A computational model of the discovery of writing

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This paper reports on a computational simulation of the evolution of early writing systems from pre-linguistic symbol systems, something for which there is poor evidence in the archaeological record. The simulation starts with a completely concept-based set of symbols, and then spreads those symbols and combinations of these to morphemes of artificially generated languages based on semantic and phonetic similarity.

While the simulation is crude, it is able to account for the observation that the development of writing systems *ex nihilo* seems to be facilitated in languages that have largely monosyllabic morphemes, or that have abundant ablauting processes. We are also able to model what appears to be two possible lines of development in early writing whereby symbols are associated to the sounds of *all* morphemes linked to a concept (as seems to have been the case in Sumerian), versus just one morpheme linked to a concept (as seems to have been the case in Chinese). Finally, the model is able to offer an account of the apparent rapid development of writing in Mesopotamia that obviates the need to posit a conscious invention of writing, as proposed by Glassner.

The proposed model thus opens a new approach to thinking about the emergence of writing and its properties, something that, as noted above, has scant direct archaeological evidence.

The software is released open-source on GitHub.

Keywords: early writing, computational simulations

1. Introduction

The genesis of writing starting about 5,200 years ago, much like the genesis of language tens or hundreds of thousands of years before it, is the stuff of conjecture. While there are many ideas on how humans first started using vocal sounds to communicate complex thoughts, and how eventually they learned to transfer those

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sounds to written media, there is a dearth of hard facts. In the case of the origin of writing, it has become clear that the token theory of the development of writing in Mesopotamia, most notably promoted by Schmandt-Besserat (Oppenheim, 1959; Schmandt-Besserat, 1996), can only be a part of the story (Woods et al., 2010, 48–49), and we have little if any clear evidence for the remaining pieces.

Compounding the problem is that while there have been hundreds of writing systems developed over the past 5,200 years, some within living memory, only in four parts of the world – Mesopotamia, Egypt, China and Mesoamerica – would most scholars agree that writing apparently developed ex nihilo. Writing is a product of civilization, but it is not a *necessary* product of civilization: many civilizations, from the Incas of South America, to the Indus Valley (Farmer et al., 2004) to the Gojoseon Kingdom of Korea, have lacked anything that is thus far clearly identifiable as writing, though they certainly had other notational systems. As shown by Wang (2014), civilizations that lacked writing proved themselves adept at doing without it for such functions as record keeping or preserving the "myths of the state".[1] Insofar as writing is merely a tool, it is like other tools that can aid civilization, but are not essential for it, such as bronze implements. In the Old World, one typically associates the notion of "civilization" with the Bronze Age civilizations of the Indus Valley, Mesopotamia or Egypt, and the term "Stone Age civilization" seems like an oxymoron. Yet that is precisely what the great civilizations of Mesoamerica were.[2]

So, were the four cultures that did develop writing smarter than the others? Or, more likely, did certain properties of their culture or their language make it more likely that they would develop writing? With only four instances to work with, it is hard to make any robust claims.

One way around such limitations is computational simulation. Simulations have already been used extensively in the modeling of historical change in language, such as the spread of linguistic features in social networks, and the emergence of linguistic properties – e.g. (Kirby, 1999; Niyogi, 2006; Steels, 2012). A more complete simulation of the evolution of writing would aim to model the

1. For example, the Inca's record keeping system, *khipu*, was evidently capable of encoding more than just numerical information, as has been shown by Gary Urton and others at the Harvard Khipu Database Project http://khipukamayuq.fas.harvard.edu/, yet it was still a highly limited system. The Incas simplified the process of accounting by the draconian approach of "imprison[ing their] craft specialists" (Wang, 2014, 119), thereby guaranteeing tight oversight of their production.

2. As a reviewer points out, the problems with Thomsen's "three-age system" of Stone Age, Bronze Age and Iron Age, have been duly noted by archeologists. See https://en.wikipedia.org/wiki/Three-age_system#The_ three-age_system_of_C._J._Thomsen for discussion.

following factors, among others. First of all, the types of non linguistic symbol systems in use in the culture, and the existence of combinatorial systems where symbols occur in "texts". Most if not all cultures use symbols to represent concepts that are, because they do not depend on language, nonlinguistic,[3] and many of these are complex systems where whole texts can be "written" in these symbols, so that the system resembles true writing in many ways (Sproat, 2014); see Figure 1 for some examples. Some of these, such as the accounting system in early Mesopotamia did eventually develop into writing, but most did not, and it is a reasonable guess that some of them could not have developed into writing.

A second class of factors is economics or other social properties (e.g. religion, including divination) that would encourage the development of better means of record keeping. Wang (2014) discusses the development of record keeping and its role in the recording the myths of the state as well as the accounting needed to keep the state functioning, and he compares societies – Mesopotamia, Egypt, China and Mesoamerica – which developed and used writing for these purposes, with societies – most notably the Inca – which did not.

Thirdly, linguistic properties have been argued to be relevant (Steinthal, 1852; Daniels, 1992; Boltz, 2000; Buckley, 2008). The key insight needed for full writing is the realization that a symbol that had been used to represent an idea, could also be used to represent the sound of a word or morpheme associated with that idea – see also the introduction to (Boltz, 1994). For this to work, it helps if the language used by the would-be scribes is one where it is easy to find homophones or close homophones. Puns, in other words, should be relatively easy to make. Alternatively the notion of what it means for something to sound like something else might be more relaxed in some languages than others: for example if a language has a Semitic-style root-and-pattern morphology, or more generally ablauting processes, where vowels may change drastically in related words, a word such as /patak/ might count as sounding like /pituk/.

3. We do not define the notion "concept", whereas this is a topic that has a long history in the philosophy of language and cognitive science, with some questioning whether one can even have concepts that do not depend on language. Unfortunately delving into this debate would take us too far afield, but fortunately it is not necessary for us to be overly precise here. It will suffice if one can allow that someone might invent a symbol representing a dog, but that one might "read" that symbol with any of the words that one could use to name dogs: *dog, pooch, canine, hound* …. If such a situation holds, then we are justified in saying the symbol is non-linguistic because it does not specify a particular reading.

A B C

Figure 1. Some non-linguistic symbol systems: A. Babylonian kudurru stone (Seidl, 1989), with symbols for deities. (Source: British Museum, released under CC BY-NC-SA 4.0.) B. Pictish symbol stone (Jackson, 1990). (Source: Wikipedia, released under CC BY-SA 3.0.) C. Tlingit Totem pole (Barbeau, 1950). (Source: Wikipedia, released under CC BY-SA 2.5.) See (Sproat, 2014) for details on the "language-like" statistical properties of some of these systems.

Finally, for writing to become practical and widespread, there must be lightweight materials available as writing surfaces (Farmer et al., 2002), with lightweight devices such as styluses, brushes or pens to incise or inscribe on the surfaces. A standing joke in the *Astérix* comics has the Romans writing on slabs of marble with a hammer and chisel: obviously such a system would not be practical for everyday use. Simulating the relevance of the type of non-linguistic system, the social and economic factors, the linguistic factors and the physical properties of the writing surfaces is clearly a tall order. But we can make some progress on some parts of the problem.

In this paper I concentrate largely on the linguistic factors and report on a system that simulates the realization, discussed above, that a symbol that had heretofore been used to represent an idea, could also be used to represent the sound of a morpheme associated with that idea. Anticipating the results, I show that languages with basically monosyllabic morphemes have a better chance of developing writing than those with longer morphemes, but that having ablaut-like vowel alternations can help in a language with longer morphemes. The model is also used to simulate two possible avenues of development of early writing: ones where all morphemes associated with a concept are taken as the basis for further phonetic use of a symbol; and ones where one particular morpheme is thus used. Finally I use the model to argue against a theory proposed by Glassner (2000) to the effect that writing was consciously invented in Sumer, rather than developing from a previous non-linguistic system.

The basic research question to be answered here is: can a fairly simple computational model of the kind presented here lend some insights on the early development of writing, even given that it overly simplifies many aspects of the problem? The point of this paper is to argue that it can.

