Finite-state script normalization and processing utilities: The Nisaba Brahmic library

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Abstract
This paper presents an open-source library for efficient low-level processing of ten major South Asian Brahmic scripts. The library provides a flexible and extensible framework for supporting crucial operations on Brahmic scripts, such as NFC, visual normalization, reversible transliteration, and validity checks, implemented in Python within a finite-state transducer formalism. We survey some common Brahmic script issues that may adversely affect the performance of downstream NLP tasks, and provide the rationale for finite-state design and system implementation details.

1 Introduction
The Unicode Standard separates the representation of text from its specific graphical rendering: text is encoded as a sequence of characters, which, at presentation time are then collectively rendered into the appropriate sequence of glyphs for display. This can occasionally result in many-to-one mappings, where several distinctly-encoded strings can result in identical display. For example, Latin script letters with diacritics such as “é” can generally be encoded as either: (a) a pair of the base letter (e.g., “e” which is U+0065 from Unicode’s Basic Latin block, corresponding to ASCII) and a diacritic (in this case U+0301 from the Combining Diacritical Marks block); or (b) a single character that represents the grapheme directly (U+00E9 or the Latin-1 Supplement Unicode block). Both encodings yield visually identical text, hence text is often normalized to a conventionalized normal form, such as the well-known Normalization Form C (NFC), so that visually identical words are mapped to a conventionalized representative of their equivalence class for downstream processing. Critically, NFC normalization falls far short of a complete handling of such many-to-one phenomena in Unicode.

In addition to such normalization issues, some scripts also have well-formedness constraints, i.e., not all strings of Unicode characters from a single script correspond to a valid (i.e., legible) grapheme sequence in the script. Such constraints do not apply in the basic Latin alphabet, where any permutation of letters can be rendered as a valid string (e.g., for use as an acronym). The Brahmic family of scripts, however, including the Devanagari script used to write Hindi, Marathi and many other South Asian languages, do have such constraints. These scripts are alphasyllabaries, meaning that they are structured around orthographic syllables (aksara) as the basic unit.† One or more Unicode characters combine when rendering one of thousands of legible aksaras, but many combinations do not correspond to any aksara. Given a token in these scripts, one may want to (a) normalize it to a canonical form; and (b) check whether it is a well-formed sequence of aksara.

Brahmic scripts are heavily used across South Asia and have official status in India, Bangladesh, Nepal, Sri Lanka and beyond (Cardona and Jain, 2007; Steever, 2019). Despite evident progress in localization standards (Unicode Consortium, 2019) and improvements in associated technologies such as input methods (Hinkle et al., 2013) and character recognition (Pal et al., 2012), Brahmic script processing still poses important challenges due to the inherent differences between these writing systems and those which historically have been more dominant in information technology (Sinha, 2009; Bhattacharyya et al., 2019).

In this paper, we present Nisaba, an open-source software library,2 which provides processing utilities for ten major Brahmic scripts of South Asia: Bengali, Devanagari, Gujarati, Gurmukhi, Kannada, Malayalam, Oriya (Odia), Sinhala, Tamil,

†See §3 for details on the scripts.
‡https://github.com/google-research/nisaba/
and Telugu. In addition to string normalization and well-formedness processing, the library also includes utilities for the deterministic and reversible romanization of these scripts, i.e., transliteration from each script to and from the Latin script (Wellisch, 1978). While the resulting romanizations are standardized in a way that may or may not correspond to how native speakers tend to romanize the text in informal communication (see, e.g., Roark et al., 2020), such a default romanization can permit easy inspection of an approximate version of the linguistic strings for those who read the Latin script but not the specific Brahmic script being examined.

As a whole, the library provides important utilities for language processing applications of South Asian languages using Brahmic scripts. The design is based on the observation that, while there are considerable superficial differences between these scripts, they follow the same encoding model in Unicode, and maintain a very similar character repertoire having evolved from the same source — the Brāhmī script (Salomon, 1996; Fedorova, 2012). This observation lends itself to the script-agnostic design (outlined in §4) that, unlike other approaches reviewed in §2, is based on the weighted finite state transducer (WFST) formalism (Mohri, 2004). The details of our system are provided in §5.

