The Reconstruction Engine: A Computer Implementation of the Comparative Method

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We describe the implementation of a computer program, the Reconstruction Engine (RE), which models the comparative method for establishing genetic affiliation among a group of languages. The program is a research tool designed to aid the linguist in evaluating specific hypotheses, by calculating the consequences of a set of postulated sound changes (proposed by the linguist) on complete lexicons of several languages. It divides the lexicons into a phonologically regular part and a part that deviates from the sound laws. RE is bi-directional: given words in modern languages, it can propose cognate sets (with reconstructions); given reconstructions, it can project the modern forms that would result from regular changes. RE operates either interactively, allowing word-by-word evaluation of hypothesized sound changes and semantic shifts, or in a "batch" mode, processing entire multilingual lexicons en masse.

We describe the algorithms implemented in RE, specifically the parsing and combinatorial techniques used to make projections upstream or downstream in the sense of time, the procedures for creating and consolidating cognate sets based on these projections, and the ad hoc techniques developed for handling the semantic component of the comparative method.

Other programs and computational approaches to historical linguistics are briefly reviewed.

Some results from a study of the Tamang languages of Nepal (a subgroup of the Tibeto-Burman family) are presented, and data from these languages are used throughout for exemplification of the operation of the program.

Finally, we discuss features of RE that make it possible to handle the complex and sometimes imprecise representations of lexical items, and speculate on possible directions for future research.

1. Introduction

The essential step in historical reconstruction is the arrangement of related words in different languages into sets of cognates and the specification of the regular phonological correspondences that support that arrangement; the well-known means for carrying out this arrangement and specification is the comparative method (see, for example, Meillet 1966; Hoenigswald 1950, 1960; Watkins 1989; Baldi 1990). Words that are not demonstrably related (via regular sound change) are explained by reference to other diachronic processes that are beyond the scope of the comparative method and of this paper. Sound change is first to be explained as a rule-governed process and other explanations (which invoke more sporadic and less predictable processes)

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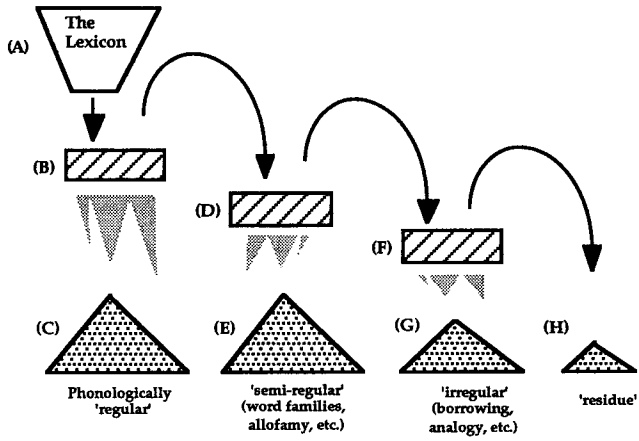


Key:

A. The complete lexicon.
B. Regular sound change (modeled by RE proper).
C. Regular, "expected" reflexes of the ancestor forms.
D. Domain of "protovariation," perhaps due to morphological/derivational processes; handled by RE with "fuzzy" constituents.
E. Sub-regularities elicited through relaxed constraints (word families, allofams,[1] etc.)
F. Sociolinguistic explanation. Domain of lexical diffusion and other sporadic processes.
G. Borrowings, analogized forms, hypercorrections, prestige pronunciations, etc.
H. The "mystery pile": counterexamples and other troublesome words.

Figure 1
The "sieve" of explanation in historical linguistics.

offered when it is clear that nonphonological forces are at work, as illustrated in Figure 1. There will always be a number of lexical items for which no scientific explanation can be advanced: not all words are entitled to an etymology (Meillet 1966).

This paper discusses problems and solutions associated with automating research into diachronic processes acting in (B) in Figure 1 above. Our solutions are implemented in a program we call the *Reconstruction Engine*, hereinafter RE (earlier versions are described in Lowe and Mazaudon [1989] and Mazaudon and Lowe [1991]).[2] RE is a prototype computational tool that automates a crucial portion of the comparative

1 The term 'allofamy,' due to Matisoff (1978), refers to relationship 'among the various individual members of the same word-family.' English *royal* and *regal*, borrowed from French and Latin, respectively, are both ultimately traceable to the same PIE root *reg-, and so are *co-allofams* in Modern English (Matisoff 1978:16–18, Matisoff 1992:160). A word family might contain both native words and words borrowed from related languages; the borrowings may be recent or ancient.

2 RE is written in SPITBOL, a dialect of SNOBOL4. The current implementation is specific to 80386 and higher microcomputers running MS-DOS. A C++ version is planned.

method: the process of creating cognate sets and proposing reconstructions on the basis of observed correspondences between modern languages. It treats those words of the lexicon that fall into pile C in Figure 1 above (and to a lesser extent those that fall into pile E). It must be emphasized that the relative sizes of the piles in Figure 1 are completely arbitrary. It would not be unusual for the list of problems (H) to be the largest. Especially in cases where languages are in close contact or are only distantly related, the regular component of the lexicon may be expected to be quite small.

RE functions as a "checker" of hypotheses proposed by the linguist. It has no inferential component in the sense usually used in describing expert systems (Charniak & McDonald 1985). Our aim is to verify the internal consistency of a set of phonological correspondences, created beforehand by the linguist, against the lexicons of an ensemble of putatively related languages, and to gauge the extent to which those data are consistent with the given phonological and phonotactic descriptions (i.e. correspondences and syllable canon).

RE has several features that represent a significant advance in the automated handling of diachronic data. First, it provides exhaustive treatment of the data in several dimensions:

- It processes complete lexicons of modern languages. Every modern form is evaluated by the program in a consistent and complete way.
- Each form is completely analyzed. Modern forms that are only partially regular are not included in cognate sets.
- The correspondences and syllable canon form a complete and unified statement of the diachronic phonology of the languages treated.

Second, RE contains a number of features that make it flexible in handling the kinds of data realistically encountered in historical research.

- Provisions exist for allowing several different transcriptions to be used in representing the data.
- There are no requirements that the data be organized beforehand by gloss, semantic field, phonological shape, or other criteria.
- The size and type of constituents used in the analysis are not limited by the program. There is no requirement, for example, that a segmental analysis be used (as opposed to the initial-plus-rhyme-plus-tone analysis commonly used for many Asian languages, for example). However, the program does not provide for nonlinear representations or discontinuous constituents: the "absolute slicing hypothesis" is assumed. Also, the linearization of constituents must be the same for all the language data used by the program. For example, the tone numbers used in the languages cited in this paper, which might equally well be ordered before as after the segmental strings to which they apply, are uniformly written at the beginning.
- Several competing analyses of the same data can be managed and compared simultaneously.

The rest of the paper is structured as follows: Section 2 introduces some terminology, explains some particulars of the group of Tibeto-Burman languages used in

examples, and describes RE in broad strokes to motivate and provide context for subsequent discussion. Section 3 reviews some of the past work in the area of computational historical linguistics, especially as it relates to the current effort. Section 4 details the algorithms and data structures used in RE. Section 5 discusses the results obtained using RE and comments on practical and methodological limitations to this approach. Section 6 discusses extensions to the "core" functions of RE: the handling of imprecise data, the treatment of variation due to diachronic and synchronic processes, the ad hoc semantic system for disambiguating homophones at both the modern and proto levels, and semi-automatic methods for generalizing over sets of phonological rules. Section 7, the conclusion, offers some caveats about computer applications in the area of historical linguistics and invites collaboration on more comprehensive software of this type.

2. Overview of Algorithms and Data Structures

2.1 A Few Preliminary Remarks about the Data and Terminology

We shall attempt to be precise in our use of the linguistic terminology related to historical reconstruction: when *lexical items*, or *modern forms* from the various lexicons of individual languages, are grouped into *cognate sets* on the basis of recurring phonological regularities (*correspondences*) they will be referred to as *reflexes*. The ancestor word-form from which these regular reflexes derive is called a *reconstruction*, *proto-form*, or *etymon*. Thus, English *father*, German *Vater*, Greek *pater*, and Sanskrit *pitr-* are all reflexes of a Proto-Indo-European (PIE) etymon reconstructed as something like *pəter- (the asterisk indicates that this word is a reconstruction and not an attested form). The relations between the constituent phonological elements of etyma and their modern reflexes are called *sound laws* and are usually written in the form of diachronic phonological rules; for example, PIE *p > English /f/. /f/ is said to be the *outcome* of PIE *p in English. Languages that share a common ancestor are said to be the *daughters* of that ancestor.

The data on which our study and these examples are based and that are used in exemplifying the operation of the program are taken from the Tamang group of the Bodic division of the Tibeto-Burman branch of the Sino-Tibetan family in Shafer's classification (Shafer 1955), spoken in Nepal (Mazaudon 1978, 1988). The reconstructed ancestor, Proto Tamang-Gurung-Thakali-Manang, is abbreviated *TGTM. Four modern tones (numbered ^{1} to ^{4}) are recognized in the modern languages and two proto-tone categories (labelled ^{A} and ^{B}) are reconstructed. The tones of both reconstructed and daughter forms are transcribed before the syllable, e.g. ^{A}bap. The eight dialects used are discussed in detail by Mazaudon (1978). The dialects and their abbreviations are (as cited in columns 5 to 12 of the Table of Correspondences in Figure 9a): Risiangku (ris), Sahu (sahu), Taglung (tag), Tukche (tuk), Marpha (mar), Syang (syang), Ghachok (gha), and Prakaa (pra).

2.2 Synopsis of the Reconstruction Engine

RE implements (i) a set of algorithms that generate possible reconstructions given word forms in modern languages (and vice versa as well) and (ii) a set of algorithms that arrange input modern forms into possible cognate sets based on those reconstructions. The first set implements a simple bottom-up parser; the second automates database management chores, such as reading multiple input files and sorting, merging, and indexing the parser's output.

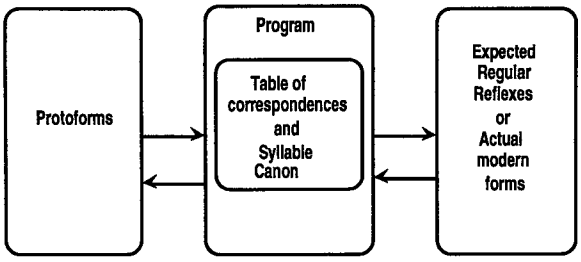


Figure 2
Input-output diagram of RE's basic projection functions.

The core functions of RE compute all possible ancestor forms (using a Table of Correspondences and a phonotactic description, a Syllable Canon, both described in Section 3.1) and makes sets of those modern forms that share the same reconstructions. Tools for further dividing of the computer-proposed cognate sets based on semantic distinctions are also provided. The linguist (that is, the user) collects and inputs the source data, prepares the table of correspondences and phonotactic description (syllable canon), and verifies the semantics of the output of the phonologically based reconstruction process. RE, *qua* "linguistic bookkeeper," makes the projections and keeps track of several competing hypotheses as the research progresses. Specifically, the linguist provides as input to the program:

(a) Word forms from several modern languages, with glosses.