Before we turn to a description of the model and of our experiments, we first need to address a couple of preliminary issues: what do we mean by writing, and why has writing proved to be so hard to discover independently?

2. Preliminaries

2.1 What is writing?

It is worth being clear at the outset what I mean here by writing. I am assuming a narrow definition of writing whereby for something to be a full-blown writing system it has to be possible, at least in theory, for one to use it to write anything that can be spoken in the language. For that to be possible, the system must encode a fair amount of phonological information, even if it might also encode semantic information (DeFrancis, 1989). This view is of course not completely uncontroversial. Sampson (1985) notably viewed writing much more broadly, claiming it was possible in principle to construct systems based solely on semantics. However, attempts to build semantically based systems have always resulted in systems that are far more restricted than true writing systems in what they can express. The most famous example of such a system is Blissymbolics (Bliss, 1965), which is noteworthy in part because Bliss was a true believer in the possibility of a complete communication system that was directly linked to meaning, and because he devoted many decades of his life untiringly to the task of developing and promoting the system. Yet as I argued in (Sproat, 2010, 15–23), Blissymbolics fails to be as richly expressive as ordinary writing for the simple reason that it could never develop a straightforward and easily learnable mechanism for encoding the subtle differences in meanings between words: how does one represent the two different concepts represented by the English words *annoyance* versus *consternation*? For ordinary writing this is not a problem, since writing encodes words by reference to phonology, and thus simply piggy-backs on whatever distinctions the language makes.

So it does not seem necessary to accept that writing systems that make no reference to sound are even possible, since certainly nobody has yet demonstrated that they are. Nor do we need to retreat to a vague definition of writing such as that of Powell (2009) for whom "writing is a system of markings with a conventional reference that communicates information". Certainly under that definition many things would be writing: a barber pole, for example, is writing since it is a system of markings that is conventional and conveys information. But symbols like barber poles are not capable of conveying the full range of information that one can communicate with language, and the ability to do that is what makes writing special. And, again, to make that possible, the system must be able to encode non-trivial amounts of phonological information. To discover and develop writing, then, a civilization must first discover phonology.

It is worth noting in anticipation of our results below that *none* of the artificial systems that we will present in this paper are true writing under the definition we have just outlined, since with none of them is it possible to encode all of the morphemes of the (artificial) languages we develop. The most that can be said is that they are a possible model of systems on the road to true writing, which is sufficient for our purposes.

2.2 Why is writing hard to discover?

It is actually somewhat of a puzzle why the independent development of writing was so rare. Non-linguistic symbol systems, ranging from pictorial representations of objects or events to specialized notational systems for accounting such as the preliterate token system of Mesopotamia (Oppenheim, 1959; Schmandt-Besserat, 1996; and see again Woods et al., 2010, 48–49, for a critique) have been common in many cultures, most of which never developed writing independently. Yet when one thinks about it, the existence of a symbol system that maps from symbols to concepts brings one ever so close to the development of true writing. Consider the neurological basis for speech and language on the one hand, and for the use of graphical symbols with more or less fixed meanings on the other; the discussion here is based in part on that of (DeHaene, 2009). As is well-known, speech and language involve at least connections between parts of the left cortex that process meaning, spread over the frontal, temporal and parietal lobes, and those that process motor control in the motor strip of the frontal lobe and sound in the parietal lobe. These are diagrammed very roughly as B and C, respectively, in Figure 2. The interpretation of visual symbols certainly involves the visual processing areas of the brain in the occipital lobe (A in Figure 2), but must also involve some of the same areas involving meaning already associated with language (B). Thus the connections between symbols and language are almost there in any culture that uses visual symbols, but still a few things are missing, and those few things are what seems to have been difficult to discover.

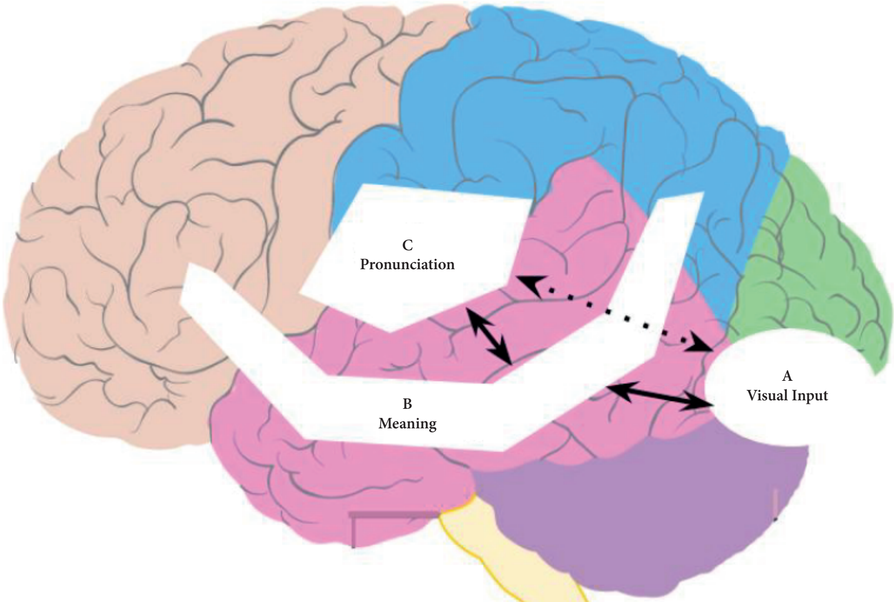

Figure 2. Schematic of the left cortex of the brain showing the frontal (flesh), temporal (pink), parietal (blue) and occipital (green) lobes. Roughly indicated are the regions of the brain associated with sound, meaning and visual input.
(Source of the brain diagram: Wikipedia, https://commons.wikimedia.org/wiki/File:Diagram_showing_some_of_the_main_areas_of_the_brain_CRUK_188.svg. This image has been released as part of an open knowledge project by Cancer Research UK via Wikimedia Commons.)

First of all, a connection must be made between the symbols and not just concepts, but rather actual linguistic entities – words, or morphemes – associated with those concepts. Second, for true writing to develop a connection must be made between the symbols and sound – thus between A and C, and for at least some of the symbols that connection must become essential to their function in the system in that they become heavily, or primarily, or exclusively used to represent sound.

Finally, it is worth remembering that while we may well have evolved to speak, we did not evolve to read, and thus there is no evolutionarily developed reading region of the brain. Inevitably for functional readers, some neurological rewiring is needed. As DeHaene (2009) argues, the occipitotemporal area in the left visual cortex, part of the apparatus for identifying objects (DeHaene, 2009, 125), has been co-opted in literate people and used for the low-level processing of scripts. It does not seem to matter what script is involved: it could be the Roman alphabet, the Hebrew alphabet, or Chinese characters.[4] In any case the initial processing of writing passes

4. But see, e.g., (Perfetti et al., 2010) for a more in-depth comparison of English and Chinese reading.

through this co-opted region that DeHaene terms the "brain's letter box". From there information flows to the parts of the brain that deal with sound and ultimately with meaning, parts that are of course also active in illiterate speakers.

We turn now to a description of the model.

Figure 3. Some of the 100 initial concepts and symbols associated with them.

3. The model

The simulation starts with two sets, namely a set of 100 concepts associated with symbols used to depict those concepts; and a set of morphs, approximately 1,000 in these simulations. Some examples of the basic concepts and their symbols are given in Figure 3. The 100 concepts and their associated symbols are fixed through all of the simulations. The morphs on the other hand are generated randomly from one of a set of phonological templates, which are described in detail in Section 4.

For each concept, from 1 to 3 morphs are randomly associated with the concept. Depending on the setting for the flag `initialize_non_primaries_with_symbol` – see Table 1 for the main flags and their meaning – only one morph, the 'primary' morph associated with the concept inherits the symbol, or they all do. Each concept, symbol (if any) and morph combination is then entered as a morpheme in the lexicon. The remaining morphs that are unassociated with concepts are now randomly associated to a random combination of concepts (e.g. a morph might be associated with the combination DEMON,STONE) and stored in the lexicon, with no symbol associated with them.

