RHYME IN CLASSICAL LATIN POETRY: STYLISTIC OR STOCHASTIC?

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ABSTRACT

This study offers the first broad quantitative analysis of the use of rhyme in classical Latin hexameter and elegiac verse. The data and tools developed for the analysis are released under a permissive open source license. These include: software to create an accurate phonetic transcription of Latin verse from the MQDQ corpus; a system for scoring rhyme via phonetic similarity; and a system for generating large amounts of metrically correct, stochastic Latin verse (useful for analysis baselines). Further to this, some initial analysis is performed: first via descriptive statistics and then with two unsupervised multivariate analyses using dimension reduction methods. The study examines 19 works by 12 authors, comprising about 96 thousand lines. First and foremost, the results show that rhyme was consciously used by classical authors, but to different extents and in different ways. There is a solid and detectable stylistic separation between the use of rhyme in elegy and epic, and possibly also between satire and the rest. Within genres, authors can be stylistically separated with a small set of features. On the negative side, it appears that the stylistic signal from rhyme is fairly faint, and so forensic analysis (e.g. for authorship attribution) is not presently recommended on texts that are shorter than several thousand lines.

Keywords: Stylometry, Latin, versification, rhyme, computational linguistics, corpus linguistics

1 INTRODUCTION

There has long been a school of thought which holds that rhyme was not a deliberate part of classical Latin poetics. The enormously influential fouth-century commentator Servius remarked against *Georgics* 3.539 that he believed Vergil 'mutavit genus, ut vitaret homoeoteleuton' ('changed the gender [of *timidi*] so that he could avoid homeoteleuton ['same ending' in *timidae–dammae*]'). He makes similar claims against *Aen.* 5.391, 8.435, and 10.571. This belief that Latin poets avoided rhyme, although not universally held, has persisted in various degrees to the present day. The waters are muddied by the fact that 'rhyme' is a slippery term. One can certainly find discussion of it in the secondary literature, but will also see euphemistic alternatives or related concepts: assonance, consonance, euphony, homeoteleuton, or even the charmingly periphrastic 'vertical phonetic effects' (Vine, 1989). Further to this, what does it mean for an author to 'use' rhyme? It is certainly clear that classical verse does not follow a formal scheme, and so which 'sonic correspondences' should be considered as rhyme and which as serendipity? Finally, the classical corpus is substantial and there has not, previously, been any way to identify rhymes short of carefully reading the text. This has led to a fairly oblique debate in which proponents of rhyme cite one or two striking examples while detractors assert coincidence.[1]

This study intends to conclusively demonstrate that rhyme *was* an aspect of poetic style in classical Latin verse via several novel contributions. As a necessary basis for automatic analysis, this paper presents the first public implementation of correct (although simplified) phonetic transcription for classical verse, including verse-specific features like elision (Nagy, 2019a). Based on this, it suggests an initial algorithm for scoring rhyme. Using these tools, some comparative analysis is performed on a large corpus of classical hexameters and elegiac couplets (the two most common metres)—19 works by 12 authors, comprising a total of 95,956 lines. No previous work has performed a study of this breadth (a natural consequence of the lack of automated analysis). The analysis provided is broad but shallow—the main intent is to establish some fundamental facts and to provide a basis for future work. Following an explanation of the key methods, some descriptive statistics are examined and supplemented by an exploratory multivariate analysis. First and foremost, the results show that rhyme *was* consciously used by classical authors, but to different extents and in different ways. There is a solid and detectable stylistic separation between the use of rhyme in elegy and epic, and possibly also between satire and the rest. Within genres, authors can be stylistically separated with a small set of features. All code and data is made freely available for extended analysis work or for replication studies (Nagy, 2021).

Of course there are some caveats. First and foremost it must be said that statistical analysis is not in the business of determining 'intention'. In technical terms, this study does not answer the question of whether rhyme was used 'deliberately', only whether it was used 'more often than chance could produce'. Broadly speaking, the results of this study are statistically conclusive, but fairly modest in scope. The methods described produce a stylistic 'fingerprint' that is fairly faint, and with significant variance. Thus, while these results are encouraging, they are not yet sufficiently robust for forensic purposes (e.g. authorship attribution).

[1] For example, Wilkinson (1963, 32) dismisses Propertius 2.34 'where there are 38 examples of caesura-to-end rhyme. . . in 94 lines, including six in succession' as 'a freak'. A more fulsome consideration of the modern literature appears in Section 2.