(b) Parameters that control the operation of the program and interpretation of input data (mostly not described here).

(c) A file containing the Table of Correspondences, detailed below.

(d) The Syllable Canon, described below.

(e) Semantic information for disambiguating modern and reconstructed homophones, described below.

The parsing algorithm implemented in RE is bi-directional (in the sense of time): the "upstream"[3] process involves projecting each modern form backward in time and merging the sets of possible ancestors generated thereby to see which, if any, are identical. Conversely, given a protoform, the program computes the expected regular reflexes in the daughter languages, as illustrated in Figure 2.

The process can be done interactively (as illustrated in Figure 3 below) or in batch using machine-readable lexicons prepared for this purpose.

Figure 3 is a representation of the contents of the computer screen after the user has entered three modern words (1). The program has generated the reconstructions from which these forms might derive (2). The list of numbers (called the *analysis*) following the reconstruction refers to the row numbers in the table of correspondences used by

3 *Upstream* in the sense of time. We had originally described the temporal directions of the program as *backward* and *forward*. The opposition of *upstream* and *downstream*, suggested to us by John Hewson, one of the developers of the first "Electronic Neogrammarian," (Hewson 1973) is much more intuitive.

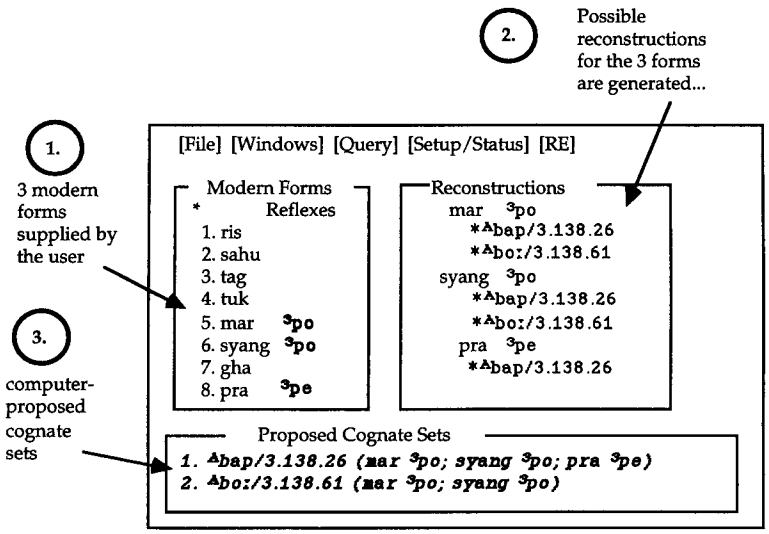


Figure 3
A simple example of interactive "upstream" computation (transcription and languages exemplified are described in Section 2.1).

the program in generating the reconstructions. In two cases reflexes have more than one possible ancestor. The program has then proposed the two cognate sets that result from computing the set intersection of the possible ancestors (3). The proposed sets are listed in descending order by population of supporting forms.[4]

Conversely, given a protoform, RE will predict (actually "postdict") the regular reflexes in each of the daughter languages. Figure 4 reproduces the results on the computer screen of performing such a "downstream" calculation. Here the etymon entered by the user (1) produced reflexes (2) through two different syllabic analyses (numbered 1. and 2. in the "Reflexes of ..." window): ᴬbap as initial /b-/ plus vowel /-a-/ plus final /-p/, and as initial /b-/ followed by rhyme /-ap/. The algorithms used in this process are described in Section 4.2.

3. Previous Research in Computational Historical Linguistics

In order to provide some context for a discussion of our efforts, we first present a brief discussion of the computational approaches to the study of sound change and review some of the software developed (see also Hewson 1989).

Applications of computers to problems in historical linguistics fall into two distinct categories: those based on numerical techniques, usually relying on methods of statistical inference; and those based on combinatorial techniques, usually implementing some type of rule-driven apparatus specifying the possible diachronic development

4 In fact, the situation is slightly more complicated than is shown here: there are two other possible reconstructions and another possible cognate set that are not shown because of space considerations. This example is discussed in more detail in Section 5.1.

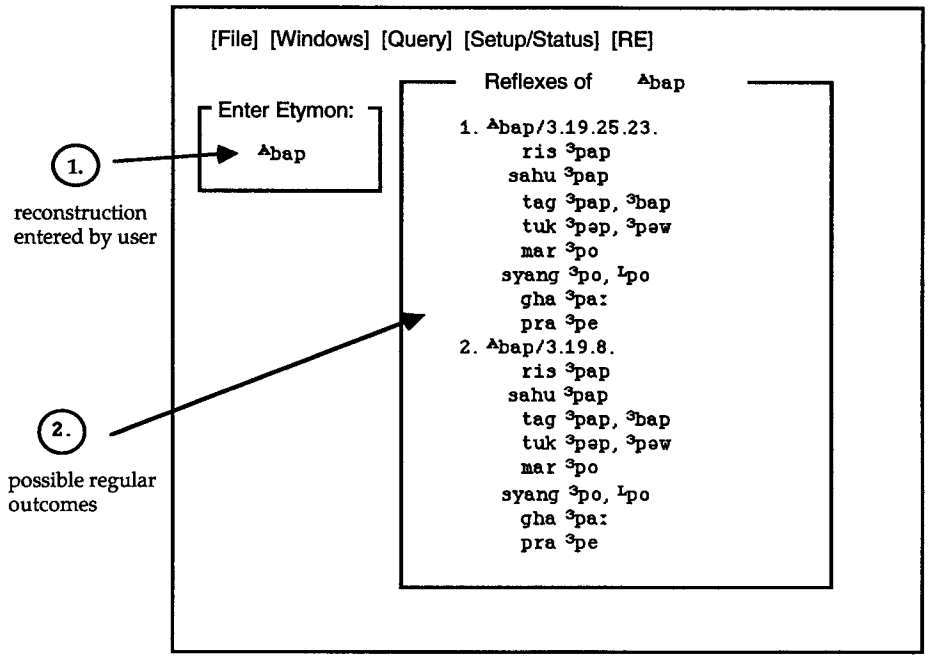


Figure 4
The expected outcomes of *ᴬbap (a "downstream" computation).

of language forms. The major features of a few of these programs are reviewed briefly below. The programs discussed by no means exhaust the field; the criteria for selecting them is that they have been described in the literature sufficiently for an evaluation, and that for this reason they have come to the attention of the authors. Indeed, the literature in this field is fragmented: starting in the 1960s and 1970s a sizable literature on the lexicostatistic properties of language change developed following Swadesh's earlier glottochronological studies (for example, Swadesh 1950). On the other hand, only a handful of attempts to produce and evaluate software of the rule-application type (for use in historical linguistics) are documented in the literature (Becker 1982; Brandon 1984; Durham & Rogers 1971; Frantz 1970; Kemp 1976). In general these programs seem to have been abandoned after a certain amount of experimentation. Certainly the problem of articulating a set of algorithms and associated data sets that completely describe the regular sound changes evidenced by a group of languages is a daunting task.

To the first class belong lexicostatistic models of language change. The COMPASS module of the WORDSURV program described below belongs to this class (cf. Wimbish 1989). It measures degree of affiliation using a distance metric based on the degree of similarity between corresponding phonemes in different languages. Also to this class belong applications that measure genetic affiliation as a function of the number of shared words in a selected vocabulary set. Any method that depends on counting "shared words," we note, assumes the existence and prior application of a means of determining which forms are cognate; and any such estimates of the relatedness of languages are only as good as the metric that determines which ones are cognate.

Language	C1	C2	C3	C4	Reflex	Gloss
Fox	p	hk	š	m	poohkešamwa	'he cuts it open'
Cree	p	sk	s	m	pooskosam	'he cuts it open'
Menomini	-	-	-	-		
Ojibwa	p	šk	š	n	paškošaan	'he cuts it down'
Ojibwa	p	kk	š	n	pakkweešaan	'he slices off a part'

Figure 5
Potential Proto-Algonkian cognates (after Hewson 1974:193–194).

To the second class belong programs that model sound change as sets of rules applied to derive later forms from earlier forms, and RE is a member of this class. Examples of programs of this sort are PHONO, being applied to Latin-to-Spanish data (and described below); VARBRUL (by Susan Pintzuk) used to analyze Old English, and two programs used to analyze Romance languages: Iberochange, based on a rule-processing subsystem called BETA, used for Ibero-Romance languages (Eastlack 1977) and one unnamed (Burton-Hunter 1976).

3.1 Hewson's Proto-Algonkian Experiment

The "proto-projection" techniques used by RE were implemented earlier by John Hewson and others at the Memorial University of Newfoundland (Hewson 1973, 1974).[5] The strategy is transparent; as Hewson notes, he and his team decided to "follow the basic logic used by the linguist in the comparative method" (Hewson 1974:193). The results of this research have recently been published in the form of an etymological dictionary of Proto-Algonkian (Hewson 1993).

The program as first envisioned was to operate on "consonant only" transcriptions of polysyllabic morphemes from four Amerindian languages. The program would take a modern form, "project it backwards" into one or more proto-projections, then project these proto-projections into the next daughter language, deriving the expected regular reflexes. The lexicon for this language would be checked for these predicted reflexes; if found, the program would repeat the projection process, zig-zagging back and forth in time until all reflexes were found. For example, given Fox /poohkešamwa/ *he cuts it open*, the program would match the correct Cree form, as indicated in Figure 5.

There were problems with this approach. In cases where no reflex could be found (as in Figure 5, where no Menomini cognates for this form existed in the database), the process would grind to a halt. Recognizing that "the end result of such a programme would be almost nil" (Hewson 1973:266), the team developed another approach in which the program generated *all possible* proto-projections for the 3,403 modern forms. These 74,049 reconstructions were sorted together, and 'only those that showed identical proto-projections in another language' (some 1,305 items) were retained for further examination. At this point Hewson claimed that he and his colleagues were then able to quickly identify some 250 new cognate sets (Hewson 1974:195). The vowels were added back into the forms, and from this a final list of cognate sets was created. A cognate set from this file, consisting of a reconstruction and two supporting forms, is reproduced below (Figure 6).

5 The authors of RE developed this technique independently and later discovered this methodologically similar computer project on Proto-Algonkian.

Language		Form	Gloss	Protomorpheme
*	(ProtoAlg.)	PEQTAAXKWIHCINWA	BUMP	(*-AAXKW)
M	(Menomini)	P3QTAAHKIHSEN	HE BUMPS INTO A TREE OR SOLID ...	
O	(Ojibwa)	PATTAKKOCCIN	BUMP/KNOCK AGAINST... [STHG]	

Figure 6
Proto-Algonkian cognate set (after Hewson 1973:273).