2 Related Work

The computational processing of Brahmic scripts is not a new topic, with the first applications dating back to the early formal syntactic work by Datta (1984). With an increased focus on the South Asian languages within the NLP community, facilitated by advances in machine learning and the increased availability of relevant corpora, multiple script processing solutions have emerged. Some of these toolkits, such as statistical machine translation-based Brahmi-Net (Kunchukuttan et al., 2015), are model-based, while others, such as URoman (Hermjakob et al., 2018), IndicNLP (Kunchukuttan, 2020), and Aksharamukha (Rajan, 2020), employ rules. The main focus of these libraries is script conversion and romanization. In this capacity they were successfully employed in diverse downstream multilingual NLP tasks such as neural machine translation (Zhang et al., 2020; Amrhein and Sennrich, 2020), morphological analysis (Hauer et al., 2019; Murkinati et al., 2020), named entity recognition (Huang et al., 2019) and part-of-speech tagging (Cardenas et al., 2019).

Similar to the software mentioned above, our library does provide romanization, but unlike some of the packages, such as URoman, we guarantee reversibility from Latin back to the native script. Similar to others we do not focus on faithful invertible transliteration of named entities which typically requires model-based approaches (Sequiera et al., 2014). Unlike the IndicNLP package, our software does not provide morphological analysis, but instead offers significantly richer script normalization capabilities than other packages. These capabilities are functionally separated into normalization to Normalization Form C (NFC) and visual normalization. Additionally, our library provides extensive script-specific well-formedness grammars. Finally, in contrast to these other approaches, grammars in our library are maintained separately from the code for compilation and application, allowing for maintenance of existing scripts and languages plus extension to new ones without having to modify any code. This is particularly important given that Unicode standards do change over time and there remain many languages left to cover.

To the best of our knowledge this is the first publicly available general finite-state grammar approach for low-level processing of multiple Brahmic scripts since the early formal syntactic work by Datta (1984) and is the first such library designed based on an observation by Sproat (2003) that the fundamental organizing principles of the Brahmic scripts can be algebraically formalized. In particular, all the core components of our library (inverse romanization, normalization and well-formedness) are compactly and efficiently represented as finite state transducers. Such formalization lends itself particularly well to run-time or offline integration with any finite state processing pipeline, such as decoder components of input methods (Ouyang et al., 2017; Hellsten et al., 2017), text normalization for automatic speech recognition and text-to-speech synthesis (Zhang et al., 2019), among other natural language and speech applications.

3 Brahmic Scripts: An Overview

The scripts of interest have evolved from the ancient Brāhmī writing system that was recorded
Table 1: Sizes of core graphemic classes: Independent vowels (iv), dependent vowel diacritics (dv), consonants (c), coda symbols (co).

| Name    | Id  | Iv | Dv | C  | Co |
|---------|-----|----|----|----|----|
| Bengali | BENG | 16 | 13 | 43 | 5  |
| Devanagari | DEVA | 19 | 17 | 45 | 4  |
| Gujarati | GUJR | 16 | 15 | 39 | 5  |
| Gurmukhi | GURU | 12 | 9  | 39 | 8  |
| Kannada | KND | 15 | 14 | 39 | 3  |
| Malayalam | MLYM | 16 | 16 | 38 | 10 |
| Oriya   | ORYA | 14 | 13 | 38 | 5  |
| Sinhala | STNH | 18 | 17 | 41 | 2  |
| Tamil   | TAML | 12 | 11 | 27 | 1  |
| Telugu  | TELU | 16 | 15 | 38 | 5  |

Table 2: NFC examples for Devanagari.

| Visual | Legacy sequence | NFC normalized |
|--------|-----------------|----------------|
| ं     | NA NKTA (U+0928 U+093C) | NNNA (U+0929) |
| क     | QA (U+0958) | KA NKTA (U+0915 U+093C) |

The vowels, virama, serve important consonants. As Bright (1999) notes, it is often translated as “syllable” although it does not bear direct correspondence to a syllable of speech, but rather to an orthographic syllable. The structure, or “grammar” of an aksara is based on the following common principles: an aksara often consists of a consonant symbol C, by default bearing an unmarked inherent vowel or attached diacritic (dependent) vowel sign v (Cv); but it may also be an independent vowel symbol V, or a consonant symbol with its inherent vowel “muted” by a special virama diacritic _CONN (Cv). In any of these preceding scenarios, the base consonant C can be replaced by a consonant cluster where all but the last consonant lose their inherent vowel. When the individual component consonants of the cluster combine to form a composite form, precluding the use of an overt virama diacritic, this is known as a “consonant conjunct” (e.g., C₁VᵣC₃C₅ vs [CᵣCₛC₅]³) (Fedorova, 2013; Bright, 1999; Coulmas, 1999; Share and Daniels, 2016).