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2 RELEVANT LITERATURE

2.1 In 'Traditional' Classics

In this section I aim to direct the reader to *some* of the most important studies in 'traditional' (by which in this case I mean non-digital) Classics. An exhaustive treatment would be a significant work in itself, so I aim rather to pick out the most quantifiable aspects of the literature, to use as a basis for more rigorous analysis. To begin with the sceptics, the most convincing treatment is Wilkinson (1963) in *Golden Latin Artistry*. He includes a relatively lengthy consideration of the issues, including a good representative selection of the arguments on both sides (such as they existed at the time). In the final analysis, Wilkinson (1963, 32–3, inc. nn) is somewhat equivocal, but tends towards the view that such rhymes as occur are not sought. Very valuably, however, he poses exactly the right question (emphasis added):

> do [rhymes] occur *in a greater degree than chance would produce*, given the nature of Latin terminations? To prove or disprove the proposition would require linguistic and statistical calculations of appalling complexity.

In some senses, the entirety of the present study might be seen as a response to this question; an attempt to perform the required calculations and finally prove the proposition. One particular argument made by Wilkinson, on the degree to which leonine[2] rhymes are intentional is that, in some cases, Ovid appears to have deliberately eschewed such rhymes—i.e. there are lines which could have easily been arranged with this rhyme and yet were not. Platnauer (1951, 49) in one of the best-known treatments of elegiac verse devotes just one page to 'Pentameters with Internal Rhyme', in which he makes much the same argument: 'S.G. Owen in his note on Ov. *Tr.* II. 104 implies that these rhymes were intentional, but a cursory inspection of any of the poems shows that Ovid often failed to rhyme where he could easily have done so; e.g. . . . '. Both arguments share the same fallacy. Simply because an author did not rhyme at every given opportunity does not mean that they did not have a propensity to rhyme.

At the other end of the spectrum are the enthusiastic believers. Rosamund Deutsch (1939) produced a well argued thesis on *The Patterns of Sound in Lucretius* in which she shows in careful detail a number of Lucretian tendencies, including a chapter devoted to rhyme schemes (mostly vertical schemes, although with some attention to the leonine style). There is much of value in Deutsch's work, but it should be read in combination with its review by Cyril Bailey (1939). While I, too, am sceptical about the hugely extended rhyme schemes Deutsch asserts (some rhyming associations are claimed to occur more than fifty lines apart) the analysis presented in the present study strongly supports her claim that Lucretius was a consistent and deliberate user of vertical rhyme (also acknowledged by Bailey (p. 189): '[t]hey are obvious in short passages'). For more in this vein, there is much of interest in Guggenheimer (1972), in particular a strong review of the historical background and a deft synthesis of the concepts across both Latin and Greek verse. In some sections, again, Guggenheimer pushes the bounds of credibility, but ideas must first be set out before they can be tested, so it is an important work. Also indispensable is Herescu (1960), although it still languishes without an English translation. Other authors overstep the mark—Clarke (1972, 51) claims that 'Vergil and Ovid have . . . placed internal and other rhymes [to emphasise sense pauses] in the conclusions and beginning of clauses', but his methods consider only the final syllable of the word (and so e.g. p. 58 **su**.cos is 'rhymed' with **at**.ros and pe.**ti**.tos). Given this, it is difficult to accept his main claim but none the less, Clarke's section (pp. 55–72) on 'concentrated' rhyme schemes is worthy of attention. Also worth reading are Foster (1909) on Propertius, Skutsch (1964) on Horace and Highet (1951) on (mostly non-rhyme) sound effects in Juvenal.

2.2 Computational Approaches

Within computational stylometry itself, versification is an emerging area of research and there is little existing work. It is covered in some detail in Plecháč, Bobenhausen, and Hammerich (2019) but the experiments described use a probabilistic tagger which requires a seed corpus containing some rhyme in predictable positions. While it is not directly relevant to this study, readers may be interested in other fairly recent work that considers versification; Marina Tarlinskaja (2016) on Shakespeare is an important monograph, and provides a rare English language window into the better established 'Russian school' of metrics; Forstall and J. Scheirer (2010) have investigated some aspects of elegiac metrical style; Nagy (2019b) demonstrates the (very strong) stylistic fingerprint in the metrical aspects of Latin hexameter. In terms of computational approaches specific to rhyme in Latin verse, this study is, as far as I am aware, the first. Since classical Latin verse did not follow a formal scheme it seemed sensible to consider wider literature. In particular, the study of 'half-rhymes' and irregular schemes in rap music were extremely useful. For English, the study by Hirjee and Brown (2009) uses a probabilistic model based on a phonemic transcription. This improved their accuracies for automatic detection of the highly interleaved and difficult rhymes that are common to the genre. The following example is from p. 712 (rhymes are indicated by typeface):