3.2 WORDSURV

The Summer Institute of Linguistics (SIL), a prodigious developer of software for the translating and field linguist located in Dallas, Texas, provides a variety of integrated tools for linguistic analysis. One of these tools, the COMPASS module of WORDSURV, allows linguists to compare and analyze word lists from different languages and to perform phonostatistic analysis. To do so, the linguist first enters "survey data" into the program; reflexes are arranged together by gloss, as illustrated in the reproduction in Figure 7.

In addition to the a priori semantic grouping of reflexes by gloss, the linguist must also re-transcribe the data in such a way that each constituent of a reflex is a single character, that is, "no digraphs are allowed. Single unique characters must be used to represent what might normally be represented by digraphs ... e.g. N for ng." (Wimbish 1989:43). The program also requires that part of the diachronic analysis be carried out before entering the data into the computer in order to incorporate that analysis into the data. For example, when the linguist hypothesizes that "a process of sound change has caused a phone to be lost (or inserted), a space must be inserted to hold its place in the forms in which it has been deleted (or not been inserted)" (Wimbish 1989:43). That is, the zero constituent must be represented *in the data itself*. The program also contains a "provision for metathesis.... Enter the symbols > *n* (where *n* is a one- or two-digit

(1) Group	(2) Reflex	(3)	(4) Language Abbreviation
0	-- no entry --		R
A	faDer		E
A	fater		G
A	padre	>4	S
B	ama		iT
C	bapa --		MPB
C	bapak--		I
C	bapa da		h
D	tataN		wm
D	tatay		ab

Figure 7
"Properly aligned word forms" for FATHER in WORDSURV (Wimbish 1989:43).

number) after a word to inform WORDSURV that metathesis has occurred with the *n*th character and the one to its right" (Wimbish 1989:43). An example of this may be seen in column 3 of Figure 7. To represent tone, the author notes that "there are at least two solutions. The first is to use a number for each tone (for example 1ma3na). The second solution is to use one of the vowel characters with an accent. ... The two methods will produce different results" when the analysis is performed (Wimbish 1989:44). While the last statement may surprise some strict empiricists (after all, the same data should give the same results under an identical analysis), it should come as no surprise to linguists who recognize that the selection of unit size, the type of constituency, and other problems of representation may have a dramatic effect on conclusions. RE is distinguished from this program in that (i) no a priori grouping of forms by gloss is required (a step that is fraught with methodological problems inasmuch as it requires the linguist to decide a priori which forms might be related), (ii) no alignment of segments is required (also a problematic step for a number of reasons), and (iii) the constituent inventory is not limited to segments. In passing, the lexicostatistics that are computed are based on the "Manhattan distance" (in a universal feature matrix) between corresponding phonemes from different languages as a measure of their affiliation. The validity of this measure for establishing genetic affiliation is suspect: corresponding phonemes may be quite different in terms of their phonological features without altering the strength of the correspondence or the closeness of the genetic affiliation. Also, the metrics of feature spaces are notoriously hard to quantify, so any distance measures are themselves likely to be unreliable. RE computes no such statistics, though some tools (described below) that might be used in subgrouping do exist.

3.3 DOC: Chinese Dialect Dictionary on Computer

DOC is one of the earliest projects to attempt a comprehensive treatment of the lexicons of a group of related languages. DOC was developed "for certain problems [in which] the linguist finds it necessary to organize large amounts of data, or to perform rather involved logical tasks—such as checking out a body of rules with intricate ordering relations." (Wang 1970:57). A sample dialect record (in one of the original formats) is illustrated in Figure 8. Note that as in the case of WORDSURV, the data must be presegmented according to a universal phonotactic description (in this case the Chinese syllable canon) that the program is built to handle. The one-byte-one-constituent restriction does not exist, though the (maximum) size of constituents is fixed with the data structure.

At least four versions of this database and associated software were produced (Cheng 1993:13). Originally processed as a punched-card file on a LINC-8, the program underwent several metamorphoses. An intelligent front-end was developed in Clipper (a microcomputer-based database management system) that allows the user to perform faceted queries (i.e. multiple keyterm searches) against the database. The database is available as a text file (slightly over one megabyte) containing forms in 17 dialects for some 2,961 Chinese characters (Cheng 1993:12). DOC has no "active" component: it is a database of phonologically analyzed lexemes organized for effective retrieval.

3.4 Phono: A Program for Testing Models of Sound Change

PHONO (Hartman 1981, 1993) is a DOS program that applies ordered sets of phonological rules to input forms. The rules are expressed by the user in a notation composed of if-then clauses that refer to feature values and locations in the word. PHONO converts input strings (words in the ancestor language) into their equivalent feature matrices using a table of alphabetic characters and feature values supplied by the user. The program then manipulates the feature matrices according to the rules, converting the

	Dialect	Tone	Initial	Medial	Nucleus	Ending
0052	192-	3	L	H1	WN	7
	PEKING	3	L	U	A	N
	XI-AN	3	L	U	A	Z
	TAI-YUAN	3	L	U	A	Z
	HAN-KOU	3	L	U	AE	Z
	CHENG-DU	3	L		A	N
	YANG-SHOU	3	L	U	O	Z
	WEN-ZHO	3B	L	U	03	
	CHANG-SHA	3B	N		0	Z

Figure 8
A dialect record in DOC (cited from Figure 7 in Wang [1970]).

matrices back into strings for output. Hartman has developed a detailed set of rules that derive Spanish from Proto-Romance. Besides allowing the expression of diachronic rules in terms of features, facilities are included to handle metathesis. Unlike RE, which handles only one step (at a time) in the development of multiple languages, PHONO traces the history of the words of a single language through multiple stages.

4. Description of Data Structures and Algorithms

We turn now to RE, which represents another step in the application of computational techniques to the problems faced by historical linguists. As will become clear, any computational tools designed to be used by historical linguists must be able to operate in the face of considerable uncertainty. In the course of carrying out a diachronic analysis the linguist is likely to have several competing hypotheses that might explain the observed variation. Data from many sources, varying in quality and transcription, will be compared. The research will proceed incrementally, both in terms of the portions of the lexicons and phonologies treated and in the number of languages or dialects included. RE as a tool helps with only a portion of this task, the problem of creating and maintaining regular cognate sets and the reconstructions that accompany them.

4.1 Principal Data Structures: The Table and the Canon

Two data structures (internal to the program) are relevant to the phonological reconstruction, and these are passed as arguments to RE. The first is a Table of Correspondences (Fig. 9a) representing the linguist's hypothesis about the development of the languages being treated. The columns of the table are (1) a correspondence set number, uniquely identifying the correspondence; (2) the distribution of the correspondence within the syllable structure (i.e. the type of syllable constituent: in this case, Tone, Initial, Liquid, Glide, Onset, Rhyme, Vowel, or Final); (3) the PROTOCONSTITUENT itself; (4) the phonological context (if any) to which the correspondence is limited; (5–12) the OUTCOME or reflex of the protoconstituent in the daughter languages.[6] The

6 The term *reflex* will be reserved for describing a complete modern form that is the regular descendant of some protoform. *Outcome* will be used for the regular descendent of a protoconstituent.

(1) N	(2) ConT	(3) *	(4) context	(5) ris	(6) sahu	(7) tag	(8) tuk	(9) mar	(10) syang	(11) gha	(12) pra
1	T	A	/_C_{vl}	1,X,H	1	1,H	1,H	1	1,H	1	1
3	T	A	/_C_{vd}	3,X,L	3	3	3	3	3,L	3	3
...											
93	I	k		k	k	k	k	k	k	k	k
94	I	k	/_w	k	∅	h	k	k	k	k	k
181	F	k		k	ː	∅,k	∅,k	∅	∅	∅	∅
...											
142	L	r	/p,p^h,b_	r	r	r	r	r	r	r	r=ř
169	0	r		r	r	r	r	r	r	r	r
...											
102	0	kr	/_eː	k	k	k	ʈ	k	k	kr	kr
103	0	kr	/_u	kr	kr	h	ʈ	k	k	kr	kr
104	0	kr	/_a	kr	kr	hw	ʈ	kj	kj	kr	kr
105	0	kr	/_at	kr	kr	h	ʈ	kj	kj	kr	kr
106	0	kr		kr	kr	h	ʈ	k	k	kr	kr
...											
31	R,V	a		a	a	a	ə	ə	ə	a	ɤ
186	V	a	/_p	a	a	a	ə	o	o	a	e

Figure 9a
Excerpt from the Table of Correspondences.

[T,Ø] [O(G),I(L)(G),Ø] [R,VF]

T	=Tone	L	= Liquid
O	= Onset	R	= Rhyme
G	= Glide	V	= Vowel
I	= Initial Consonant	F	= Final consonant
Ø	= Zero		

Figure 9b
Syllable canon in Proto-Tamang.

CONSTITUENT TYPES (T, I, F, L, etc. in column 2) are specifiable by the user. So, for example, C and V could be chosen if no other types of constituents need to be recognized for the research. Note that the table allows for several different outcomes depending on context; the absence of context indicates either an unconditioned sound change or the Elsewhere case of a set of related rules (as discussed below).

The second data structure is a syllable canon that provides a template for building monosyllables. It specifies how the constituents of the table of correspondences may be combined based on the (syllable) constituent types (column 2 of the table). Thus, the outcomes for a final /k/ (correspondence 181) and an initial /k/ (correspondence 93) are never confused by the program. The program takes the syllable canon as an

argument expressing the adjacency constraints on the constituents found in the table. For example, the canon for *TGTM, illustrated in Figure 9b, has three *slots*, each of which has its own substructure: first, a tone (optional, as indicated by the possibility of a zero element); followed by an (also optional) initial element consisting of various combinations of Onset, Glide, Initial, and Liquid; and terminating with either a Rhyme element or a Vowel plus Final consonant. A syllable is composed of zero or more elements from each of these slots. Picking the longest possible combination from each slot produces the maximal syllable permitted by the canon containing six constituents (TILGVF), one from each constituent type except O and R. Similarly, the minimal one has only one constituent (R). Parentheses indicate optional elements and brackets separate sequential slots in the syllable structure.

This description, a type of regular expression, provides a shorthand device for expressing several possible syllable structure trees. Indeed, the Proto-Tamang Syllable Canon is quite complex in this respect, because several hypotheses about syllable structure are encoded in it. For other languages, in which only consonant and vowel need be distinguished in describing syllable structure, a simpler canon (e.g. CV(C)) might suffice. Polysyllabic syllable canons can be expressed and used by the canon in two ways:

- Explicitly, for example [CV(C)][CV,Ø] a bisyllabic canon in which the minimal form is CV and the maximal is CVCCV.
- As a recursive application of a single syllable. This is done via a software toggle that allows the canon structure to be repeatedly mapped over an input form. For example, if the polysyllable toggle is turned on, the canon [(C)V(C)] would match forms of the form V, CVC, CVCCV, CVCVCVV, etc.