At this point, the symbols are associated with morphemes, and the system can be described as *logographic*. Now the system iterates and tries to find spellings for other morphemes according to the value for the flag `probability_to_seek_spelling`. The system searches the lexicon for symbols associated with morphemes that have similar meanings as well as morphemes that have similar sound. Similar meaning is determined on the basis of whether the symbol in question is associated with a morpheme that has a concept shared with the new morpheme: thus DEMON would match DEMON,STONE, or whether the entire combination (DEMON,STONE) is already associated to a morpheme with a symbol.

Table 1. Main flags for the program. `ablaut` and `base_morph` control aspects of the phonology of the system that figure in Experiment 1 (Section 4). `initialize_non_primaries_with_symbol` and `freeze_semantics_at_iter` model, respectively, whether only one or more than one concept-associated morph should be initialized with a given symbol, and whether after a given iteration a symbol should spread to other morphemes on the basis of meaning (Experiment 2, Section 5). `probability_to_seek_spelling` controls the speed with which the system evolves (Experiment 3, Section 6)

`niter`	number of iterations
`ablaut`	whether to apply ablaut (Section 4)
`base_morph`	shape of base morph (Section 4)
`initialize_non_primaries_with_symbol`	whether non-primary morphs associated with a concept should inherit the symbol (Section 5)
`freeze_semantics_at_iter`	freeze semantics at iteration *n* (Section 5)
`probability_to_seek_spelling`	probability of seeking a spelling (Section 6)

Phonetic similarity is based on a phonetically weighted edit distance (see Section 5 for discussion of edit distance) that allows segments to match to themselves freely, but assigns varying costs to substitutions and deletions depending upon the severity of the change. For example changing a /p/ to a /b/ is cheap, but it is more expensive to change a /p/ to a /k/, more expensive still to change /k/ to an /m/, and most expensive to change it to a vowel. For example the cost of /pak/ matching to /bak/ is 0.5, but /pak/ to /bam/ is 10.5, and /pak/ to /pik/ as 5.0.[5] The edit distances are then normalized by the lengths of the strings. All pronunciations within a bounded edit distance of the target are kept as potentially similar. In ad-

5. The full details of the phonological similarity measure can be found in the distribution in the grammar `Grm/soundslike.grm`: see below on the grammar formalism used.

dition to single phonetic symbols, we allow for *telescoping* (DeFrancis, 1989, page 81), a common phenomenon in early writing systems whereby, say, /bak/ could be written with symbols for /ba/ + /ak/.

Once a set of symbols based on phonetic similarity and semantic similarity is collected, the system attempts to assign a spelling to a new morpheme by either using an already used semantic or phonetic spelling – with a small probability the system allows spellings to be reused – or by a combination of semantic and phonetic spellings. The latter simulates the property of all ancient writing systems that new spellings are often created by combining symbol(s) representing the sound of the morpheme or word, with symbol(s) indicating the meaning.

Table 2. Basic phonemes of the systems. Notation: *uvstop* = unvoiced stop, *vstop* = voiced stop, *uvfric* = unvoiced fricative

	uvstop	**vstop**	**uvfric**	**nasal**
labial	P	b		m
dental	t	d	s	n
velar	k	g		N
	liquids		l, r	
	semivowels		w, y	
	vowels		a, e, i, o, u	

After some iterations of attempting to find spellings for morphemes, in the final state of the system, many (though usually not all) of the morphemes will have acquired spellings, some of which are complex combinations of symbols associated with the meaning and the sound of the morpheme. For example a morpheme /yurk/ having the meaning components STAR,WOMB might end up being written as ☆☣, where ☆ represents the semantic component STAR, and ☣ from a morpheme meaning MEAT, with the pronunciation /urk/, is a close phonetic match to the target /yurk/. ☆☣ in turn might be used as a phonetic in /yuk/, WINTER,KING, with the semantic component ☃ WINTER, and the resulting complex spelling ☃☆☣. Pseudocode for the algorithm just described is given in the Appendix.

We end with a few details on the implementation of the system. The phonological grammars are written in Thrax (Roark et al., 2012) (http://www.openfst.org/twiki/bin/view/GRM/Thrax). The simulator consists of about 1,500 lines of Python and the current implementation depends on the Pynini (Gorman, 2016) (http://www.openfst.org/twiki/bin/view/GRM/Pynini) module. The code is freely available at https://github.com/rwsproat/writing_evolution.

4. Experiment 1: Simulating different phonological conditions

Our first experiment addresses the question of under what phonological conditions is the development of writing easiest. As described in the previous section, our simulation starts by generating a set of morphemes according to a morpheme template: a 'language' for our purposes, is simply a set of morphemes generated from a template, each associated to semantic features. In the first set of experiments we use three templates, namely **monosyllable, sesquisyllable**, and **disyllable**.

Table 3. Sample morphemes from each of the three morpheme structure conditions

monosyllable	alp, alt, byun, byut, klilk, milk, newt, nort, prerk, rok
sesquisyllable	adiNk, agrot, astamp, aul, beuyp, duop, edu, gaek, gi, milk
disyllable	awpblap, daykru, glutilt, gu, guNk, ilkuy, liak, lurtimp, prot, ratgla

The basic phonemes of the system are given in Table 2. The basic syllable template is specified as:

```
(s? P? L? V (L | M)? P2)? | (s? M? V L? P2?)
```

where 's' is exactly /s/, 'P' is any stop, 'L' is any liquid, 'V' is any vowel, 'M' is /n/ or /m/, 'P2' is any voiceless stop, '?' marks optional elements and | represents disjunction. In addition a rule of nasal assimilation is applied to pre-stop nasals: this has the effect of introducing the velar nasal before velar stops in codas, though only /n/ and /m/ may occur in onsets. Given these definitions, there are 9,150 possible syllables.

The **monosyllable** condition selects approximately 1,000 morphemes randomly generated from this template. In the **disyllable**, morphemes may consist of one or two syllables from the template. Finally in the **sesquisyllable** condition, a morpheme may be a single syllable or a "half-syllable"followed by a syllable, where a half-syllable is defined as follows:[6]

```
(s | P | L)? V
```

Examples of morphemes from each of these classes can be found in Table 3.[7]

6. As a reviewer notes, the normal notion of "half-syllable" in (South) East Asian linguistics is a bit more restricted than the notion we use here, with V typically being restricted to a single schwa-like vowel.

7. Some of these forms are a bit phonotactically unlikely, as noted by a reviewer. This is true, but they are a fair reflection on what comes out of the system. They could be modified with further tweaking to the grammar, but it is unlikely this would affect the results reported below.

In addition, for some disyllabic languages, an ablaut rule is applied to modify vowels to produce alternate forms of the morpheme. In the present implementation the following changes occur under ablaut. Note that these rules apply in parallel:

```
a → o
e → o
i → u
o → u
u → ∅
```

Thus for example a morpheme *waltemp*, would have an ablauted form *woltomp*, and *utbak* might have a zero-grade alternate *tbok*.

Table 4. Results from the first experiment. 'Tot' is the total mean proportion of morphemes with a spelling, across the various runs for the condition; Φ is the proportion of spellings that are purely phonetic; SΦ those that are semantic- phonetic; and S purely semantic spellings. The first row is the means, the second the standard deviations

monosyllable				sesquisyliable				disyllable				disyllable + ablaut			
Tot	Φ	SΦ	S	Tot	Φ	SΦ	S	Tot	Φ	SΦ	S	Tot	Φ	SΦ	S
0.81	0.23	0.32	0.45	0.35	0.12	0.20	0.67	0.34	0.12	0.18	0.70	0.45	0.17	0.25	0.58
0.03	0.02	0.03	0.02	0.02	0.01	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01

There are thus four experimental conditions:

- **monosyllable**
- **sesquisyllable**
- **disyllable**
- **disyllable** with ablaut

For all of the experiments reported in this section, only primary morphemes were used as the basis for the phonetic use of a symbol (`initialize_non_primaries_with_symbol=0`) and `probability_to_seek_spelling` was set to 0.5. As noted above, roughly 1,000 morphemes were generated, each experiment was run for 10 epochs, and 5 instances of each experiment were run – thus there were five **monosyllable** languages generated, five **sesquisyllable** languages, and so forth. The results here are reported for each condition, averaged over the five runs.