> **How I made it** you **salivated** over my **calibrated**
> RAPS that **validated** my ghetto *credibility*
> *Still I be* PACKin *agilities* <u>unseen</u>
> Forreal-a my killin *abilities* <u>unclean</u> *facilities*. . .
>
> Pharoahe Monch, *Internal Affairs*

Note how difficult some of these rhymes are to identify through orthography alone, and the balance between 'true' rhymes and half rhymes (RAPS / PACKin). Although this work was unknown to me at the time I wrote the phonetic transcription and rhyme scoring (Section 3.2), the present study follows a similar approach in that it constructs a vowel and consonant similarity matrix (cf. Hirjee and Brown (2009, 713–4)). Kawahara (2007) follows a more formal linguistic approach, seeking to detect 'half-rhymes' in Japanese rap (again using a corpus containing known rhymes). Kawahara's work is interesting in that it attempts to correlate linguistic phonological features with an odds-ratio score for rhyme. Considering shared features offers an empirical basis to consider phonemes to be 'similar'. As

[2] A rhyme between the word ending at the central caesura and the final word of the line—see Section 4.1.3. Unlike some other poetic traditions, a 'caesura' occurs in Latin verse whenever a word ends inside a metrical foot. A 'diaeresis' occurs when the end of a word and the end of a foot coincide.

an example, in English /g/ and /k/ share the linguistic feature 'velar' (place of articulation) but differ in the feature 'voice' (/g/ is voiced, /k/ is not). Kawahara (2007, 127), via multiple regression, shows that some phonological features are more important than others when forming rhymes. Some consideration of consonant features has been included, in rudimentary fashion, in the scoring system used here, but further improvements are almost certainly possible.

Considering the work on rap raises a possible improvement to the present methods. In rhymes like 'How I made it / salivated' (above) the correspondence occurs in a continuous string of syllables, not on word boundaries—such an approach might be interesting to pursue in future work on Latin. In particular, it might provide an opportunity to engage with the ideas of Ahl (1985) on sub-word soundplay.

3 METHODOLOGY

3.1 Producing a Phonetic Representation

The first step in any analysis of rhyme is the conversion of the input text to a phonetic representation. For modern languages, there are usually a variety of available options, but this was not, unfortunately, the case for Latin. The widely used, and generally extremely useful Classical Language Toolkit (CLTK) (Johnson, Burns, Stewart, and Cook (2014–2020)) offers, notionally, phonetic transcription, but its performance was not strong enough for this analysis. The transcriber in the CLTK (`cltk.phonology.latin.transcription`) suffers from three classes of regular errors (over-formation of diphthongs, misplaced stress, and lack of elision/prodelision) which make it unsuitable for the transcription of verse. A key cause for some of these errors (and something outside the CLTK authors' control) is that their analyser must cater heuristically for text where the syllable count is unknown—in fact in Latin the correct syllabification is sometimes impossible to determine without context (for example *seruit* might be [ser.wit] 'he serves' or [se.ru.it] 'she has joined').

For the present study, I was able to take advantage of the fact that the works were drawn from the digital Musisque Deoque (MQDQ) corpus (Mastandrea et al., 2007), which includes full scansion. Using this, I was able to perform accurate syllabification. Then, by combining the MQDQ scansion with a modified version of the CLTK code it was possible to produce a much better phonetic representation. This code is included in the open-source Python package *MQDQParser* (Nagy, 2019a) that accompanies the paper. The precise phonetic representation (both in CLTK and in my own extensions) is based on the reconstruction of Allen (1965) but I chose a simplified representation which omits many features that would be present in a 'tight' IPA transcription (rounding, dental 't's, consonant aspiration, etc.). These did not seem to be relevant to rhyme. I retained nasalisation of final vowels, but, for the sake of simplicity, *not* vowel length, a choice which may alarm some—so 'peek' would rhyme with 'pick'. [3] Vowels were mapped onto a Roman (aeiou) representation as opposed to an IPA one; a transformation that has no effect on the analysis but is easier to read.