4.2 Algorithms

4.2.1 Generating Proto-Projections. Given a form, three steps are required to project or transform a modern form into a set of possible reconstructions or vice versa: (i) tokenizing the given form into a list of row numbers in the table of correspondences (column 1 of Figure 9a), (ii) filtering the tokenized forms according to syllabic and phonological constraints, and (iii) substituting the actual outcomes in the Table of Correspondences for the tokens.

Tokenization. On a first recursive pass RE generates (recursively from the left of the input form) all possible segmentations of the form. That is, starting from the left, the program divides the form into two, and then repeats the process on the right-hand part until the end of the form is reached. Essentially, this algorithm implements a standard solution to a standard problem, that of finding all parses of an input form given a regular expression (encoded in this case in the syllable canon and table). As the segmentation tree is created, the program checks to see that the node being built is actually specified as an element of the Table of Correspondences and thus avoids building branches of the tree that cannot produce outcomes (according to the Table of Correspondences). The pseudocode in Figure 10 outlines the algorithm. Consider for example the segmentations of:

(1) *ᴬkra *head hair*

```
/* GENERATE:   STEP ONE: Tokenize input form  */

Tokenize(InputString,TokenList)
   /* base case */
   if InputString is null then return(TokenList)
   for i = 1 to the length of InputString
      leftside = leftmost i characters of InputString
      rest  = the rest of InputString
      lookup leftside in list of constituents for this table column
      if found then
         add tokens (i.e. TofC row numbers) for this constituent to TokenList
      otherwise
         /* abandon this parse */
      end if
   Tokenize(rest,TokenList)
   end for
end Tokenize
```

Figure 10
Pseudocode for tokenizing forms into table constituents.

There are eight ways to segment this protoform:

(2) ^{A}kra ^{A}-kra ^{A}k-ra ^{A}kr-a
^{A}-k-ra ^{A}k-r-a ^{A}-kr-a
^{A}-k-r-a

Of these eight segmentations, only two are composed completely of elements that occur in the protoconstituent column (3) of the table. For each of the valid segmentations, RE constructs a tokenized version of the form, in which each element of the segmented form is replaced with the correspondence or list of correspondences for that constituent in the table. *k, for example, has three possible outcomes (given by rows 93, 94, and 181 of the Table of Correspondences), depending on its syllabic position and environment.

(3) Segmentations whose elements are ALL constituents of the table:

(a)	Segmentation:	^{A}	k	r	a
	Tokenized form:	(1,3)	(93,94,181)	(142,169)	(31,186)
(b)	Segmentation:	^{A}	kr		a
	Tokenized form:	(1,3)	(102,103,104,105,106)		(31,186)

(4) Segmentations that contain elements NOT found in the table:

	Segmentation	Tokenized form
(c)	^{A}kr-a	(?)(31,186)
(d)	^{A}kra	(?)
(e)	^{A}-k-ra	(1,3)(93,94,181)(?)
(f)	^{A}k-ra	(?)(?)
(g)	^{A}k-r-a	(?)(142,169)(31,186)
(h)	^{A}-kra	(1,3)(?)

```
/* GENERATE: STEP TWO: Convert Tokenized form into possible outcomes */
FilterAndSubstitute(TokenList,ListofPossibleForms)
   /* base case */
   if TokenList is NULL then return(ListofPossibleForms)
   /* recursive step */
   for each RowNumber of first segmented element in TokenList
      if phonological and syllabic context constraints are met then
         for each language in the table
               add outcomes for this RowNumber to each output form in
                  ListofPossibleForms for this language
         end if
      otherwise
         /* do not use this token in building output forms */
      end if
   end for
   remove first segmented element from TokenList
   FilterAndSubstitute(TokenList,ListofPossibleForms)
end FilterAndSubstitute
```

Figure 11
Pseudocode for filtering possible projections and substituting regular outcomes.

Filtering. Having created and tokenized a list of all valid segmentations, the algorithm traverses each tokenized form, looking up each correspondence row number of each segment in the table and substituting the outcome of that row from the appropriate column of the table. As the output form is being created, the phonological and phonotactic contexts are checked to eliminate disallowed structures, as illustrated in the pseudocode given in Figure 11.

The segmentation in (3b) above

(5) `A-kr-a` (1,3)(102,103,104,105,106)(31,186)

would produce 20 ($= 2 \times 5 \times 2$) different outcomes based on the different ordered combinations of its tokens were it not for syllabic structure constraints and phonological context constraints:

(6)

1.102.31	1.104.186	3.106.31
1.103.31	1.105.186	3.102.186
1.104.31	1.106.186	3.103.186
1.105.31	3.102.31	3.104.186
1.106.31	3.103.31	3.105.186
1.102.186	3.104.31	3.106.186
1.103.186	3.105.31	

With these constraints, however, only one combination is licensed: 1.104.31, because: (i) only the tone correspondence for row 1 applies since it specifies the outcome of prototone A for voiceless initials; (ii) only outcomes of row 104 for *`kr-` are generated since this is the most specific rule that applies; and because (iii) row 186 is eliminated as a possibility for *-a in this case, since these outcomes only occur when *-a is followed by *-p.

Some complications in the application of the rules should be noted here. The program *does* apply Panini's principle, also known as the Elsewhere Condition (Kiparsky 1973, 1982). Thus, of all the possible *`kr-` correspondences, only the most specific is

selected. For example, though the context in line 104 *-a is a substring (or subcontext) of line 105 *-at, only one or the other is selected for any particular segmentation of a protoform ending in *-at (i.e. 104 for *-a- + *-t vs. 105 for *-at). If the "specificity" of several applicable contexts is the same, all are used by the program in generating the forms.[7] Also, note that since the context is stated in terms of proto-elements, when computing backwards (*upstream*) the program must tokenize *and* substitute ahead to determine if the context of a correspondence applies.

Substitution. In the final step, the program substitutes the outcomes for each correspondence row in each of the language columns of the table and outputs the expected reflexes. The expected outcome *of just the segmentation* A-kr-a in Tukche, for example, (Figure 9a, column 8 tuk) is either 1ʈə or Hʈə.[8] The segmentation A-k-r-a, though a valid segmentation of the input form into table constituents, would fail to produce any reflexes because the phonological context criterion is not met.

This process is performed for each language column in the table, resulting in a list of the modern reflexes of the input protoform. This assumes, of course, that the reconstructed forms are correct, the rules are correct, and no external influences have come into play. By comparing these computer-generated modern forms with the forms actually attested in the living languages we can check the adequacy of the proposed analysis, and make improvements and extensions as required.

4.2.2 Combinatorial Explosion and Syllable Structure. The example given above has only a few possible segmentations. Consider, however, the possible *valid* segmentations of the *TGTM form *Bgrwat *hawk, eagle*, schematized in Figure 12. There are, of course, a substantially larger number of invalid segmentations. Each token of a segmentation may have a sizable list of possible outcomes. One can see that even relatively uncomplicated monosyllables are capable of causing massive ambiguity in structural interpretation. Indeed, some of the monosyllabic forms in the Tamang database generate nearly 100 reconstructions, even given the limitations of syllabic and phonological context.

4.2.3 Computing Upstream and Creating a Set of Cognates. The preceding discussion (i.e. in Section 4.2.1) shows how the Table of Correspondences can be read from ancestor to daughter (left to right), *downstream* in the sense of history. It can also be read from daughter to ancestor (right to left), *upstream*, revealing all the possible ancestors of a given modern segment of a particular language. For example, we can see from the excerpt in Figure 9a that Syang /k/ (in column 10 of the table) could derive from either *k- or *kr- (to be read from the column of protoconstituents (column 3) of the table).

By combining, according to the syllable canon, all the possible permutations of *initial, *tone, and *rhyme for the initial, tone, and rhyme of a modern word, the

7 There is a great deal more to say about specificity and the complexity of the environmental constraints, so much so that a separate and rather lengthy discussion of it is merited. As currently implemented in RE, context must be stated in terms of immediately adjacent constituents (remote context cannot be used). Also, the context must be stated in terms of constituents (i.e. *atoms*), or lists of constituents: regular expressions and other possible definitions are not supported. Specificity is measured in a straightforward way: correspondence rules with no context have low specificity (specificity = 0). Rules with a one-sided context have specificity 1. Rules with a contextualizing element on both sides have specificity 2. Only integer specificities are supported.

8 The cover symbol H is used to permit the upstream reconstruction of Tukche forms in which the tone of the modern form is not precisely known. In the downstream direction, however, it licenses the generation of two possible reflexes.

	Type of syllable constituent								
	T	I	L	O	G	R	V	F	Structure
(1)	B			gr	w		a	t	TOGVF
(2)	B			gr	w	at			TOGR
(3)	B			gr			wa	t	TOVF
(4)	B			gr		wat			TOR
(5)	B	g	r		w		a	t	TILGVF
(6)	B	g	r		w	at			TILGR
(7)	B	g	r				wa	t	TILVF
(8)	B	g	r			wat			TILR

Figure 12
Segmentation of *Bgrwat 'hawk, eagle.'

computer can, using exactly the same procedures as described in Section 4.2.1, create a list of its possible reconstructions. If the possible reconstructions of a set of words that are cognate are compared, it must be true that one or more of the reconstructions is the same for all words in the set (assuming, of course, that the words are related via regular sound changes).

In the example in Figure 13, this computation has been done on the modern forms for the word *snow* in four languages of the TGTM group. Each column contains the possible reconstructions for the modern reflex listed on top of the column. A comparison of the columns (or examination of the Venn diagram below) shows that one reconstructed form, *Bgliŋ (in row 1), is indeed supported by all the members of the cognate set, and that these four languages provide sufficient data to rule out some of the other reconstructions proposed on the basis of one language alone.[9]

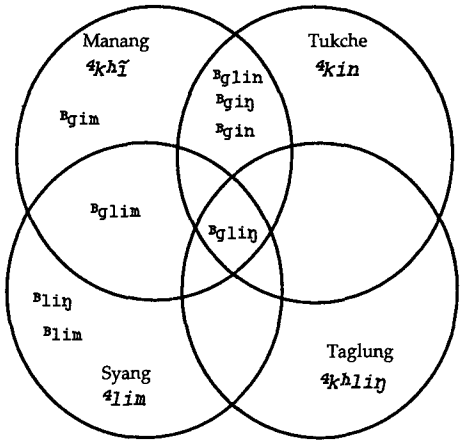
4.3 The Database Management Side of Historical Reconstruction

Using the interactive mode of RE described above is a good way to "debug" the table of correspondences and canon. However, RE is most useful as a means of analyzing complete lexicons. The four processes involved in creating reasonable cognate sets from a set of lexicons of modern forms are schematized in Figure 14. They are:

1. segmentation of lexemes and generation of proto-projections,
2. comparison of proto-projections and creation of tentative cognate sets,
3. merging (conflation) of subsets in the list of tentative cognate sets, and
4. conflict resolution within and between cognate sets of homophonous reflexes and homophonous reconstructions (i.e. the application of semantic information).