As we stated in the introduction to this section, the question we are primarily interested in answering is: under which phonological conditions is the development of writing easiest? This can be answered in two ways, first by considering the number of morphemes that end up with a spelling at the end of the simulation; and second by considering the percentage of spellings that are at least in part phonetic.

The results are presented in Table 4. All conditions are significantly different at at least the $p < 0.01$ level for all measures,[8] except for the sesquisyllable and disyllable, which are not significantly different for any measures. We also present the evolution in one simulation for each of three systems in Figure 4.

A few observations summarize the results. First, it is significantly easier to find spellings for words under the **monosyllable** condition than under any other condition, thus confirming previous claims (Daniels, 1992; Boltz, 2000; Buckley, 2008). Second, the proportion of both pure phonetic and semantic-phonetic spellings are higher under the **monosyllable** condition, again confirming previous claims, since this is a direct consequence of the fact that it is easier to find close homophones under that condition. On the other hand, presence of ablauting processes resulting in morphemes appearing in a variety of shapes also facilitates the evolution of spellings, suggesting that a language that has polysyllabic morphemes, but also has morphophonemic processes akin to Semitic root-and-pattern morphology, may also have an advantage over languages that have polysyllabic morphemes that do not vary in their form. This in turn may help explain why Egyptian was well-suited to the development of a writing system.

Finally we note that the proportion of Semantic-Phonetic spellings in the **monosyllable** condition, 0.32, is close to the rate of 34% reported by DeFrancis (1984, Table 3, page 84), for semantic-phonetic characters in Shang Dynasty Oracle Bone texts, the earliest extant form of Chinese writing: Keightley (1978, 68, footnote 49) quotes Li (1968) as giving a somewhat lower percentage of 27%,[9] but still in a range close to 30%. The earliest form of Chinese that scholars usually try to reconstruct is what is normally called Old Chinese, a version of the language evidenced, for example, in the Book of Songs (詩經 Shi Jing), dating from at least 500 years after the Oracle Bone texts. Morphemes in that version of Chinese were largely monosyllabic (Baxter & Sagart, 2014), and if we assume that the earlier Shang Dynasty language was similar,[10] this suggests in turn that the amount of semantic-phonetic spelling in our artificial systems is not an unreasonable simulation of what one finds in a real language that has similar phonological structure for its morphemes.

8. Per a Welch Two Sample t-test.

9. A reviewer notes that Li's estimate is probably a "gross underestimate".

10. As a reviewer points out, this is of course not clearly the case.

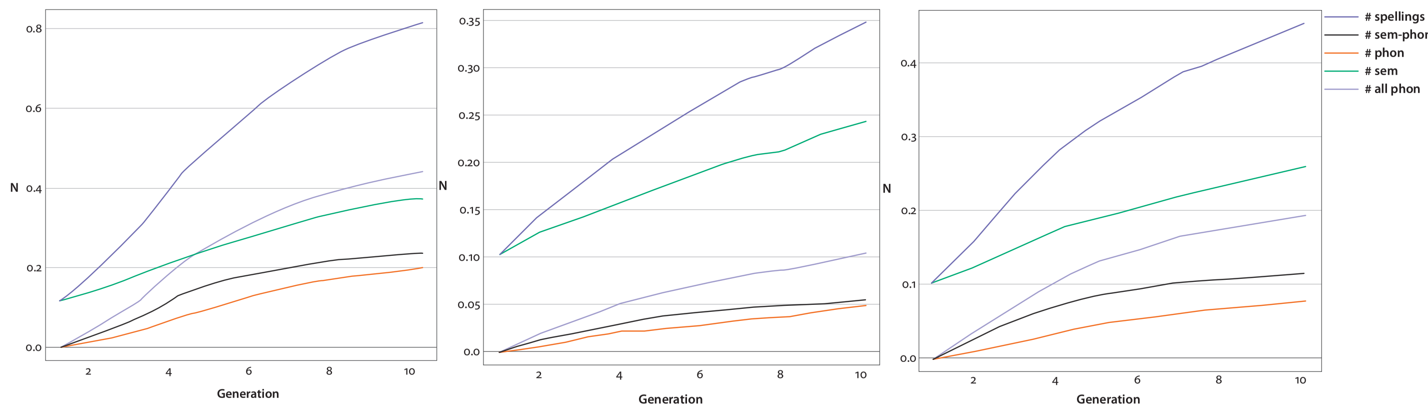

Figure 4. Results showing the evolution for one of the simulations for each of the **monosyllable, disyllable** and **disyllable** with ablaut. Shown are the growths in the proportion (N) of spellings (relative to the total number of morphemes, the total proportion of semantic spellings, the proportion of semantic-phonetic and pure phonetic spellings, and the total proportion of phonetic spellings.

5. Experiment 2: Symbols representing concepts versus morphemes

The previous discussion made a rather strong assumption: when a symbol became conventionally associated with a concept, it also became associated with a *particular* morpheme related to that concept. Let us call such systems *monovalent* writing systems. While this seems to be a good model of the origins of some writing systems, it does not seem to be a good model of all. The alternative is that symbols were associated initially with concepts, and then became conventionalized in their association with a variety of morphemes that were associated with each concept, and then finally became phonologized. We term these *polyvalent* writing systems.

When polyvalent systems start to use their symbols for their phonological values, one would expect that the phonological values possible for any given symbol would be fairly diverse, reflecting the polymorphemic origins of the values. On the other hand, a monovalent system would tend to select a range of phonological values similar to that of the single morpheme associated with a symbol. Put another way, in polyvalent systems, the symbol is associated with the concept, and only with particular linguistic morphemes by inheritance from this concept. In contrast, in monovalent systems the symbol is associated early on with a particular morpheme, and therefore, the use of symbols to represent linguistic rather than conceptual entities is realized earlier on in monovalent systems. Indeed, one could go one step further and suggest that monovalent systems are more evolutionarily advanced than polyvalent systems, since in order to associate a symbol to a particular morpheme, one must first arrive at the concept that a symbol should be associated to a linguistic, rather than merely a conceptual entity. Then, either the inventors of monovalent systems made the leap of understanding in representing linguistic units more quickly than the inventors of polyvalent systems; or alternatively they learned the idea of writing from somewhere else. We return to this point below.

One way to get at the polyvalence of the original system that a writing system was derived from is to consider how similar phonetically the various uses of a given phonetic symbol are. To do this, one can consider the set of cases where a phonetic symbol is found in the spelling of more than one morpheme, and compute a measure of similarity across that set. In traditional Chinese terminology a series of characters sharing the same phonetic component is termed *xiesheng* (諧聲).

Take, for example, the Old Chinese examples involving the phonetic component 丘 according to the reconstruction in (Baxter & Sagart, 2014), shown in Table 5. As one can see, there is some broad similarity among the pronuncations of the morphemes, except perhaps for the final element, reconstructed as /ŋˤrok/, which is rather more divergent. And as a reviewer notes, in fact this last form 岳 is unattested in pre-Qin material, was written with a different form in early texts, only later becoming conventionalized to this form. Thus the series in Table 5 is even more regular than it appears.

Table 5. Characters with the phonetic component 丘 and their Old Chinese pronunciation according to Baxter and Sagart (2014)

Char.	Phonetic component	Mand.	Middle Chinese	Old Chinese
丘	丘	qiū	khjuw	k^{wh}ə
蚯	丘	qiū	khjuw	k^{wh}ə
虛	丘	xū	khjo	q^{h}a
岳	丘	yuè	ngæwk	ŋˁrok

Contrast this with the case of a Sumerian symbol A_2, taken from (ETCSL, 2006), as shown in Table 6. While there are clearly some clusters of phonetic uses that are similar, the case seems rather more divergent than the Chinese example. To actually measure the difference quantitatively, we need a measure of similarity.