3.2 Finding and Scoring Rhyme

Although it may seem unbelievable, there does not appear to be any universally agreed definition of 'rhyme', or at least not in terms that are sufficiently precise for practitioners who are tasked with measuring it. In general, one could do much worse than to adopt the definitions from Herescu (1960). Herescu draws distinction between assonance and rhyme (p. 136) in that assonance involves only the vowel; and between homeoteleuton and rhyme in that homeoteleuton considers only the final syllable whereas rhyme considers the final stressed syllable and every syllable afterwards (p. 170–3). Having said that, I should make it clear that I do not believe it is useful to draw such sharp distinctions when locating and scoring 'rhyme'.

My approach aimed at the generous discovery of sonic correspondences that would be sensed as such by a regular speaker or listener, and not at any rigid theoretical model. As will become clear, I would prefer to stretch the appellation of a 'rhyme' than to rule out on a technicality correspondences which are obvious. So, to proceed: in this study two words were considered to rhyme if they correspond in the syllabic nucleus (a vowel or diphthong, by definition) of both their stressed and final syllables.[4] To 'correspond', in this study is more permissive than 'to match', and so /i/ and /e/ correspond quite closely (mid–high front vowels) as do /ae/ and /e/ (identical place of articulation at the end of the diphthong). For words with two syllables following the stress, a pedantically perfect rhyme would require correspondence in both—this I have not enforced, and so '**pro**.ba.ble' and '**hor**.ri.ble' would achieve an almost perfect score. Additionally I have permitted, with a penalty, words with mismatched 'tails'. This allows 'slurred' rhymes of the form '**ca**.li.dus' and '**cal**.dus'. From a phonetic point of view, this is natural in speech. For classical Latin in particular, it is supported by Quintillian, who reports that 'Augustus again in his letters to Gaius Caesar corrects him for preferring calidus to caldus, not on the ground that the former is not Latin, but because it is unpleasing and as he himself puts it in Greek περίεργον (affected)' (Quint. *Inst.* 1.6.19, transl. Butler). In short, I accept under the broad moniker of 'rhyme' a fairly rag-tag bunch of homophonies that would be called a variety of different things by other authors.

In fact, the system goes even further. Instead of a binary classification (rhyming or not), rhymes were scored. The score is based mostly on the 'closeness' of the vowels, but also considers the onset of the final syllable and the coda of both the final and the stressed syllable. Similar approaches can be seen in the work which focused on rap, where imperfect rhymes are extremely common (as discussed above). A vowel similarity matrix was constructed from first principles,[5] using the phonetic

[3] It would require a lengthy discursion to properly justify this decision, but, briefly: vowels in Latin poetry that we believe were pronounced short in normal speech are often scanned 'long' (sometimes called 'heavy') due to technical aspects of the metre. It is not clear how these were pronounced. Also, for a poet who wishes to create a sonic correspondence, vowel length can be stretched either way—these kinds of rhyme are easy to see in modern spoken-word poetry.

[4] Note that in Latin, almost without exception, the final syllable in a multi-syllable word is unstressed, so the stressed and final syllables can only be identical in single syllable words.

[5] Unlike the related work by Hirjee and Brown (2009) and Kawahara (2007) there is no corpus of classical Latin verse containing known

vowel positions (i.e. the positions on a two-dimensional formant frequency plot, as can be seen in any introduction to phonology). The similarity for consonants was decided using broad linguistic features (alveolar, velar, voiced, unvoiced etc.). Finally, some bonuses were applied for perfect matches, and the final syllable was weighted slightly more than the stressed syllable (based on subjective feedback). Of course there is a great deal of imprecision, here, and so the scoring system went through a number of tuning phases in which experienced Latinists were asked to review the rhyme scores. This approach may not seem particularly scientific and objective, but (I argue) neither is the human experience of rhyme. Even poets might be expected to disagree on the quality of this rhyme or that and so a computer can hardly be expected to produce a perfect result. What is most important is that the scores can be applied systematically and consistently. For reference, Table 1 presents the automatic analysis and rhyme scores for twenty-five random pairs of words that exceed the global threshold for a 'rhyme' as defined in this study. The rhymes with scores near the lower threshold are, by definition, 'barely rhymes'.

Table 1: Phonetic analysis and calculated rhyme scores for twenty-five random word pairs. The final score is composed of one score for the stressed syllable and another for the final syllable. Higher scores are better, maximum possible is 2.30, minimum threshold is 1.75.