9 While the Taglung form itself is sufficient to determine the 'proper' reconstruction in this case, and if the Syang form were not available, it would break the tie between the other competing reconstructions (Bglin, Bgiŋ, and Bgin), it is usually difficult to pick out such decisive lexical items from a list of words.

	Tukche	Manang	Syang	Taglung
	⁴kin	⁴kʰĩ	⁴lim	⁴kʰliŋ
1.	ᴮgliŋ	ᴮgliŋ	ᴮgliŋ	ᴮgliŋ
2.	ᴮglin	ᴮglin		
3.		ᴮglim	ᴮglim	
4.	ᴮgiŋ	ᴮgiŋ		
5.	ᴮgin	ᴮgin		
6.		ᴮgim		
7.			ᴮliŋ	
8.			ᴮlim	



ᴮgliŋ *snow* in Proto-Tamang
(8 different protoforms produced from 4 reflexes)

Figure 13
ᴮgliŋ *snow* in Proto-Tamang (8 different protoforms produced from 4 reflexes). Selecting the 'best' reconstruction from the list of possible reconstructions.

The algorithms for each of these processes are outlined in the pseudocode in Figures 15a–c. First, the Tokenize and FilterAndSubstitute procedures are performed for each form in each source dictionary.

Next, the list of reconstructions generated is examined and those reconstructions that fail to have sufficient support are eliminated. The remaining reconstructions are retained.

Third, each set is compared with each other set to get rid of those which are subsets of other sets (a type of "set covering problem," discussed in Section 5.1 below). This is primarily a data reduction process, and not interesting algorithmically. We have therefore not provided pseudocode describing it. It is, however, NP-hard, and therefore takes a lot of time for a dataset of any size.[10]

10 For a discussion of set-covering and NP-complete problems, see, for example, Ralston and Reilly (1993), 938–941.

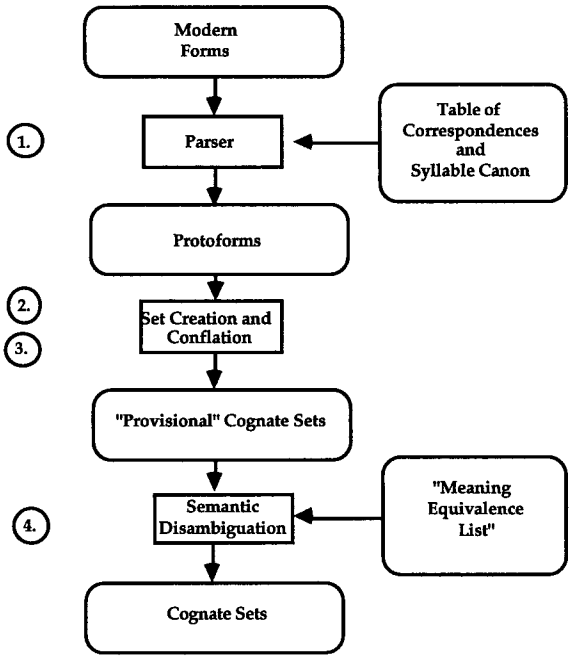


Figure 14
Input-output diagram of RE's basic batch functions.

```
/* STEP ONE: Backward projection of modern forms
setup tables for the language data file to be processed
    get appropriate columns from TofC
    set language codes, etc. for output
    Initialize list of reconstructions
end setup
for each language_dictionary
    for each modern_form from language_dictionary /* i.e. for each word in
                                                     dictionary */
      Initialize TokenList
      Tokenize(modern_form)  /* see pseudocode for this function above */
      Initialize ListofPossibleForms
      FilterAndSubstitute(TokenList,ListofPossibleForms) /* upstream! */
      Apply Panini's Principle (Elsewhere condition) to select ''allowed''
         reconstructions
     check each reconstruction generated against list of reconstructions:
       if the reconstruction already exists in the list,
           link modern_form to existing reconstruction
       otherwise
           add reconstruction and link to modern_form into list
       end if
    end for
end for
```

Figure 15a
Pseudocode for RE's basic batch functions—first create reconstructions.

Finally, if the linguist is able to provide (on the basis of analysis of previous runs) semantic criteria for distinguishing homophones, the program can separate the sets

```
/*   STEP TWO: create ''pseudo'' cognate sets   */
for each reconstruction in list of reconstructions
   if reconstruction is supported by data from two or more languages then
         output reconstruction
         output supporting forms
   end if
end for
```

Figure 15b
Pseudocode for RE's basic batch functions—next, create first group of cognate sets.

```
/* STEP FOUR: semantic processing: splitting and remerging of */
/* sets based on semantics */
divide a set into two based on list of glosses selected
for each of the newly created divided sets
   if (it is supported by data from at least two different languages) and
      (it is not now a subset of some other existing cognate set) then
      retain the divided set
   otherwise
      delete the divided set
   end if
end for

/* check the division in the rest of the sets */
for all other sets containing any subset of these glosses
   if words with semantically incompatible glosses appear then
      divide the set (as was done above)
   end if
end for
output cognate sets
```

Figure 15c
Pseudocode for RE's basic batch functions—semantic component.

into sets that contain only semantically compatible reflexes. The method for accomplishing this is described in Section 6.1 below.

The first step, creating the list of proto-projections, is merely a matter of iteratively applying the reconstruction-generating procedures described in Section 4.2.1 to all the forms in the files. The list of protoforms obtained by running all the entries of a modern dictionary backward through the program is saved for later combination with reconstructions generated by words from other languages. The process is illustrated in Figure 16. Note that forms that fail to produce any reconstructions are saved in a residue file for further analysis. In the example below (Figure 16), we see that a Nepali loan word, Tukche /^{2}gar/ *house*, failed to produce any reconstructions in the proto-language, because there exists a phonological subsystem for Nepali loans in Tukche that does not conform to the phonology of native words (i.e. the phonology described by the Table of Correspondences). In particular, no voiced initials have survived in Tukche. In other cases, forms collected in the check files may indicate a mistake in the Table of Correspondences, which needs to be corrected to allow the word to reconstruct successfully. Note that the Tukche words in this example are glossed in French (*neige* "snow," *oeil* "eye," *maison* "house"), as they are taken from a French–Tukche dictionary. This is a significant fact, as will be explained in Section 6.1.

Combining the lists of reconstructions for several languages into a single sequence and sorting by the proposed reconstructions brings together all reflexes that could descend from a particular reconstruction (Figure 17).

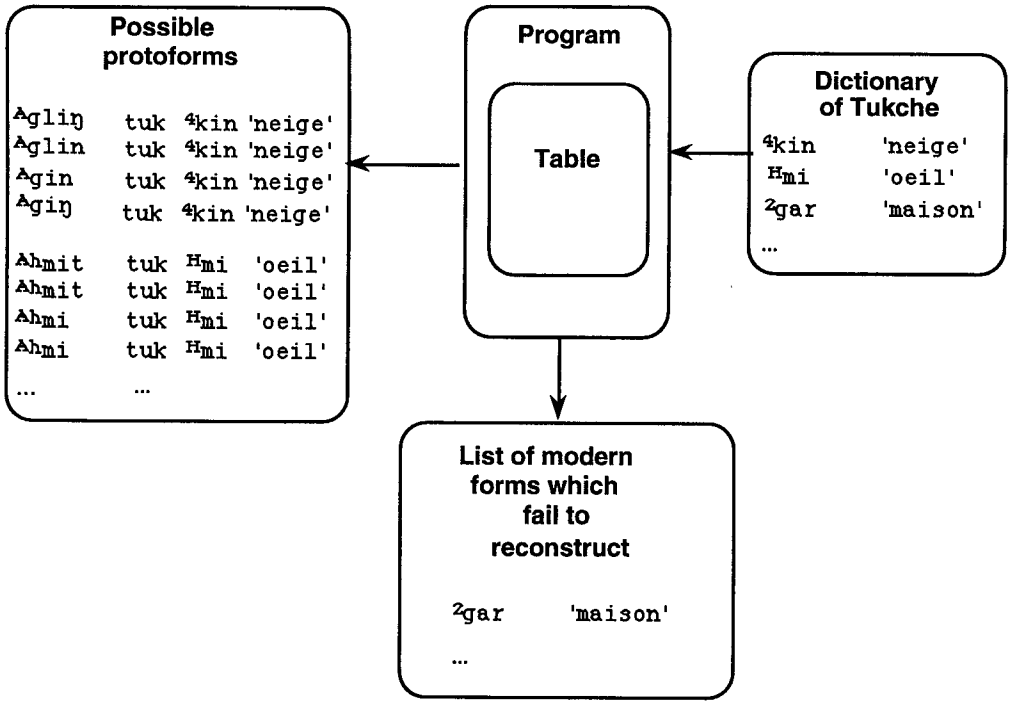


Figure 16
Proposition of protoforms and the residue ("check") file.

From this sorted list, RE extracts matching reconstructions, with their supporting forms, and proposes them as potential cognate sets (Figure 18). Ideally, rules would be sufficiently precise for the program to propose only valid sets, and sufficiently broad not to exclude legitimate possibilities. However, there is a certain amount of redundancy and uncertainty in the rules that tends to result in several possible reconstructions for the same cognate set. On the other hand, some forms that do produce possible reconstructions cannot be included in a cognate set because their reconstruction does not match that of any word in the other languages. These isolates (not illustrated) are collected by the program during the set creation process and maintained as a separate list.

The first evaluation measure hypothesized for establishing the validity of a cognate set was the number of supporting forms. The program retained cognate sets when the number of supporting forms from different languages reached a certain threshold value. However, many reasonable cognate sets had forms from only a few languages. The handling of this problem and other problems having to do with the composition of the proposed cognate sets is dealt with in more detail in Section 5.

5. The Constituency of Cognate Sets

If sound change proceeded in such a way as to perfectly maintain semantic and phonological contrasts through time, the diachronic situation would be quite simple.