Table 6. Example of the Sumerian symbol A_2, from (ETCSL, 2006). The left column is the conventional transcription for the symbol, the center column the actual cuneiform symbol, and the right column its various phonetic uses

A_2 |  | a_2, ed, et, id, it, it, te_8

One can model phonetic similarity or dissimilarity in terms of the well-known Levenshtein distance (Levenshtein, 1966), whereby one expresses the distance between two strings as the optimal number of insertions, deletions, or substitutions needed if one were to edit one string into the other. For example if we consider two pronunciations associated with the phonetic 丘, namely $k^{wh}ə$ and $q^{h}a$, one could edit the first into the second by deleting three symbols (k, ^{w}, $ə$), and inserting two (q, a). There are efficient algorithms for computing this distance for arbitrary pairs of strings. By default, each insertion, deletion or substitution counts the same (say, 1), but one could if desired make the distance sensitive to phonetic differences. Since one expects longer string pairs to involve more edits, it is common to normalize the distance by the lengths of the strings: in our case we normalize by the mean of the two lengths.

A simple procedure using the Levenshtein distance is the following:

1. For each distinct phonetic symbol k in the set V of phonetic symbols used in more than one morpheme:

a. For each pair of distinct phonetic values p_i, p_j of k, sum Lev(p_i, p_j) where $i < j$ and Lev is the normalized Levenshtein distance, into *subtot*.
b. Sum $\frac{subtot}{N}$ into *tot*, where N is the number of distance computations performed.

2. Return *divergence* = $\frac{tot}{|V|}$, where |V| is the size of the set V.

Note that a perfectly regular phonetic system would have *divergence = 0.*

We performed this computation on 1,102 phonetic symbols from (Baxter & Sagart, 2014), and 212 symbols from (ETCSL, 2006).[11] For Old Chinese, the overall phonetic divergence was 0.57, whereas for Sumerian it was a much higher 0.89, reflecting the fact that there was much more variability in the use of phonetics in Sumerian. Chinese is thus more consistent with a model whereby most of the phonetic symbols were derived from their use for a single original morpheme, whereas Sumerian is more consistent with positing a polyvalent origin for the phonetic uses.

How do we simulate these two situations? Obviously we need to allow phonetics from other than just the single 'primary' morpheme to be used. The simulation has a flag `initialize_non_primaries_with_symbol`, that allows this. However this is not enough, as we can see in Figure 5. Here we plot the evolution of phonetic divergence of two monosyllabic systems, one where `initialize_non_primaries_with_symbol` is set to false, as in simulations in Section 4, and the second where it is set to true, allowing for the use of pronunciations of 'secondary' morphemes associated with the concept. In our simulation, we consider the set of simplex symbols and their phonetic uses, as they evolve over the epochs. For comparison, we plot as horizontal lines the Old Chinese and Sumerian divergences. Not surprisingly, the monovalent system "only primaries" system (red solid curve) starts out with a much less divergent phonetic usage, but it quickly converges after a couple of epochs to be roughly the same as the polyvalent "non-primaries" system (dashed green curve). This happens because the system continues to allow symbols to be used for new morphemes due to semantic similarities, and once the symbol has been adopted for another morpheme, there is nothing to stop it being co-opted for the phonetic value of that morpheme.

Suppose instead we freeze extension due to semantic similarity early in the process? In Figure 6 we plot what happens when this freezing is done after epoch 2. This rather more closely models what we see in actual writing systems. In

11. Baxter and Sagart (2014) do not identify the phonetic symbols in their data, but rather just give the pronunciations of the whole Chinese character. In order to identify the phonetic symbols, we merged their data with mapping from characters to semantic and phonetic components that I had developed previously for my earlier work (Sproat, 2000), using data from www.zhongwen.com.

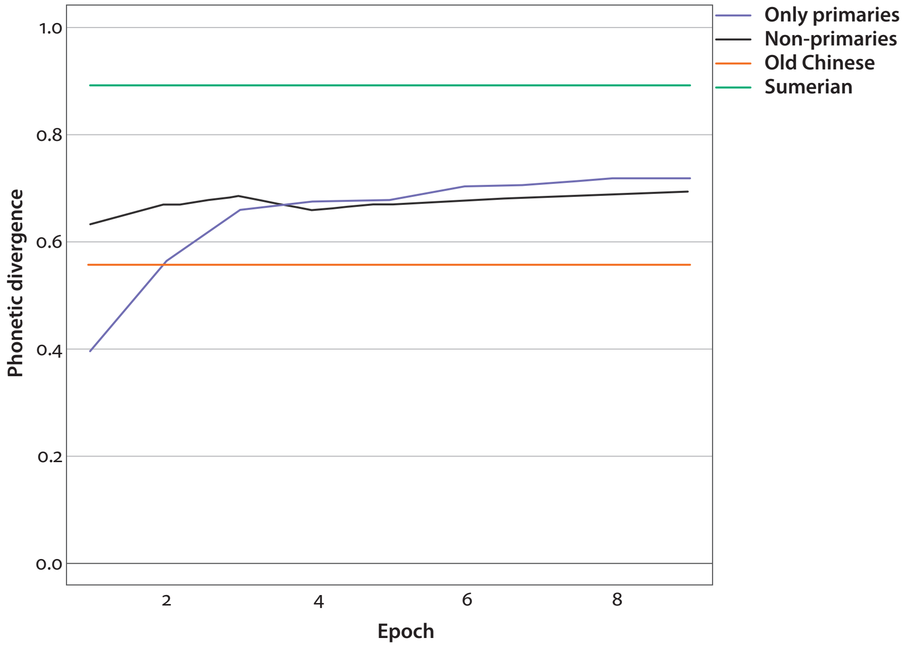

Figure 5. Evolution of phonetic divergence for phonetic equivalence classes in two monosyllabic systems: one where the initial system only spells the primary morpheme associated with a concept; and one where the initial system encodes all morphemes associated with a concept. Phonetic divergences for Old Chinese and Sumerian are given for comparison.

particular the monovalent system closely tracks the actual value for Old Chinese, while the polyvalent system, though still well below what we find in Sumerian, is nonetheless consistently about 10% higher than that of the monovalent system.

Freezing the use of semantics may seem rather draconian, but it serves as a way of implementing the concept that once one realizes that one can write morphemes based on their pronunciation, one can start to move away from the use of semantic information. This does in fact represent a direction that is common in the evolution of writing systems, even those that, like Chinese, have retained a significant amount of semantic information. Thus if one looks at Modern Chinese writing, the standard set of semantic 'radicals' is those of the Kangxi dictionary (originally due to 梅膺祚 Mei Yingzuo in his 字彙 *Zihui* of 1615), numbering 214. In contrast the set of characters used as phonetic components is quite a bit larger – one source (Wieger, 1965) lists 858, suggesting that while the set of semantic indicators changed relatively little, the set of elements used for their phonetic value continued to grow over time. Terminating the semantic spread of symbols as we do in our simulations is of course too restrictive, but it is not completely off the mark either, and does allow us to simulate what one actually observes in writing systems.