Orthographic		Phonetic		Score	(Stress /	Final)
pingues	puerique	**ping**.wes	pu.e.**rī**.kwe	1.77	0.72	1.05
sortemque	tristes	sor.**tem**.kwe	**tris**.tes	1.77	0.60	1.17
erroribus	callidus	ēr.**rō**.ri.bus	**kal**.li.dus	1.78	0.48	1.30
ait	redit	**a**.it	**red**.it	1.78	0.48	1.30
apte	pariterque	**āp**.te	pa.ri.**ter**.kwe	1.78	0.48	1.30
habet	sparsit	**ha**.bet	**spar**.sit	1.79	0.80	0.99
inpetus	frondibus	**īn**.pe.tus	**fron**.di.bus	1.80	0.50	1.30
herbosaque	foret	her.**bō**.sa.kwe	**fo**.ret	1.87	1.00	0.87
fetus	iratus	**fē**.tus	ī.**rā**.tus	1.90	0.60	1.30
anguiferumque	uoce	ang.wi.fe.**rum**.kwe	**wō**.ke	1.90	0.60	1.30
recens	ingens	**re**.kens	**īn**.gens	1.90	0.60	1.30
caede	uetuere	**kae**.de	we.tu.**ē**.re	1.92	0.70	1.22
habebat	iniqua	ha.**bē**.bat	i.**nī**.kwa	1.92	0.75	1.17
nouissima	media	no.**wis**.si.ma	**me**.di.ā	1.93	0.71	1.22
certaminis	satis	ker.**tā**.mi.nis	**sa**.tis	1.95	1.00	0.95
mihi	digiti	**mi**.hī	**di**.gi.tī	1.95	1.00	0.95
dixit	accessi	**dik**.sit	āk.**kes**.sī	2.01	0.71	1.30
manumque	forte	ma.**num**.kwe	**for**.te	2.01	0.71	1.30
verba	bellica	**wer**.ba	**bel**.li.ka	2.03	0.95	1.08
serta	solebat	**ser**.ta	so.**lē**.bat	2.04	0.80	1.23
praebuit	aequoris	**prae**.bu.it	**ae**.kwo.ris	2.05	1.00	1.05
damni	magni	**dam**.ni	**man**.ji	2.17	0.95	1.22
curis	putes	**kū**.ris	**pu**.tes	2.17	1.00	1.17
rogum	cyclopum	**ro**.gũm	kü.**klo**.pũm	2.30	1.00	1.30
sororum	locum	so.**rō**.rũm	**lo**.kũm	2.30	1.00	1.30

3.3 Which Rhymes to Look For?

The next determination was to select a set of target rhymes. The leonine pattern was clearly interesting, because it is considered in most of the traditional literature. End rhymes were another obvious target, since they form the basis for structured rhyme in many languages. I also chose to investigate initial rhymes, because of the convincing arguments put by Deutsch (1939, 121 ff.) concerning the use of this feature by Lucretius. After that, some investigation was required. There is no reason to suppose that Latin poets should follow modern traditions, if indeed they consciously engaged in rhyme at all. With this in mind, I investigated the work of multiple poets with a variety of rhyme-search functions. These search functions are named as follows: for rhymes that occur in two different lines, the matching lines are denoted 'a' and the intervening lines 'x'. The position (for vertical rhymes) is denoted with an index, '0' for the first word, '-1' for the final word, '-2' for the penultimate, 'mid' for the word ending at the central caesura. Thus the search `axxa -2` would look for a rhyme in the penultimate word at the first and last lines of a quatrain. Patterns that were investigated but which do not appear in the study include 'chiastic' rhymes where, for example, the midword rhymes with the end of the following line, and ante-penultimate rhymes ('-3'). Those rhymes do occur (as chance insists they must) but did not appear to be present to an interesting degree. However, ante-penultimate rhymes do occur from time to time in the rarer mosaic rhymes (Section 4.1.2), and so further studies of mosaic rhymes in particular might be wise to consider them. The final set of searches that were performed for each work can be seen in Table 2 (an example analysis for Prudentius' *Apotheosis*) in the 'Test' column.