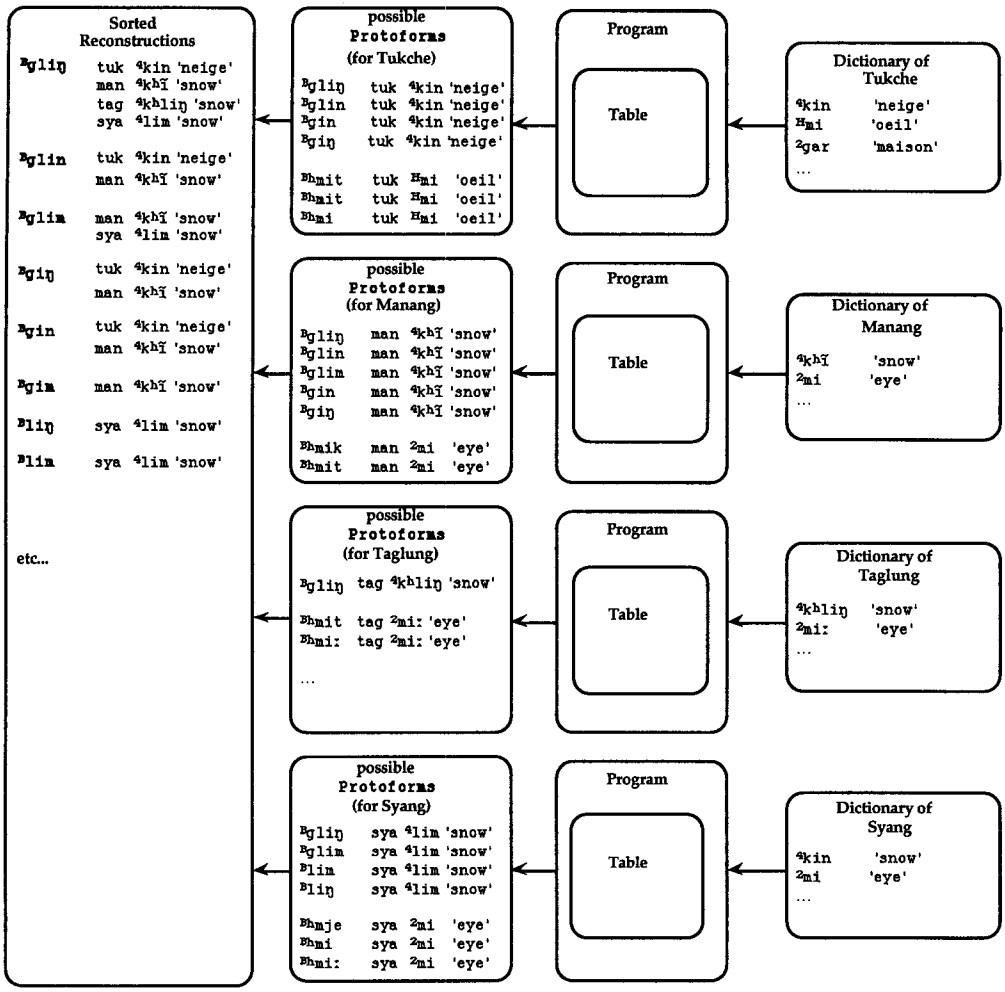


Figure 17
Upstream computation in batch.

Phonemes would change into other phonemes but not merge or split.[11] Words would mutate in phonological shape, but would remain distinct from other words in both form and meaning. Making cognate sets in such a situation would be quite straightforward. In reality, neither semantic nor phonological distinctions are maintained over time. We will examine some of the implications of this situation.

5.1 Many Reconstructions May Be Possible for a Given Set of Cognates

The process of "triangulation" (discussed in Section 4.2.3 and in some detail in Lowe and Mazaudon [1989, 1990] and Mazaudon and Lowe [1991]) provides a means for

11 *Merger* refers to the diachronic process by which the distinction between two (or more) phonemes is lost. Words that were minimal pairs on the basis of this distinction become homophones. *Split* refers to the process by which a phoneme becomes two (usually because of some modification in the context).

*TGTM ᴬba:/3.136.32.

gha	³po	leaf
man	³pa:	leaf
ris	³pa:	feuille d'arbre
sahu	³pa:	leaf
tuk	³pa	leaf

Figure 18
A "Cognate Set" generated by RE.

selecting the best reconstruction out of several candidates. If it were possible a priori to determine which reflexes might fall together based on the correspondences, it would be possible to preserve just those reconstructions from which all the reflexes might descend (and discard the other reconstructions). This situation is the one illustrated with the words for snow in Figure 13. However, when entire lexicons are processed, it is not necessarily possible nor even desirable to attempt to partition the lexemes into comparable sets to begin with. It is necessary to generate all possibilities and later to eliminate the undesirable ones through a sort of competition. Using the number of supporting forms in a cognate set as the sole or primary criterion for keeping the set was found to be an inadequate heuristic: some perfectly good sets have only three members, while others with more members are shaky and in some cases simply wrong.

An example of this competition is illustrated in Figure 19 (another representation of the data presented in Figure 3). Here, as in the ᴮgliŋ *snow* example (Figure 13), several different cognate sets composed of the same reflexes but having different reconstructions have been generated. The reflexes clearly fall together into the same overall cognate set, but the reconstruction of several of the forms is non-unique: the reconstruction *ᴬbo: is supported by forms from Marpha and Syang, while *ᴬbap is supported by all four languages. This cognate set, then, reflects a merger of several smaller sets, as indicated in the Venn diagram. The Risiangku form disambiguates the reconstructions, showing that *ᴬbap should be recognized as the winning reconstruction (it is marked with the *; other reconstructions supported by various subsets of the reflexes are marked with !*). As an aside, this process of set conflation can only be accomplished once all the words in all the lexicons are processed. The problem then presented is a set-covering problem (one of the various kinds of NP-complete problems for which no fast or easy solution exists). In the case of our Tamang database, in which about 7,000 modern forms yield about 8,000 different reconstructions that have supporting forms from at least two languages, set conflation takes several hours on our 386-based machine.

5.2 Other Kinds of Competition for Reflexes

A number of other types of overlapping can occur. And in general, the cognate sets of competing reconstructions do not nest as neatly as they do in the previous example. It is often the case that the cognate sets may merely overlap to some extent. These cases fall into several distinct classes:

First, there exist some overlapping sets in which neither set is a proper subset of the other; the reflexes fit semantically, so the problem is one of reconciling the recon-

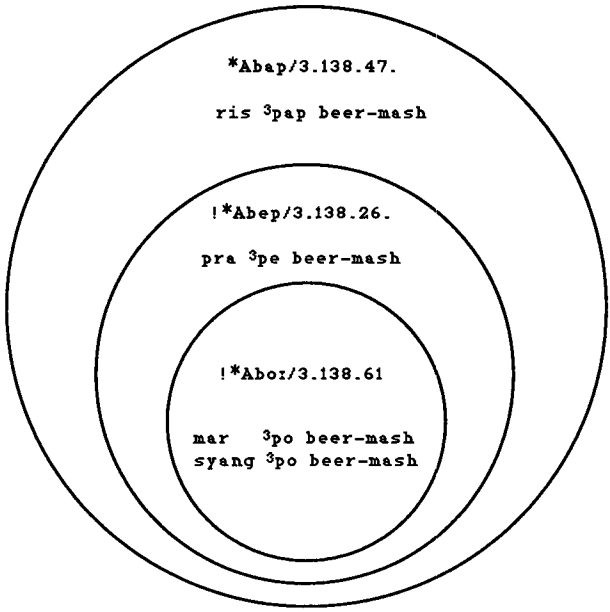


Figure 19
Nested cognate sets.

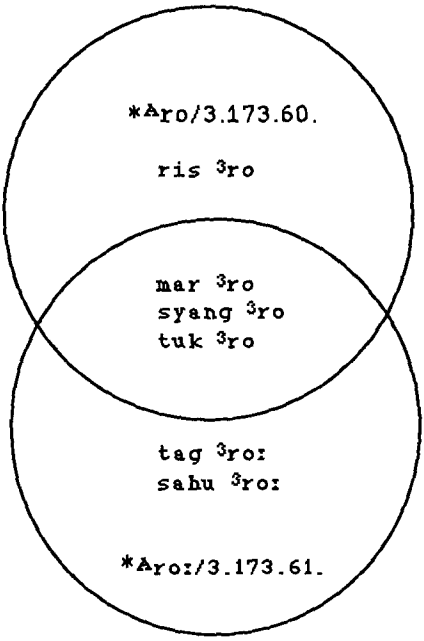
structions. Figure 20 illustrates the problems that arise when semantically compatible reflexes support different reconstructions.

This particular situation results from an uncompensated merger (of length) that is now in progress: the length distinction appears to be on its way out in the Risiangku dialect (abbreviated "ris" in Figure 20). This explanation is based on knowledge of the language and an internal analysis of its phonology. At this time it is not clear what algorithm (if any) could be used to sort out cases like these.

A similar but more complicated situation can be seen in Figure 21. Here the free variation in vowel length generates additional possible reconstructions, and those dialects where final consonants have been lost permit the reconstruction of variants with a final stop as well. However, the form from the Risiangku dialect, which normally preserves finals, cannot reconstruct (according to the table) to either the short vowel or stopped rhyme, and so another cognate set supporting a long vowel reconstruction is created.

6. Extensions to RE

The processing described above produces cognate sets that are often found wanting when examined. For example, homophones may be conflated in the same set though they can be derived from different etyma. Also, small irregularities in the data, which may be partially understood by the linguist, may cause forms to fail to reconstruct into the set in which they plausibly belong. We discuss below extensions to RE that deal with some of these problems.



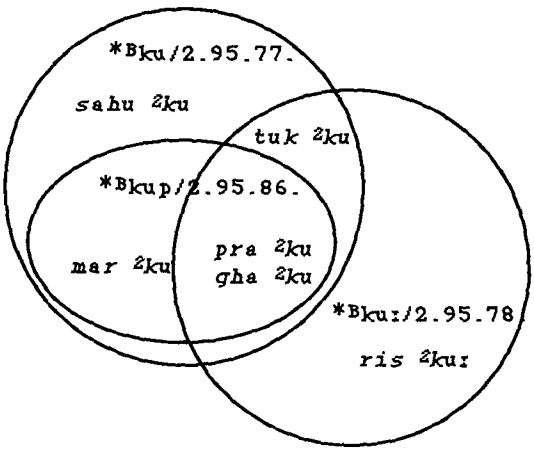
***Aro/3.173.60.**

mar	3ro	*friend*
ris	3ro	*friend*
syang	3ro	*friend*
tuk	3ro	*friend*

***Aro:/3.173.61.**

mar	3ro	*friend*
sahu	3ro:	*friend*
syang	3ro	*friend*
tag	3ro:	*friend*
tuk	3ro	*friend*

Figure 20
*Aro(:) 'friend.'



***Bku/2.95.77.**

sahu	2ku	*nine*
tuk	2ku	*nine*

!*Bkup/2.95.86.

gha	2ku	*nine*
mar	2ku	*nine*
pra	2ku	*nine*

***Bku:/2.95.78.**

gha	2ku	*nine*
pra	2ku	*nine*
ris	2ku:	*nine*
tuk	2ku	*nine*

Figure 21
Bku(:) 'nine.'

6.1 Constraining Cognate Sets: Incorporating Semantics

Note that we have nowhere mentioned semantics in the backward computation process: in its search for new cognate sets, the algorithm works strictly on form, not on meaning. Indeed, one of the strengths of RE is that it initially ignores the glosses altogether, operating strictly on the forms themselves. This approach has the advantage

TGTM *Abam/3.136.53.

gha	3pãː	thigh
tag	Xbam-ba	to soak
ris	3pam	épaule
ris	3pam	mouiller, tremper
sahu	3pam	shoulder
tuk	3pom	wet (v.i.)