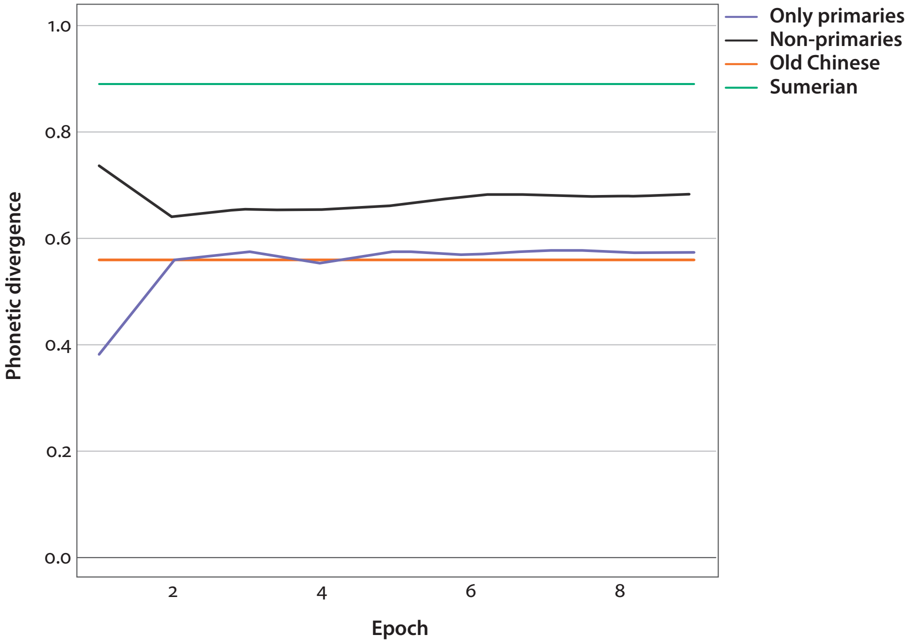

Figure 6. Evolution of phonetic divergence for phonetic equivalence classes in two monosyllabic systems, under the assumption that the further extension of semantic categories is "frozen" after epoch 2.

Getting back to a point raised earlier, does the difference in phonetic divergence between Sumerian and Chinese reflect a difference in how 'primitive' or 'advanced' the two systems were? Sumerian, it seems, developed from an ideographic system where symbols were associated with concepts, and each of these concepts had a range of lexical values associated with them.[12] But in Chinese the basic symbols were rather more associated initially with actual specific morphemes. As we suggested above, this is more advanced in the sense that the developers of the system already had the concept that each symbol should be associated to a particular linguistic unit rather than to a concept.

There are two very important caveats here: the Baxter-Sagart reconstructions are for a form of the language that was spoken several hundred years after the first full-fledged Chinese writing of the Shang Dynasty Oracle Bones. Obviously it would have been better if one could compute phonetic divergence values over Shang Dynasty Chinese, rather the later Old Chinese, but at the time of writing, only the Baxter-Sagart reconstructions of Old Chinese were readily available. It is thus in principle possible that for Shang Chinese the phonetic divergence

12. Christopher Woods, personal communication.

would have been, say, greater than what we estimate for the Western Zhou form of Chinese that Baxter-Sagart reconstruct.

Secondly, as Baxter cautions us (Baxter, 1992, 347–355), the forms of the characters used for particular words or morphemes changed often substantially during the Old Chinese period, so that a word might have been written in the Zhou period with a quite different character from that used during the later Han, when the writing system became more standardized (cf the discussion of the character 岳 above). Thus a character in a particular *xiesheng* group in post-Han spelling, might not have been in that group at all in earlier Zhou spelling (much less in the even earlier Shang Oracle Bone spelling). Nevertheless, the principle of *xiesheng* spelling was the same. According to Baxter (1992, 348), basically:

> In order to be written with the same phonetic element, words must normally have identical main vowels and codas, and their initial consonants must have the same position of articulation.

So, even if the precise details changed, the assumption underlying Old Chinese reconstruction is that characters belonging to the same *xiesheng* series must be phonetically similar in this rather narrow sense. In other words, the phonetic use of a symbol was based on the pronunciation of one morpheme. In (Baxter & Sagart, 2014) the target of the spelling has changed from words to roots, possibly ignoring various affixes and vowel changes. But this does not change the situation dramatically: the spelling is still based on phonological properties of one linguistic element. Assuming, then, that our results above are at least somewhat reflective of the true state of early Chinese writing, one might consider two possible explanations for why Chinese is less divergent than Sumerian. One is that the system that we know from the Oracle Bones developed and was to some extent standardized from an even earlier now lost writing system that was more like Sumerian in its phonetic divergence. This is of course possible, since one of the puzzles of Chinese writing is that it seemed to emerge as a fully formed system from the earliest times. Another possibility, equally consistent with the evidence, is that China got the idea of writing from somewhere else, and thus learned from elsewhere the key insight that symbols could be used for specific linguistic units, rather than merely for concepts. Boltz (1994, 12), points out that "Chinese historians and archaeologists rightly condemn …conjectures [of an external influence on the invention of writing in China] as unfounded", as indeed they are. Nonetheless, the arguments suggested in this section suggest that there may be something to explain here: that while Chinese writing did indeed, as Boltz (1994) goes on to argue, develop along the same lines as all other known early writing systems, early Chinese writing does seem to be more advanced along the path of development than one might have expected of a writing system that evolved organically out of a pre-linguistic system.

6. Experiment 3: Was writing "invented"?

The model we have developed in this paper has made the explicit assumption that writing evolved originally from a non-linguistic notation system that gradually became extended to encode linguistic units – morphemes and ultimately sounds. This view is certainly a common one, and one might have taken it to be uncontroversial, but for the fact that it has been challenged in work of Glassner (2000) for whom writing was instead consciously invented by its creators and that "il ne peut y avoir, par définition, ni pré- ni proto-écriture, ni écriture en gestation" (Glassner, 2000, 279). If Glassner is right, then of course the preceding arguments have been pointless: at some point, scribes (or a scribe) sat down to invent writing for their language, and the whole notion of evolution of the writing system out of prelinguistic forms is simply wrong.

Glassner bases his argument on defects with what he takes to be the two main received theories of the origins of writing: the older and more general pictographic theory, and the later and rather more specific theory of the accounting origins of Mesopotamian writing, in particular the work of Oppenheim (1959) and Schmandt-Besserat (1996). The problems with the accounting token theory of Schmandt-Besserat have been duly noted elsewhere and Glassner merely amplifies on the critique. By pictographic origins, Glassner is thinking in particular of the kind of pictography used by various indigenous peoples of North America, often to convey narratives (Mallery, 1883), and he emphasizes the total lack of evidence for any such pictography in Mesopotamia (page 122). He goes on to to stress that "the basic characteristics of the earliest Sumerian writing become clear, that is, its phonetic character" (Glassner, 2003, 144), and that writing itself was an object of study from the very earliest moment of its creation (Glassner, 2000, 136): by the latter he intends the introduction of lexical lists, which are obvious metalinguistic devices intended to help the user of the system learn how it works. So in other words, the Sumerians quickly discovered the key insight – that words could be encoded on the basis of their sound – and treated the new technology as one treats any technology, providing guides for its use. But the system, per Glassner, did not evolve from a previous system that encoded only non-linguistic information.

It is worth noting at this juncture that that Sumerian would seem to be a very poor choice for Glassner's theory since as we argued in the previous section, the rather diverse sets of phonetic values that any given symbol could take on is much more in tune with a theory where the symbol originally represented a concept or related set of concepts, and then became associated with several morphemes associated with those concepts, each with a rather different pronunciation. If the Sumerians had sat down to invent their system, why could they not have been more consistent?

Glassner's theory has been criticized by a number of scholars (Dalley, 2005; Robson, 2005), and Englund (2005) in particular attacks Glassner's analysis on basic Sumerological grounds. Besides the arguments adduced by these scholars, one might point out that Glassner's rather lengthy arguments about pictography are beside the point in at least a couple of ways. First of all, while narrative pictographic systems are often discussed as precursors to writing – Gelb (1963), discusses them, for example – nobody has presented a shred of evidence that such systems have ever been the basis for a true writing system.

Second there is, I believe, a confusion in terminology here. To state the obvious truth that some of the symbols of ancient writing systems evolved from pictures – nobody questions that the Chinese character 馬 'horse' (Oracle Bone form ) was originally a picture of a horse – is not to subscribe to the view that the systems evolved from pictographic systems like those that Glassner focuses on. Symbols thus clearly could have – and in many cases apparently did – evolve from pictures of objects, but these pictures were not part of some broader non-linguistic narrative pictographic system. Indeed it would have been surprising if they had been: the *uses* of the earliest Sumerian writing were in any case very limited (accounting was in fact the most common use) and it was only centuries later that one started seeing writing that actually reflected the forms and sequences found in speech (Woods et al., 2010, 44), something clearly needed for narrative prose. This would hardly be as expected if Sumerian writing had evolved from some sort of narrative pictographic system, and so Glassner's target is to a large extent a straw man.