The elements of the aksara grammar described above can be grouped into several natural classes. The sizes of the core classes are shown in Table 1 for each writing system and its corresponding ISO 15924 identifier in uppercase format (ISO, 2004). The major classes are the independent vowels (e.g., the Devanagari diphthong ं, the dependent vowel diacritics (e.g., the Gujarati ञ), and the consonants (e.g., the Gurmukhi ं). Another important class consists of the coda consonant symbols, like anusvara, chandrabindu, and visarga, which modify the aksara as a whole (and follow and vowel signs in the memory representation). Finally, there is a class of special characters, such as the religious symbol Om ः, that behave like independent aksara.

Unicode Normalization Unicode defines several normalization forms which are used for checking whether the two Unicode strings are equivalent to each other (Unicode Consortium, 2019). In our library we support Normalization Form C (NFC) which is well suited for comparing visually identical strings. This normalization generally converts strings to the equivalent form that uses composite characters. Table 2 shows two examples of legacy sequences corresponding canonically equivalent forms for Devanagari.

Visual Normalization As was mentioned above, an aksara may be represented by multiple Unicode character sequences and the goal of NFC normalization is to convert them to their unique canonical form. However, there are many Unicode character sequences that fall outside the scope of NFC algorithm. We provide visual normalization that, in addition to providing the NFC functionality, also supports transforming such legacy sequences. Some of the rules are provided as “Do Not Use” tables by the Unicode Consortium (2019) that recommends transformations from legacy sequences to their corresponding canonical form, such as Devanagari { ं (U+0905), “ (U+0945) } → ः (U+0972). We also included transformations for visually identical sequences (under many implementations) which are commonly found on the Web, such as Devanagari { ं (U+0910), “ (U+0947) } → ः (U+0910).³

Well-formedness Check A well-formedness acceptor verifies whether the given text is readable in a particular script or not. It would be hard for the native reader to visually parse the text if the script rules are not followed. For example, the reader

³These classes are documented in https://github.com/google-research/nisaba/blob/main/nisaba/brahmic/mappings.md.

³Here the combining vowel sign U+0947 does not affect the compound glyph’s visual appearance hence is removed.
Table 3: Examples for additions to ISO 15919.

does not expect two vowels signs on a single consonant and such a thing may not even be possible to reasonably draw. Furthermore, unlike the Latin script, acronyms are not written using arbitrary letter sequences, they are formed only as a sequence of aksāra. Our approach verifies whether the text is a sequence of well-formed aksāra using the grammar described above.

Reversible ISO Transliteration ISO 15919 represents a unified 8-bit Latin transliteration scheme for major South Asian Brahmic scripts (ISO, 2001). Since it has not been updated with the characters that were introduced to the Unicode standard after 2001, we have added additional mappings, with some examples shown in Table 3. These additions are crucial because they allow us to reverse the romanizations to get the original Brahmic strings back reliably. This property allows various data processing pipelines to use the romanized text as an internal representation and convert it back to the original native script at the output stage.

Language-specific Logic Several South Asian languages often share the same script with some, often minor, language-specific differences. Our library supports language-specific customizations that can be combined with language-agnostic script logic. For example, the modern Bengali–Assamese script (Beng) is shared by both Bengali and Assamese languages, among others (Brandt and Sohoni, 2018). For both of these languages our library provides customizations, such as the transformations required for visual normalization of Assamese that transform Bengali letter ra into its Assamese equivalent when it participates in a consonant conjunct (which generally occurs when following or preceding virama, e.g., \{ র (U+09B0), র (U+09CD) \} → \{ র (U+09B0), র (U+09CD) \}.

4 The Finite-State Approach

The Brahmic script manipulation operations described above have a natural interpretation grounded in formal language theory. We treat the text corpus in a given script as a set of strings over some finite alphabet Σ that defines a set of admissible script symbols. The set of zero or more strings is known as language which, in its simplest (regular) form, can be succinctly described (or recognized) by a finite state automaton (FSA) or acceptor (Yu, 1997). Two simple FSAs that represent the Gujarati word દસ ("ten") over an alphabet of Unicode code points (top) and bytes (bottom).