Figure 22
Sample of comparative set proposed by RE (without semantic component).[12]

of letting a set like *Aba: (shown in Figure 18) be created, in spite of the fact that two different metalanguages (French and English, as illustrated in some of the earlier examples) are used in the data files for the glosses; meaning is not being taken into consideration in creating the set. However, in cases of homophony in the protolexicon (like *Abam, shown in Figure 22) it is undesirable to conflate all reflexes that support the same reconstruction. Here we can see that words belonging to at least two different etyma (*shoulder/thigh* vs. *soak/wet*) are mixed into a single proposed etymon.

Besides allowing incompatible forms within a cognate set, a lack of semantic differentiation permits the creation of some spurious cognate sets, as is illustrated in the Venn diagrams in Figure 23. The set supporting the three reconstructions Abe:, Abet, and Abat should be eliminated and the reflexes permitted to migrate to the cognate set to which they are semantically related. Were some means available to specify in this case that no set could contain reflexes meaning both *wife* and *beer-mash*, the superfluous middle set and the overlap it causes would be eliminated (and the reconstructions would be listed under the *wife* and beer-mash sets of which their supporting reflexes form a proper subset in the same way as depicted in Figure 19).

General theories of semantics and semantic shifts are not yet sufficiently developed to be used as an a priori reference framework to constrain the search for cognates.[13] Moreover, using such a framework would preclude the possibility of discovering any new semantic relationships that might be specific to the linguistic group or the linguistic area under study. So we do not wish to constrain the program at all in its first pass through the data in search of cognate sets. On subsequent passes, though, it would be convenient not to repeatedly encounter putative cognate sets that contain semantic discrepancies. It should be noted in passing that semantic discrepancies should not be confused with semantic distance.

In order to separate incompatible etymological sets, we devised an ad hoc sys-

12 The X that occurs in the Taglung form is a cover symbol meaning "unspecified tone") and is used when the tone of the form is unknown. This allows RE to reconstruct the form under any of the tones. If this cover symbol were left out, RE would reconstruct this form without a prototone (permitted by the canon), and the form would fail to form a set with other forms that do have the tone specified.

13 It might be possible to apply the results of some recent research in the area, for example, Wordnet (Miller 1990), to part of the problem. Indeed, the "semantic formulas" developed for RE are similar structurally and conceptually to the "synsets" of Wordnet. Ultimately, any solution would have to be sensitive not only to synchronic relationships in a single language (like Wordnet) but also to semantic shifts (both universal and language-specific) and the possibility of several different glossing metalanguages (in this case both French and English are used).

***ᴬbe/3.138.19.**

mar	³pe	*wife*
pra	³pɪɛ	*wife*
syang	³pe	*wife*
tuk	³pe	*wife*

***ᴬbeː/3.138.20.**
***ᴬbet/3.138.25.**
***ᴬbat/3.138.44.**

mar	³pe	*wife*
pra	³pe	*beer-mash*
syang	³pe	*wife*
tuk	³pe	*wife*

***ᴬbap** (only the largest subset from Figure 19 above is used here)

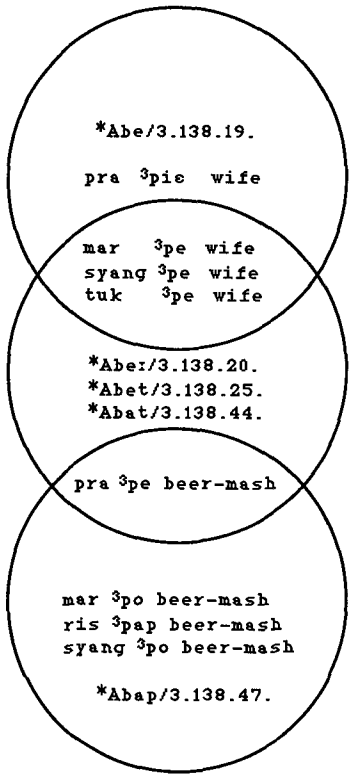


Figure 23
*ᴬbe and *ᴬbap 'compete' for reflexes.

tem of "semantic tagging" using a structure we call a "semantic formula." These are bracketed lists of glosses specifying which glosses are semantically compatible and so might be found glossing reflexes in the same cognate set. The formalism used is as follows:

(7) $[G_1, G_2, \ldots G_n]$

"Extract sets which contain any gloss G_1 to G_n and eliminate from those sets reflexes with any other gloss. Eliminate any sets which as a result have too few members or become subsets of other sets."[14]

(8) $[G_1, G_2, \ldots G_m][G_{m+1}, G_{m+2}, \ldots G_n] \ldots [G_{p+1}, G_{p+2}, \ldots G_q]$

"Divide any set which contains any of the glosses G_1 to G_q into sets each of which contains reflexes which

- contain glosses only from one of the subsets $[G_1, G_2 \ldots G_m][G_m + 1, G_m + 2, \ldots G_n]$, etc.; but

14 In cases where a set is eliminated as a result of becoming a subset of another set, the reconstructions of the set being eliminated may have to be merged into the larger set.

*Abaː/3.136.32.		
gha	³po	leaf
man	³paː	leaf
ris	³paː	feuille d'arbre
sahu	³paː	leaf
tuk	³pa	leaf

Figure 24
Sample of comparative cards proposed by RE (with semantic component). No separation (all glosses found in the same semantic formula, (12) above).

- retain any reflexes which are NOT specified in any of the subsets.

Eliminate any sets which as a result of the division have too few members or become subsets of other sets."

Some examples of these semantic formulas are:

(9) [SHOULDER, THIGH, ÉPAULE] [MOUILLER, SOAK, TO SOAK, TREMPER, WET (V.I.)]

(10) [BEER-MASH] [WIFE]

(11) [ANSWER, DIRE, REPLY, SAY, TELL, TO SAY]

(12) [FEUILLE D 'ARBRE, LEAF, SMALL LEAF]

etc...

Specifically, these lists identify words *in the specific language data sets being processed* that are homophonous or might have homophonous reconstructions. They also bring together glosses from different languages that should be equated for purposes of diachronic comparison.

The semantic formulas are created based on examination of the initial sets proposed by the program. On subsequent passes through the data, RE can be instructed to take semantics into account and (by processing a file containing these lists) divide sets of potential cognates according to the semantic formulas.[15] The result is that reflexes that would otherwise fall together into one semantically incompatible cognate set can now be differentiated on the basis of meaning, and separate sets can be created (see Figures 24 and 25). The set conflation process described in Sections 4.3 and 5.1 can be applied after this differentiation, giving a more reasonable list of cognates.

This device is presently conceived of as a simple tool to reduce noise in the output, but the semantic formulas might be studied later for an analysis of semantic shift in the

15 Using semantic formulas such as those defined in (7), for example, creates precise cognate sets composed only of reflexes that are assured to be semantically compatible (though some likely candidates might be eliminated when the semantic formula is incomplete). Using semantic formulas such as those defined in (8) would remove semantically incompatible reflexes, but leave those for which semantic compatibility is unspecified.

*Abam/3.136.53.		
gha	³pã:	thigh
ris	³pam	épaule
sahu	³pam	shoulder
*Abam/3.136.53.		
ris	³pam	mouiller, tremper
tag	Xbam-ba	to soak
tuk	³pom	soak
tuk	³pom	wet (v.i.)

Figure 25
Sample of comparative cards proposed by RE (with semantic component). A set (exemplified in Figure 22) divided using semantic formula (9) above.

particular group of languages. Note that the gloss lists are created from and therefore specific to the particular language data sets and glossing metalanguages used.

6.2 Extension to Allofamic[16] Families and Systematic Imprecision in the Table of Correspondences

As has often been noted and deplored, irregular sets of quasi-cognates, or simple groups of look-alikes, are a necessary evil of comparative linguistics.[17] If we discarded immediately all sets that are not absolutely regular according to the rules of phonological change already uncovered for the language group, we would stand no chance of ever improving our understanding of the facts. Using a computer to mechanically apply a set of rules to the data implies that we believe to a large extent in the regularity of sound change. But the comparative method itself implies such an assumption. This does not mean that we cannot also admit that "each word has its own history," when we take into account competing trends or influences on the languages. This flexibility toward irregularity has been incorporated everywhere in the computing mechanism.

One example of this flexible approach is evident in examining the table of correspondences. Turning back to the table excerpt (Figure 9a), notice the presence of multiple outcomes separated by commas in the columns of modern outcomes (columns 5–12). These mean that we do not know yet what the regular outcome of a given change is. Question marks are also allowed, in which case the program can (with the proper switch settings) borrow the outcomes from adjacent languages. Neither of these conventions should remain in the table of correspondences when the analysis of the group of languages is completed. But, as a working tool, the table of correspondences tolerates them, and they do not hamper the functioning of RE.

6.3 "Fuzzy" Matching in the Table of Correspondences

We can also reduce some of the specificity of the rules in the Table of Correspondences in a controlled way in order to produce "allofam" sets or "irregular cognate" sets.

16 Allofamy, the relationship between words in a word family, is described in more detail in Section 1, especially in the footnote to Figure 1.
17 For example, English *have* and Latin *habēre*.

```
TGTM X=A,B
TGTM G=k,kʰ,g
TGTM GR=kr,kʰr,gr
TGTM GL=kl,kʰl,gl
TGTM GW=kw,kʰw,gw
TGTM GJ=kj,kʰj,gj
...
TGTM P=p,pʰ,b
TGTM PR=pr,pʰr,br
TGTM PL=pl,pʰl,bl
TGTM PW=pw,pʰw,bw
```

Figure 26
A "Fuzzy file."

These cognate sets are composed of reflexes that are irregular only by one or two features specified as parameters by the linguist. This is accomplished using a "fuzzy file" in which elements of the table of correspondences are conflated, allowing the linguist to systematically relax distinctions between segments. In Figure 26, distinctions in tone and the mode of articulation at the proto-language level (symbolized by TGTM) are being ignored in order to concentrate on patterns of correspondences between rhymes and between initial points of articulation.

The "fuzzy file," which states that TGTM proto tones ^{A} and ^{B} should be equated to the "cover symbol" X, and that TGTM *k, *k^h, and *g should be conflated into *G, a velar stop, unspecified for aspiration and voicing. Similar conflations are stated for *p, *p^h, *b, and so on.

The result of conflating certain segments is to bring together certain reflexes that would otherwise not be included in cognate sets. Figures 27a and 27b illustrate how this procedure brings reflexes that are tonally irregular into the appropriate cognate sets for further study. In Figure 27a, an "irregular correspondence" (that is, a lack of a correspondence where one might be expected to exist) results in forms from Tukche and Ghachok being left out of the cognate set. With a "fuzzy" value for the tone (illustrated in part B of Figure 27a), the two aberrant forms fall into place. In Figure 27b, the features conflated are tone and voicing.

6.4 Directions for Further Development: Phonological Research Using RE

When the table and canon are "complete," that is, when the linguist is satisfied with the contents of the cognate sets and "residue" files created by RE, the table and canon can themselves be subjected to further study. The table, for example, is a compact statement of the sound changes exemplified in the set of data being studied. Indeed, these sound changes encode linguistic generalizations waiting to be teased out by the linguist.