The real issue for Glassner comes down to the rapidity with which Sumerian writing appeared with the trappings of a fully developed writing system, in particular with a large use of phonetics. To some extent this is also a bit misleading: it is generally recognized that true writing always encodes phonetics (DeFrancis, 1989), and attempts to show that heretofore unrecognized writing systems are in fact writing, invariably present evidence that the system in question has standardized ways to encode certain sounds. A good example is recent work by Whittaker (2009) on Nahuatl writing. So it is somewhat meaningless to argue that the earliest Sumerian writing showed evidence for phonetics since, if it did not, then we probably would not consider it writing anyway. But perhaps we can accept that what is meant is that writing seemed to appear on the scene full-fledged, and that the appearance of such a complex system could not easily be explained by natural processes of cultural evolution, but rather suggests conscious creation.

This seems to be a category error of the same type that has plagued discussions in evolutionary biology of the evolution of complex structures, such as the vertebrate eye. Ever since Paley (1826), some have argued that the existence of such structures is evidence for special creation.[13] For the evolutionary biologist, the debate surrounds the role of the incipient structure: what adaptive advantage did a partial eye serve? Darwin (1859, 168–171) devoted discussion to what he termed "organs of extreme perfection," but it is often a problem to understand how an incipient version of a complex structure can be useful. As Gould (1974, 104) so pithily put it: "The dung-mimicking insect is well-protected, but can there be any edge in looking 5 percent like a turd?" In biology one tries to solve such problems by proposing a Darwinian history whereby an incipient form of a complex structure was adaptive, possibly in some quite different way from how the present-day adaptation serves the organism that bears it.

In the case of our problem, we can view writing as a complex structure, and non-linguistic symbology as the incipient structure from which it evolved. The adaptive advantage of the non-linguistic symbology was that it allowed its users to notate a few things of importance to them. As that set of things increased, the notational system evolved into something quite unanticipated: a system that allowed the users, ultimately, to write down anything that could be spoken. The switch-over to a linguistic notation system – writing – might appear to be a conscious invention, especially if the system evolves rapidly, at least as far as we can tell from the archaeological record. Yet in fact such an assumption is not necessary, any more than one need invoke a creator to explain the eye. Crucially, given that phonologization is critical to an incipient writing system evolving beyond a certain point, even if there was no explicit intention to spell things phonetically, as pressure on the system to increase the number of representable terms increased, so must the pressure to increase the amount of phonology present in the system. It thus simply comes down to the amount of pressure.

One of the parameters of our model is the `probability_to_seek_spelling` for a new term, which was set to 0.5 in the previous simulations. Raise it, and on each epoch the system will try to find spellings for a larger number of morphemes; lower it, and the opposite will occur. Now consider the evolution of three monosyllabic systems with the settings 0.2, 0.5 and 0.9, shown in Figure 7. Clearly the higher the pressure to find a spelling for something – perhaps due to the economic need to come up with a way of writing a new commodity, or a personal name of one of the parties to a transaction – the more quickly the system evolves. The system with the 0.9 setting shows a higher overall number of spellings than the

13. This has been a favorite argument of the so-called "Scientific" Creationists of later years, an example of such an argument being the following, from (Morris, 1974, 53): "A new structural or organic feature which would confer a real advantage in the struggle for existence – say a wing, for a previously earth-bound animal, or an eye, for a hitherto sightless animal – would be useless or even harmful until fully developed."

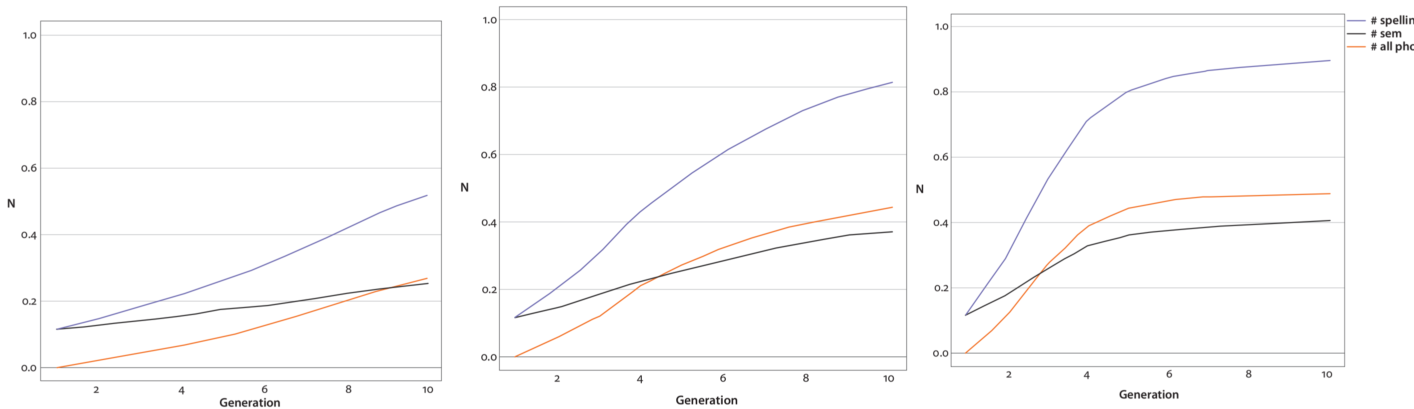

Figure 7. The evolution of writing in three monosyllabic languages with different probabilities of seeking a spelling for morphemes: 0.2, 0.5, 0.9. Again, the vertical axis N is the proportion of morphemes that have a spelling.

system with 0.2. Furthermore, in an earlier epoch of the 0.9 system phonetic encoding beats semantic encoding as the major mechanism used in the system, than is the case with the 0.2 system.

These differences can be seen more starkly in Figure 8, where we have generated random sample 'texts' from each of the languages of Figure 7, at the second epoch – i.e. the epoch at which the system is first starting to evolve beyond its original purely semantic non-linguistic base. Phonetic symbols are indicated in red, and the proportion of 'words' (delimited by | in the texts) that have at least some phonetic spelling in the entire set of generated texts is given under each figure. Those proportions vary across different random text generations, but in general the system with the least pressure to spell a new word shows a small proportion of phonetic spellings (15% in the example shown), whereas that with the highest pressure of 0.9 has a large proportion (36%) even at this earliest phase. It is easy to see how these differences might affect one's view of the system. If in one's excavations of an ancient site one discovered a sample of the text in the leftmost column, one would find only a small amount of evidence for phonetics. Whereas on the other hand if the sample were from the rightmost column, a third of the words written would have at least some phonetic component. If one had previously seen the phonetic-free non-linguistic precursor to this system, then one might well conclude that between those two stages there had been an active attempt to invent writing by the people using the system. But in fact all that happened was that they had a large economic pressure to come up with ways to notate different terms, and they discovered that the best way to do that was on the basis of sound.

In summary, we see no reason to suppose, with Glassner, that the Sumerians somehow sat down one day to invent their writing system. Rather, the traditional

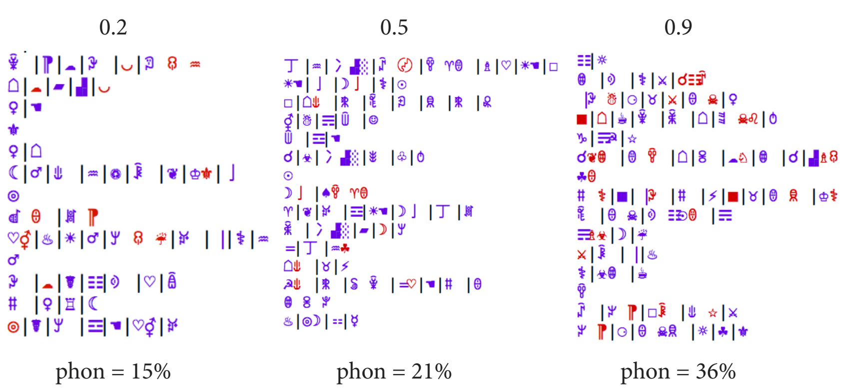

Figure 8. Sample of 'texts' generated at the second epoch for each of the configurations from Figure 7. Red glyphs encode phonetic information. Last row shows the proportion of words that are spelled with at least some phonetic information (in the whole set of generated texts, not just the sample shown).

view that the system evolved, though possibly quite rapidly, from an earlier non-linguistic system, seems adequate. This is something that is relatively easy to see in the kind of computational model we have presented here, where we can easily tune a parameter of the system to put more or less pressure on the system to invent new spellings.