Figure 1: String acceptors for Gujarati word દસ ("ten") over an alphabet of Unicode code points (top) and bytes (bottom).

Figure 2: Simplified construction of the well-formed automaton \( W \).

Figure 3: Automata constructed from sequences of letters in the Gujarati script.
formed check from the previous section is shown in Figure 2. In this simplified example, the paths through the automaton that define a legal consonant cluster (line 2 of the algorithm) are represented by a sub-automaton that recognizes the language that consists of strings formed from the consonant and virama symbols only, where each consonant, apart from the last one, must be followed by the virama that removes an inherent vowel.

The rest of the operations on the Brahmic scripts, namely the normalization and transliteration, involve modifications of the Brahmic script inputs. Such operations are naturally expressed by finite state transducers (FSTs), which are a generalization of the FSA concept used to encode string-string relations (or transductions), by modifying the automata arcs to have pairs of labels from input and output alphabets, instead of single labels. A trivial romanization in our representation of the two Sinhala words එක වර්මා (eka, “one”) and බොර්මා (deka, “two”) is shown in Figure 3. Note the “vocalization” of the final consonant by insertion of a schwa via an input $\varepsilon$-transition. Also note that the path accepting the second word is longer. The word බොර්මා consists of three asra-initial independent vowels (line 9).

The two remaining operations on asra, namely NFC and visual normalization, are represented in our library using the context-dependent rewrite rules from the formal approach popularized by Chomsky and Halle (1968). The normalization rules are represented as a sequence $\{ \phi \rightarrow \psi \lambda \rho \}$, where the source $\phi$ is rewritten as $\psi$ if its left and right contexts are $\lambda$ and $\rho$. For an earlier example from §3, a single NFC normalization rule rewrites the Devanagari string $\phi = "\text{n}"$ (na, $U+0928$) $\rightarrow"\text{n}"$ (nnna, $U+0932$) into its canonical composition $\psi = "\text{n}"$ (nnna, $U+0929$).

Kaplan and Kay (1994) proposed an algorithm for compiling such sequences into an FST. This approach was further improved and extended to WFSTs by Mohri and Sproat (1996), whose algorithm we use to compile sequences of NFC and visual normalization rules into transducers denoted $N$ and $V$.

Finally, the transducers representing language-specific customizations of a particular script operation are compiled by composing the generic language-agnostic transducer, such as the Devanagari visual normalizer, with the transducer representing transformations that capture language-specific use of the script, e.g., Devanagari for Nepali.

5 System Details and Demo

The core of the Nisaba Brahmic script manipulation library resides under the brahmic directory of the distribution. In this section we provide details for how to build and use the library and also explore its application to visual normalization of Wikipedia-based text in 9 of these scripts.

Prerequisites We use Bazel (Google, 2020) as a primary build environment. For compiling the
Table 4: Properties of script FSTs arranged by operation and symbol types (Unicode code points and UTF-8 bytes), where 𝒴 denotes the ISO transliteration operation, 𝑽 is the NFC normalization, 𝑴 denotes visual normalization, and 𝔾 is the well-formed check. The numbers of states and arcs are denoted by 𝑁 , and 𝑁 𝑎, respectively.