6.4.1 Subgrouping and Typology. The Table of Correspondences and Syllable Canon contain a considerable amount of information about the relationships among the languages. Analysis of the table shows which languages share features and innovations

A. Without "Fuzzy" Constituents

recon	ᴮgla:	
analysis	4.117.32.	
mar	⁴lja	place
pra	⁴kʰja	place
sahu	⁴kla:	place
syang	⁴lja	place
tag	⁴kʰla:	place

B. With "Fuzzy" Constituents

recon	Xgla:	
analysis	4.117.32.	
analysis	**3.116.32.**	
mar	⁴lja	place
pra	⁴kʰja	place
sahu	⁴kla:	place
syang	⁴lja	place
tag	⁴kʰla:	place
gha	**³ɬo**	**place**
tuk	**³kja**	**place**

Figure 27a
*ᴬgla: ~*ᴮgla:.

A. Without "Fuzzy" Constituents

recon	ᴬbap	
analysis	3.136.46.	
mar	³po	beer-mash
pra	³pe	beer-mash
ris	³pap	beer-mash
syang	³po	beer-mash

B. With "Fuzzy" Constituents

recon	XPap	
analysis	3.136.46.	
analysis	**2.135.46.**	
mar	³po	beer-mash
pra	³pe	beer-mash
ris	³pap	beer-mash
syang	³po	beer-mash
gha	**²pa:**	**beer-mash**

Figure 27b
*ᴮpap ~*ᴬbap.

and where they differ. Such analysis could be useful to produce a more refined characterization of the genetic relationship among the languages.

On one hand, the table could be analyzed to determine what traits the languages have in common. An example of this is shown in Figure 28. Here the correspondences have been re-analyzed to show cases in which languages share a common outcome and cases in which they differ. Where the outcome is the same, a '1' appears in that language's slot in column (2). If all or most of the columns have a '1,' we conclude that this type of change is universal (within this language group). Looking at the types of change that are universally shared, we further note that a generalization over a feature (in this case a devoicing rule) is possible. Such a generalization is the result of two levels of abstraction: bringing together all languages that have an outcome in common, and then comparing those outcomes at the level of phonological features. We hope to have the computer hunt through the table of correspondences attempting to make such generalizations. This would require that the algorithm be able to analyze table constituents at the feature level and to characterize the changes in proto and modern feature sets in some reasonable way.

(1) Corr Nº	(2) Languages: RSTTMSGP	(3) Proto Segment		(4) Outcome		(5) Environment
(138)	11111110	*b	>	p	/	B_j,r
(136)	11111111	*b	>	p	/	A_
(144)	11111110	*bl	>	pl	/	B_
(143)	11111111	*bl	>	pl	/	A_
(132)	11111110	*d	>	t	/	B_
(121)	11111111	*dz	>	ts	/	A_
(97)	11111111	*g	>	k,g	/	A_

etc....

Generalization: C_{vd} > C_{vl}

Figure 28
Devoicing: An innovation common to all languages in the group.

Corr No.	Languages: RSTTMSGP	Proto Segment		Outcome	Environment
Finals Lost:					
(85)	00?0111?	*jup	>	ju	
(44)	00011111	*at	>	e,je,ɛ	
(46)	00001111	*ap	>	o	
Finals Preserved:					
(85)	11?0000?	*jup	>	jup	
(44)	11000000	*at	>	Vt	
(46)	11100000	*ap	>	ap	

Figure 29
Innovations shared by subgroups.

A similar process could be used to distinguish strata of linguistic development and structural similarities *within* the group. A pattern of innovation shared consistently by a subset of the languages but not by the rest may be evidence of close genetic relationship, continued contact, or typological similarity arising from some other source. As Figure 29 illustrates, the languages on the left side of the table (Risiangku, Sahu, and perhaps Taglung) seem to preserve final consonants better than the rest of the languages in the group. It would be useful to be able to catalog sets of shared innovations and provide an interpretation of them along genetic or other typological grounds.

N	Syll	*	Context	ris	sahu	tag	tuk	mar	syang	gha	pra
46	R	ap		ap	ap	ap	əp,əu	o	o	a:	e
94	I	k	*/-w	k	Ø	h	k	k	k	k	k
137	I	b	*/B-	p	p	p,b	p	p	b	b	p^h

Figure 30a
Three Correspondence Sets from the Table of Correspondences.

A close look at the examples shows some of the obstacles that any analysis (and especially an automated one) must confront. Some method for handling cases where data is missing or inconsistent in some "minor" way must be developed. Should the assumption be that missing data supports a generalization, refutes it, or should it not affect the interpretation at all? It is unclear how to have the computer generalize intelligently.

6.4.2 On the Notions "Rule" and "Correspondence." Elaboration of the relationship between the protolanguage and each of the daughter languages implies an item-by-item comparison of modern reflexes with their ancestors. A correspondence, in the strictest sense, reflects only an observed or even hypothesized relationship between modern constituents. It need not embody a claim about the exact features of the ancestor.

When correspondence sets are matched with a protosegment, as is the case in the table used by RE, each correspondence set can be viewed as a set of simultaneous rules. The three correspondence sets given in Figure 30a, for example, can be rewritten as a number of "input-output" type rules as expressed in Figure 30b. Note that these are not "rules" in the sense the word is used by generative linguists, where there is the implication of some kind of process or "rewriting" of material. One indication of this is that some of the rules in Figure 30b are of the form "X remains X" (see rules 181, 366, and 505). The status of such rules in a generative sense is suspect. However, in RE, as shown below, such rules have quite concrete implications.

Figure 31b illustrates what a "feature bundle" in RE looks like. To create this representation, the linguist provides a list of features, and specifies the set of constituents to which the feature applies (as exemplified in Figure 31a).

The feature sets represent a statement of the significant distinctions *in each language*; we note in passing that RE thus implements the notion that the phonemes of each language pattern in their own way, and that even though the same symbol may be used to transcribe words in different languages, this does not necessarily indicate that they share features in common. Consider the feature set for Risiangku exemplified in Figure 32a. /k^h/ is also a constituent in this language, but it has a different analysis from that in 31b inasmuch as the voicing distinction (conjectured for the protolanguage) is not distinctive.

Now consider a rule (rewritten from the table of correspondences as in Figure 30b) like:

(13) Rule 459. `*kl > kj /_ a` (in Tukche and Prakaa)

RN (CN)	Syll	*TGTM	>	Outcome	Context	in Language(s)
181(0046)	R	ap	>	ap		ris,sahu,tag
182(0046)	R	ap	>	aː		gha
183(0046)	R	ap	>	e		pra
184(0046)	R	ap	>	o		mar,syang
185(0046)	R	ap	>	əp,əu		tuk
365(0094)	I	k	>	h	/_w	tag
366(0094)	I	k	>	k	/_w	ris,tuk,mar,syang,gha,pra
367(0094)	I	k	>	∅	/_w	sahu
505(0137)	I	b	>	b	/B_	syang,gha
506(0137)	I	b	>	p	/B_	ris,sahu,tuk,mar
507(0137)	I	b	>	p,b	/B_	tag
508(0137)	I	b	>	pʰ	/B_	pra

Figure 30b
Correspondences 46, 94, and 137 expressed as rules.

TGTM	Unvoiced	= k,**kʰ**,ʈ,ʈʰ,ts,tsʰ,t,tʰ,p,pʰ,ʰŋ,ʰɲ,ʰn,ʰm,ʰj,ʰr,ʰl,ʰw...
TGTM	Aspirated	= **kʰ**,ʈʰ,tsʰ,tʰ,pʰ,kʰr
TGTM	Velar	= k,kʰ,g,ŋ,ʰŋ,kr,**kʰ**,gr,kl,kʰl,gl,kj,kʰj,gj,kw,kʰw,gw
TGTM	Stop	= k,**kʰ**,g,ts,tsʰ,dz,ʈ,ʈʰ,ɖ,t,tʰ,d,p,pʰ,b
TGTM	Cluster	= gr,gl,gj,gw,bl,bj,ml,mj,Hl,Hrkr,kl,kj,pl,pj,pʰj...
...etc		

Figure 31a
Excerpt from the *TGTM feature set.

TGTM	/kʰ/	=	MODE(Aspirated) MODE(Unvoiced) MANNER(Stop) PLACE(Velar)

Figure 31b
Feature analysis of a *TGTM segment as a "feature bundle."

Rewriting each side of the rule in terms of features, we get:

(14)	*kl	=	MANNER(Cluster) MODE(Unvoiced) PLACE(Velar) PLACE(***Lateral***)	>	*kj	=	MANNER(Cluster) MODE(Unvoiced) PLACE(Velar) PLACE(***Palatal***)

ris	Cluster	=hl,hr,kj,kr,kʰr,kl,kw,pj,pʰj,pr,pl,ŋj,mj,ml,mr
ris	Stop	=k,kʰ,ts,tsʰ,ʈ,ʈʰ,t,tʰ,p,pʰ
ris	Aspirated	=kʰ,ʈʰ,tsʰ,tʰ,pʰ,kʰr,pʰj
ris	Unaspirated	=k,ʈ,ts,t,p,kj,kr,kl,kw,pj,pl
ris	Velar	=k,kʰ,ŋ,kj,kr,kʰr,kl,kw

Figure 32a
"Feature set" for Risiangku (excerpt).

Risiangku	/kʰ/	=	MODE(Aspirated) MANNER(Stop) PLACE(Velar)

Figure 32b
"Feature bundle" for a modern segment (note: voicing is *not* distinctive).

Deleting 'like' features leaves a diachronic feature rule:

(15) PLACE(***Lateral***) > PLACE(***Palatal***)

This procedure demonstrates how rules expressed in terms of segments can be automatically or perhaps semi-automatically converted into rules expressed in terms of features. This aspect of the program is the subject of ongoing research.

7. Conclusion

While both the program and the results of its first application are incomplete, some conclusions are warranted. First, we have shown the validity of this approach by producing reasonable, defensible, and well-defined cognate sets using the program. Second, a concrete understanding of semantics and of morphological and phonological variation at the proto level, both quite external to the core phonological functions of the program and perhaps only available via the intuitions and experience of the linguist, are required to interpret the initial results of upstream computations. Finally, the combinatorial complexity of the reconstruction process and the potentially large linguistic data sets that might be treated make the problems of performance and data reduction computationally challenging. There is much room for work here applying techniques already developed in other areas of computational linguistics.

We have occasionally been asked why we have not developed software that would create tables of correspondences based on universal or at least subgroup-wide phonological principles of analysis and comparison. Such an algorithm has already been proposed by Martin Kay (Kay 1964). Our research has focused on evaluating existing hypotheses rather than the process of creating new ones. There is indeed much work that could be done here and we hope that the burgeoning interest in computational historical linguistics will lead to the investigation of this question.

Finally, we recognize that for these algorithms to be useful to other researchers in historical linguistics they must ultimately be implemented as part of a larger software

suite providing conventional (and standardized) database management functions and other computational linguistic tools; we have begun design of this software and invite collaboration from interested specialists.

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