as a consonant or a vowel depending on its syllabification, which can change depending on a variety of factors.

To determine syllable structure, we adopt an approach outlined in Karttunen (1998), in which Optimality Theory-like violable constraints (Prince and Smolensky, 1993) on syllable structure are implemented via the “lenient composition” of transducers.

A lenient composition X .O. Y acts as a regular composition X .o. Y when the range of X overlaps with the domain of Y; otherwise, X is used alone. This allows the expression of constraints that can be violated: they apply if they would produce output – that is, if there are some “live” candidates that would successfully pass their test – but if they would result in an empty set of outputs they do not apply.

5.4 Counting constraints

Much of the implementation complexity – and the resulting size of the network – comes from the necessity for some constraints to count how many violations of them occur.

For example, consider a DEP constraint (“don’t epenthesize”) against the epenthesis of schwas – call this “NoSchwa”. We can compose this (by lenient composition) with our generator function GEN (which
define NoSchwa `[$ schwa ] ;
define GRAMMAR GEN .O. NoSchwa

Figure 3: Example XFST code illustrating a constraint that cannot count the number of violations.

creates candidate forms) to exclude forms with schwas when schwa-less forms exist, but to allow forms with schwas when that is the only possibility (Fig. 3).

This is not, however, what we want from the system: we want it to minimize the number of schwas. The automaton above cannot count schwas; a word with two schwas (like ṅ̓̓t̓̓m̀̓, “hat”) is just as bad within this system as a word with three (like ṅ̓̓t̓̓m̓̀), so any input that successfully generates the correct form ṅ̓̓t̓̓m̀̓ will also generate every possible form with additional schwas like ṅ̓̓t̓̓m̓̀m̀.

It is therefore necessary to compose constraints that count schwas (Fig. 4).

define NoSchwa0 `[$ schwa ] ;
define NoSchwa1 `[$ schwa ]>1 ;
define NoSchwa2 `[$ schwa ]>2 ;
define NoSchwa3 `[$ schwa ]>3 ;
define GRAMMAR GEN .O. NoSchwa .O. NoSchwa1 .O. NoSchwa2 .O. NoSchwa3 ;

Figure 4: Example XFST code illustrating constraints that can count violations.

Each of these constraints allows a specific number of schwas through, but no more. This allows us to capture the idea that violable constraints are sensitive to the number of violations; we can picture this implementation as a decomposition of the tableau on the left of Fig. 5 to the tableau on the right.

| /Atml/ | NoSchwa | /Atml/ | NoSchwa0 | NoSchwa1 | NoSchwa2 | NoSchwa3 |
|-------|---------|-------|----------|----------|----------|----------|
| ṅ̓̓t̓̓m̀̓ | ** | ṅ̓̓t̓̓m̀̓ | * | * | * | * |
| ṅ̓̓t̓̓m̓̀ | *** | ṅ̓̓t̓̓m̓̀ | ** | * | * | * |

Figure 5: Left: An Optimality-Theoretic tableau illustrating how a form with fewer schwas is preferred over a form with more. Right: A representation of the actual implementation of this constraint in a finite-state system. The pointing finger indicates the “winning” candidate: the form that remains when all other forms have been excluded due to violating a higher-ranked constraint.

Since this is largely boilerplate code, we automate it by defining a slightly higher-level language in Python (e.g., a macro-style function constrain("schwa", max=3)) and then transpile that to code like that in Fig. 4.

6 Experiment and Results

In this paper, we evaluate the phonological transducer by considering whether it can generate the attested surface forms in a corpus that contains both surface (e.g. ṅ̓̓t̓̓m̀̓) and proposed underlying (e.g. ṅ̓̓t̓̓m̓̀) forms.

We are primarily interested in recall here (how many of the attested surface forms the system can generate), but since the underlying-to-surface relationship in this corpus is one-to-many (there are multiple valid ways to transcribe a given form), we also report precision and F1, as an attempt to avoid overgenerating and producing unattested surface forms.7

6There is little valid ambiguity, however, in how a surface form corresponds to an underlying form. There are many instances where the underlying form is unclear due to our incomplete understanding of the phonology, and many instances where the corpus happens to be inconsistent in how it presents underlying forms, but there are few if any instances in which different underlying forms happen to be pronounced identically.

7Although this transducer is scored on a somewhat “canned” dataset, it is still not possible to achieve 1.0 precision and F1; leaving aside errors in the corpus and loanwords that do not follow Kwâk’wała phonology, there is genuine variation in
The documents in the corpus are divided into a 75% development set (on which we did error analysis while writing the grammar) and a 25% test set (which we did not look at), to test whether the rules proposed to handle the development set generalize to unseen documents.

### 6.1 Corpus

|                | Development set | Test set |
|----------------|-----------------|----------|
| Documents      | 230             | 77       |
| Word types     | 4575            | 1490     |
| Word tokens    | 12610           | 3317     |

Table 1: Document, type, and token counts for the development and test sets

This transducer was tested on our own fieldwork corpus, currently part of the private archives at the Whatcom Museum in Bellingham, WA, representing field interviews with eight speakers of Kwak’wala.

Each word in the corpus is given a proposed underlying form, although there is some variation in how these forms are presented. In particular, there are cases where morphemes are or are not separated, or distinctions that are or are not made, according to the purpose of this example. In addition, there are various morphemes whose status as a suffix or enclitic is unclear, and which may at different points be analyzed as either. For this reason, we are only interested here in evaluating the “downward” direction of the transducer (that is, generating possible orthographic surface forms from underlying forms), rather than the “upward” direction (that is, parsing surface forms into proposed underlying forms); the latter represents a set of changing conventions of little current practical interest.