| Op. | Symb. | Prop. | BENG | DEVA | GUJR | ORYA | KODA | MLYM | ORYA | SJMU | TAMIL | TELU |
|-----|-------|-------|------|------|------|------|------|------|------|------|-------|------|
| Unicode | 𝒴 | 𝑁 | 127 | 130 | 113 | 93 | 119 | 122 | 105 | 122 | 75 | 112 |
| Unicode | 𝑽 | 𝑁 | 475 | 546 | 476 | 418 | 487 | 522 | 452 | 513 | 326 | 485 |
| Unicode | 𝔾 | 𝑁 | 248 | 235 | 195 | 171 | 210 | 201 | 178 | 192 | 126 | 181 |
| Unicode | 𝔾 | 𝑁 | 384 | 399 | 334 | 288 | 350 | 345 | 305 | 339 | 229 | 318 |
| Byte | 𝒴 | 𝑁 | 158 | 248 | 75 | 78 | 349 | 261 | 160 | 352 | 228 | 163 |
| Byte | 𝑽 | 𝑁 | 31 | 55 | 1 | 28 | 70 | 27 | 31 | 55 | 37 | 14 |
| Byte | 𝔾 | 𝑁 | 1,812 | 1,841 | 255 | 1,047 | 2,884 | 2,322 | 1,813 | 2,611 | 3,098 | 1,543 |
| Unicode | 𝒴 | 𝑁 | 103 | 51,710 | 98 | 119 | 1764 | 287 | 60 | 182 | 209 | 57 |
| Unicode | 𝑽 | 𝑁 | 2,423 | 121,157 | 2,234 | 2,322 | 6,136 | 3,021 | 1,732 | 2,129 | 1,280 | 2,249 |
| Unicode | 𝔾 | 𝑁 | 369 | 165,168 | 356 | 425 | 5,611 | 965 | 232 | 624 | 703 | 225 |
| Unicode | 𝔾 | 𝑁 | 18,896 | 266,441 | 18,684 | 20,733 | 30,422 | 18,598 | 16,146 | 15,363 | 11,830 | 18,717 |
| Byte | 𝒴 | 𝑁 | 11 | 7 | 7 | 7 | 10 | 10 | 7 | 7 | 4 | 6 |
| Byte | 𝑽 | 𝑁 | 427 | 446 | 388 | 341 | 465 | 485 | 380 | 361 | 158 | 335 |
| Byte | 𝔾 | 𝑁 | 38 | 23 | 21 | 23 | 33 | 33 | 22 | 22 | 11 | 19 |
| Byte | 𝔾 | 𝑁 | 297 | 321 | 284 | 257 | 309 | 297 | 279 | 279 | 195 | 130 | 239 |

Figure 5: Software dependency diagrams for the three modes of operation: compile stage (left), Python runtime (center) and C++ run-time (right).

We provide lightweight run-time interfaces for

Compiling the Transducers Figure 6 presents the sequence of steps to compile the transducers, including downloading the repository (line 2), compiling the library and its artifacts (line 5) and running the unit tests (line 7). The artifacts are compiled by Bazel using Pynini and consist of the finite state archive (FAR) files that contain collections of WFSTs (Roark et al., 2012). For each of the four Brahmic script operations we generate two FAR files: one for WFSTs over the byte alphabet, and another over the Unicode code point alphabet. Each FAR file contains ten script-specific transducers whose names correspond to the upper-case ISO 15924 script codes. Since the transliteration operation is bidirectional, the name of each script-specific transliteration transducer has the prefix FROM_ for the native-to-Latin direction, and TO_ for the inverse. The numbers of states (𝑁 ) and arcs (𝑁 𝑎) of the resulting transliteration (𝒴), NFC (𝑽), visual normalization (𝑽) transducers and well-formedness acceptors (𝑽) for each script and alphabet type are shown in Table 4.

Offline and Online Usage Once the transducers are compiled, they can be applied offline to the input files using the rewrite-tester tool provided by Thrax, as shown in lines 8–13 of the example in Figure 6, where the visual normalization transducer 𝑽 for Kannada that resides in the visual_norm.far archive is applied to words in input file words.txt.

We provide lightweight run-time interfaces for
We normalized publicly available corpora and measured how frequently words in the samples were modified. The Dakshina dataset (Roark et al., 2020) includes (among other things) collections of monolingual Wikipedia sentences in 12 South Asian languages, 10 of which use Brahmic scripts. We applied visual normalization to the training partitions of the collections in these 10 languages, and Table 5 presents the percentage of both types and tokens that were changed by the normalization.\textsuperscript{[11]} Malayalam is the language with the highest percentage of both types and tokens changed by visual normalization, largely due to frequent conversion to chillu letters from alternative encodings. For example, the relatively frequent word மேல் (“yours”) is normalized to the encoding with the chillu letter வ instead of த.

### 6 Conclusion and Future Work

We presented finite-state automata-based utilities for processing the major Brahmic scripts. The finite state transducer formalism provides an efficient and scalable framework for expressing Brahmic script operations and is suitable for many NLP applications, such as those reported in Kumar et al. (2020) and Kakwani et al. (2020), which may benefit from the reduction in “noise” present in unnormalized text. In the future, we will continue to improve the support for existing scripts and extend our work to other Brahmic scripts.

\textsuperscript{[11]}Tokenization was simply based on whitespace, with no other processing such as punctuation separation, so the total number of distinct types is accordingly relatively high. The texts from that dataset were already NFC normalized.
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