We now turn to a summary of the results presented above, as well as some ideas on where one might take such a line of research in the future.

7. Conclusions and future research

In this paper, we have presented a computational model that captures some aspects of the early evolution of writing systems. The model provides a new way of thinking about a phenomenon for which there is scant direct evidence.

In Section 4 we showed that the system more easily evolves a writing system if the language in question has basically monosyllabic morphemes, which accords with some previous suggestions in the literature (Daniels, 1992; Boltz, 2000; Buckley, 2008). On the other hand, in a system with mono- and disyllabic morphemes, there is an advantage of having ablaut-like processes that change the form of the stem.

In Section 5 we argued that writing systems seem to have followed two courses in their development from non-linguistic systems. The first, exemplified by Sumerian, involved associating a symbol to many or all of the morphemes associated with a given concept, and then basing further phonetic development on the pronunciations of all of these morphemes. The second, which seems to better characterize Chinese, is that the symbol becomes associated in particular with one of the morphemes, and the phonetic development spreads from there. We showed how one could simulate both of these types of development.

Finally in Section 6 we presented some evidence against Glassner's (2000; 2003) theory that Sumerians consciously invented their writing system, and that it did not evolve in the ways we have suggested from a previous non-linguistic system. Pressure to develop ways of writing new terms is the key variable, and once the users of the system have discovered that they can write new words on the basis of their phonetic rather than just semantic properties, how rapidly the system develops depends only on that pressure.

As we noted in the introduction there are many other aspects of the development of writing that one would want to simulate. Obviously the scribes who developed the system were not just making random choices as our simulations have, and so there was clearly conscious involvement in the development of the writing system. This would have grown as the script became more complex and used for a wider variety of purposes, and various conventions, e.g. for how to spell particular phonetic forms, would have developed. The current simulations model none of this.

As Wang (2014) has argued, different ancient cultures took very different approaches to record-keeping, depending in part on how severe they were willing to be in controlling the laborers and craftsmen who produced the goods. It is perfectly possible for a relatively advanced and highly structured civilization to get by without a record keeping system that we can identify as writing. Again the current simulations do not model this at all.

Figure 9. Shang Dynasty divination scapula prepared with tabular drill holes. Source: Wikipedia, released under CC0 1.0.

Once the system has become a full-fledged writing system, one would also wish to be able to model its further spread through the use of lightweight materials (Farmer et al., 2002).

Our simulations say nothing about the *types* of non-linguistic system that might evolve into writing. In one way this is even more difficult a question to answer than the evolution of writing itself, since the only clear model that has been proposed for this evolution is the token theory of Oppenheim (1959) and Schmandt-Besserat (1996). Even if one accepts that the Tomb U-j seals from Abydos (Stauder, 2010) are precursors to Egyptian writing, there is no generally accepted model of how these short texts evolved into the later full-fledged writing. The origins of the Chinese and Mesoamerican writing systems are, so far, lost. So we have only one really solid proposal for a non-linguistic precursor to writing, namely an accounting system where symbols represented concrete goods or quantities of those goods. It seems a priori unlikely that this is the only route that the evolution of writing could have taken.

And factors other than just what the symbols denoted may have been at play. Keightley (1978, 5) observes that while pyroscapulomancy – the use of fire in the cracking of bones and shells for divination – was widespread throughout much of East Asia and North America, only in China do we, if only rarely, find the bones and shells prepared with a tabular arrangement of holes; see Figure 9. During divination the diviner would insert a flaming thorn into the hole and then interpret the resulting crack shape. The interpretation associated with each hole was usually written next to the hole. The tabular arrangement could be used to enumerate a set of choices in a line-by-line fashion: "it is due to father Jia", "it is not due to father Jia"; "it is due to father Geng", "it is not due to father Geng"; etc (Keightley, 1978, 80). Jack Goody (Goody & Watt, 1968; Goody, 1977) has emphasized the importance of tables in the kind of structured thinking associated with literate cultures. But as the case of pre-linguistic accounting documents in Mesopotamia show, tables did not originate with literacy but rather predated it. Could the tabular arrangement of symbols have had just as much relevance for the development of writing as what the symbols actually denoted? As a reviewer notes, this is a speculative argument insofar as the tabular arrangements of holes were much rarer than implied by Keightley, the writing related to the results of the divination was not systematic in its placement, and clear cases of grid-like arrangement of writing only occur later in Western Zhou, first on the 大盂鼎 *dayu ding* (10th c. BCE). But the fact that tabular arrangements occurred at all may have been enough to structure early Chinese thought in a way that facilitated the development of writing. The current simulation does not model this either.

Acknowledgements

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Appendix. Pseudocode

The following pseudocode covers the main parts of the algorithm. For more details, see the actual code at https://github.com/rwsproat/writing_evolution.

```
procedure RunSimulation(N, S, C, n) ▷ Number of morphs N, morphological shape S, concepts C, number of iterations n
L ← GenerateInitialAssignments(N, S, C)
if ablaut then
    ▷ Apply ablauting to forms in L
end if
for i ∈ 1 … n do
   if freeze_semantics_at_iter = i then
      ▷ Freeze further extension of semantics in L
   end if
   GenerateNewSpellings(L)
 end for
end procedure


procedure GenerateInitialAssignments(N, S, C)
 L ← [] ▷ Lexicon
 M ← [] ▷ Set of morphs
 for i ∈ 1 … N do
   μ ← generate random morph from S
   M ← M + μ
 end for
 S ← [] ▷ Records morphs we have already dealt with
 for all c ∈ C do
   M′ ← randomly select 1–3 morphs from M
   primary ← true ▷ This morph is primary for c
   for all μ ∈ M′ do
     sym ← ∅
     if primary or initialize_non_primaries_with_symbol
```

```
                    then
        sym ← sym(c)
      end if
      L ← L+morpheme(μ, c, sym, primary) ▷ Add to L new morph. w/ form μ, conc. c, sym. sym, val. of primary
      primary ← false
      S ← S + μ
    end for
  end for
  for all         μ ∈ M
                    do
    if             μ ∈ S
                    then
      continue
    end if
    c ← random combination from C ▷ Random combination of concepts
    if have seen combination c
                    then
      primary ← true
    else
      primary ← false
    end if
    L ← L+morpheme(μ; c; ∅; primary) ▷ Add to L new morph. w/ form μ, conc. c, no spelling, val. of primary
  end for
  return
                    L
end procedure
procedure GenerateNewSpellings(L)
  M ← morphemes in L without spelling
  for all         μ ∈ M
                    do
    if random_p1 < probability_to_seek_spelling then
        Φ ← morphs in M phonetically close to μ ▷ Includes 'telescoped' cases (see text)
        Σ ← morphs in M semantically close to μ ▷ If semantics is 'frozen', only includes prev. used spellings
        S ← [] ▷ Set of spellings
        for all ϕ ∈ Φ do
          S ← S+spelling_of(ϕ)
          for all σ ∈ Σ do
            S ← S+spelling_of(σ)
            combo ← spelling_of(σ)+ spelling_of(ϕ)
            S ← S+combo
        end for
      end for
      ▷ Randomly shuffle S. Remove 'long' spellings (length > 5).
      for all s ∈ S do
        if s is a new spelling or random_p2 < 0.01 then ▷ Small prob to reuse spelling
            spelling_of(μ) ← s
          break
        end if
      end for
    end if
  end for
end procedure
```

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