3.4 The Propensity Index (Π)

Having determined which rhymes to consider, the next problem is how to determine whether these rhymes occur more (or less) than chance would suggest. A simplistic approach (the obvious one being a simple percentage) would be deceptive here for a number of reasons. The most important observation is that the lexical set (and hence the expected number of rhymes) differs not only by author, but also by word position. In Latin verse, the ends of the lines generally fall into correspondence between the word stress (the ictus) and the foot patterns (the accent). To put it inelegantly, the stress pattern for the end of a line is typically 'DUM di di DUM dum'. Fitting words to this stress pattern (which also possess the required syllable quantities) constrains the available lexicon for both the penultimate and the final position. The effect of this constraint is that the baseline expectation for rhyme is much higher for penultimate words and finals. In the *Metamorphoses*, for example, if one selects two final words at random they will rhyme around 7.4% of the time; for penultimate words the figure is about 9.6%, whereas for the relatively unconstrained set of initial words the figure is just 3.9%. Clearly, then, we cannot simply compare percentages, because some positions, as well as some authors, are 'rhymier' than others.

To address this, the figures in this study are based on the *propensity* of an author to rhyme in a given position, considering the number of observed rhymes as compared to the number expected. This measure was dubbed the Propensity Index and is denoted 'Π' throughout. If there are twice as many rhymes of a certain type as chance would suggest then the Π score would be 2.0. A score of less than 1.0 indicates a negative preference. For many readers, the question that immediately arises will be 'how are the expected values determined?'—and this will be discussed in the following sections. Broadly speaking, Π is similar to the 'odds ratio', but not precisely the same; it was therefore thought less confusing to introduce the burden of new terminology than to provide a lengthy explanation of the ways in which I have deviated from a textbook measure. The essential motivation for the changes is that the odds ratio can exhibit significant variance when dealing with rare events, especially with fairly small sample sizes. For this study a more robust measure of expectation was therefore seen to be critical.

rhymes to use as a training set for a deep-learning or probabalistic approach.

3.5 Building the Binomial (Theoretical) Model

Now we come to the nub of the motivating question. As put by Wilkinson (1963, 33 (in note)): 'do [rhymes] occur in a greater degree than chance would produce'? So, just how many rhymes *would* chance produce? This study constructs two models so that the results can be compared and cross-validated. This section describes the theoretical model based on a binomial distribution, the next describes an empirical (simulated) model. For the binomial model, we first estimate the probability with which any two words (from just the set of words appearing in that position) rhyme. For a set of n words, this yields $n(n-1)$ pairs, a potentially large number. In cases where the sets were prohibitively large, the probability was taken to be the median of the probabilities calculated from 100 sets of 50,000 random pairs. This supplies us with a notional 'ground truth'.

Next, to derive an expected number of rhymes, the problem is modelled as a series of Bernoulli trials, in which each eligible pair of words should rhyme (or not) with some baseline probability P. The expected number of rhymes can then be calculated using the binomial distribution, or alternatively, the P-value for any given observation can be calculated the same way (using a standard binomial test).[6] There are some theoretical concerns with this construction. In the first place, the eligible pairs overlap. In looking for couplet rhymes (`aa -1`) we would consider the pairs of lines numbered {(1,2), (2,3), (3,4) . . . }—this means that the trials are not independent. Further, there are many other factors which might make it more or less likely for a position to rhyme as compared to the baseline. A line of Latin verse is a complicated compromise between quantity, rhythm, caesurae, diaereses and any number of other factors which impose conditions as to which words may be placed in which positions. In view of these potential issues with the binomial model, it was sensible to cross-check the results.

3.6 Building the (Simulated) Null Model

To better understand the plausibility of the theoretical model I then set out to construct a simulated model that would build stochastic Latin verse. The aim was to produce verse that obeyed the formal rules (and also respected the informal ones like foot distribution, caesura positions, and ictus/accent conflict) but paid no attention to semantic or grammatical content. As a curiosity, I note that there is some precedent to this effort, although not for the same reasons (nor with the same properties). The 'Eureka Machine' in 1845 used a series of mechanical drums inscribed with various Latin words to create lines of random hexameter, to the amusement of many (and for the admission price of one shilling).[7] Eureka created verses according to a fixed grammatical (and metrical) pattern (ADJ, N, ADV, V, N, ADJ), and so such an approach would hardly possess the properties needed here. Instead, I once again made use of the fact that the MQDQ corpus is fully scanned, and so for every word there is metadata recording its metrical position in the line (e.g. a word might start at the beginning of a second-foot spondee and end at the first breve of a third-foot dactyl). This allowed words to be 'stitched together'. After selecting a random first word, the code selects another word which begins at the correct metrical position, and thus continues until an entire line has been created. Of course it is not quite so simple—not all words can be joined, because they must also respect the rules for elision (a word that does not begin with a vowel cannot be joined to a word that ends with elision) and quantity (a word ending with a short syllable and a consonant final cannot be followed by a word that begins with a consonant, otherwise the syllable would have 'lengthened by position'). The final output has the very desirable quality that it respects metrical style to a fairly high degree. For example, since Ovid almost never writes a line without a third-foot caesura, there is almost no chance that the simulator will construct one. An example of the output can be seen in Fig. 1.[8]