### 6.2 Results and Discussion

Figure 6 gives the recall, precision, and F1 for the baseline system and a number of improvements to the phonological rules and constraints.

While this is more detail than is typically reported for grammar development, and the particular changes are probably of interest only to Wakashanist phonologists, we thought it was illustrative to show the progression of development. In particular, it illustrates that expert system development is not always hill-climbing, and some changes cause losses that are repaired only by later development; for example, the epenthesis of schwas leads to a large precision drop due to overgeneration, but many of these forms are later avoided by allowing a more complex syllable structure.

The baseline system only removes elements like word and morpheme boundaries, and makes no further changes in between the underlying form and the surface form. As the baseline system only has a recall of 30.6%, this means that about 69.4% of Kwak’wala word tokens\(^8\) have a more complex syllable structure or undergo some sort of phonological or morphological change before surfacing.

Beyond the baseline, additional improvements to the phonological system typically made steady improvements to recall, and had various effects (positive and negative) on precision. We generally did not take a loss of precision to be necessarily bad, as typically many of the new forms predicted were indeed possible pronunciations of words, although not attested in this small corpus; a precision loss is something to investigate further here, but not necessarily reject a rule or constraint over.

Of special note is the spirantization of /ň/, /k/, /kw/, /q/, and /qw/ in syllable codas to [ı], [x], [xw], [x], and [xw] respectively. This change is nearly (but not entirely) obligatory in the speech of our consultants, but historically it was more variable. Specifying this change as optional caused a noticeable drop in precision (as many of the predicted non-spirant forms are not attested in our modern corpus), but it is still valuable to allow them given that such forms do occur more frequently in historical texts.

Analysis of a sample of errors suggests that most are of two types: errors in the corpus itself, and phenomena that we had inadequately annotated in underlying forms (especially which initial phonemes pronunciation (both free variation and variation between speakers) such that not every possible realization of an underlying form is attested in the corpus.

\(^8\)At the word type level, the baseline system has a recall of 14.1%, meaning that about 85.9% of word types have more complex syllable structure or phonology.
| System                                      | Development set | Test set          |
|---------------------------------------------|-----------------|-------------------|
|                                             | Recall          | Precision | F1     | Recall | Precision | F1     |
| Baseline system                             | 0.306           | 0.595     | 0.404  | 0.288  | 0.558     | 0.380  |
| Epenthesis of schwas                        | 0.382           | 0.405     | 0.393  | 0.351  | 0.372     | 0.361  |
| Avoid final schwas                          | 0.382           | 0.436     | 0.408  | 0.351  | 0.400     | 0.374  |
| Resonant and special nuclei                 | 0.479           | 0.548     | 0.511  | 0.458  | 0.523     | 0.488  |
| Additional coda possibilities               | 0.523           | 0.607     | 0.562  | 0.492  | 0.571     | 0.528  |
| Monophthongize /aw, ay, aw, ay/             | 0.525           | 0.604     | 0.562  | 0.494  | 0.564     | 0.527  |
| Fortition/lenition of plain consonants      | 0.589           | 0.576     | 0.582  | 0.561  | 0.539     | 0.550  |
| Fortition/lenition special cases            | 0.599           | 0.582     | 0.590  | 0.573  | 0.548     | 0.560  |
| Glottalization of /m, l/                    | 0.633           | 0.586     | 0.609  | 0.610  | 0.561     | 0.584  |
| Spirantization of /k, k, kw, q, qw/ in codas| 0.652           | 0.546     | 0.595  | 0.634  | 0.515     | 0.568  |
| Avoiding resonant onsets                    | 0.684           | 0.624     | 0.653  | 0.667  | 0.591     | 0.627  |
| Morpheme-initial deletion                   | 0.722           | 0.662     | 0.690  | 0.716  | 0.635     | 0.673  |
| Hiatus resolution special cases             | 0.757           | 0.612     | 0.677  | 0.743  | 0.610     | 0.670  |

Figure 6: Improvements to recall (red solid line), precision (purple dashed line), and F1 (black dotted line) on the development (left) and test (right) documents by the implementation of specific phonological rules and constraints.

...of suffixes can and cannot be dropped). We did not, however, fix any errors during the course of this experiment, so that score improvement would reflect only development effort, not re-annotation.

The remaining errors, however, suggest there are still some missing aspects of our understanding of Kwak’wala morphophonology (e.g., exactly when [a] or [a] is inserted at morpheme boundaries) or that some of the assumptions that we had made when proposing underlying forms may be too strict (e.g. the assumption that there are only three underlying vowels). These are things we had previously suspected, but the development of an explicit computational system such as this helps to identify (and perhaps even quantify) those parts of Kwak’wala phonology and morphophonology for which our understanding is incomplete.

7 Further development

As continued development unearths an increasing percentage of errors and idiosyncrasies in the corpus itself, it may be beneficial in further development to switch to a new corpus, so that additional rules/constraints are more likely to generalize to text by other authors, rather than overfit to our own style of
transcription and analysis. Also, this component is only one part of the intended OCR pipeline, which will also require:

- An OCR model to extract texts in historical orthographies. Fortuitously, Hubert et al. (2016) has already trained a model to recognize historical text in Haida that used the same font and almost all the same diacritics.

- A conversion system between the historical orthography and modern orthographies. Such a system already exists at orth.nfshost.com, however it implements a one-to-one correspondence that would be inappropriate for this task. A many-to-many orthographic transducer may, however, be adapted using its conversion tables as a starting point.

- A morphological component specifying the known roots, suffixes, and enclitics of Kwak’wala, as well as the possible arrangements of these.

These three components, along with the phonological component here, should help to correct and normalize errors in the recognition of historical texts, and thus help make the Boas corpus more accessible to modern readers and researchers.

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