Figure 1: Two elegiac couplets from Simulated Tibullus. The content is nonsense, but an attempted 'translation' is supplied. Emphasised words indicate that the grammatical form does not quite match the translation.

at frustra custodit anus: mihi, *Coa* poetas!
 praemoneo, uinclis iam super illa cubet.
at *mihi* paeniteat sortes, mea *sobrius* aetas,
 nempe age! praedico, flebitur *exsequias*.

The old woman guards in vain: the poets of Cos are mine!
 I warn you, let her sleep now above the chains.
Yet if chance is against me, my sober age,
 well then do it! I foresee weeping at my funeral.

Given this software, it was now possible to create a 'null model' which produced lines by chance, and yet was still constrained by the technical and conventional features of the medium. From there it was a simple (although computationally intensive) matter to simulate a 'pseudo *Aeneid*' or a 'pseudo *Pharsalia*' and count the number of each kind of rhyme that occurred. The chosen approach was to produce 101 simulated texts, each matching the length of its original, and then use the median count as the statistic for the expected number of rhymes. There is more variation in the expected values from shorter texts (as can be seen in the distances between the high and low 95th percentiles (H_{95} and L_{95})). This was a deliberate choice (more text could easily have been simulated) because the results for the smaller texts probably *are* less reliable, and so there is no sense in obscuring the fact. Observed results were then marked with a significance level using stars (which are much loved by users of statistical software). For a result outside the 90th (simulated) percentile, one star, and another for the 95th and the 99th.

Comfortingly, the simulated and theoretical models correspond fairly closely. In particular, differences of opinion regarding the levels of significance (0.1, 0.05, 0.01) are quite rare. For the Π scores, I chose to use expected values from the simulated model because it tends to be more conservative than the binomial, but probably either approach would have been reasonable. The binomial model is certainly quicker to calculate, but it is much less

[6] In the included tables, the binomial P-values have been calculated using a 'one-sided' binomial test. The 'two-sided' test tells us whether it is likely that an observed score is within a sensible range (higher or lower). For the present purposes it was more interesting to know specifically whether an observation was unusually high *or* low.

[7] For a detailed and entertaining account of the Eureka, see Blandford (1963)

[8] The translation, although still somewhat vexed, assumes the following grammatical emendments: for *Coa*, Coas; for *mihi*, mei (gen. of cause); for *sobrius*, sobria; for *exsequias*, exsequia.

flexible. Some baseline probabilities are essentially impossible to calculate (see the discussion of the `slant_leo` test in section 4.1.3), whereas the results of any rhyme search are as easy to count in the simulated lines as in the original text.

3.7 The Rhyminess of Whole Texts

In section 3.3, we explored the individual rhyme tests that were applied to each work. Works were also characterised by two more statistics—global measures (mean per-line) for `rhyme amount` and `rhyme strength`. The former is intended to express rhyme *density* and the latter to capture the degree to which an author would use clearly obvious rhymes (disparagingly called 'jingles'). In the meta-analysis of the multi-variate models these scores are strongly correlated, and so perhaps this could have been captured in a single statistic, but some authors have a bias towards one or the other feature, so for now they remain distinct.

The scoring algorithm is fairly straightforward. The scanner proceeds word-by-word and marks all words within a four line window which qualify as a vertical or leonine rhyme. The best rhyme for each word is then used for the final mean. For the purposes of manual investigation, rhymes are also assigned a deterministic colour, calculated based on the nuclei of the syllables which constitute the rhyme (as can be seen in Figs 3, 4 and 5). The scoring calculation is configurable, allowing the software to scan for the 'best' leonine rhymes, mid-rhymes, general mosaics etc. Finally, and unlike the Π scores, these rhyme scores are *z*-transformed and standardised to a zero mean and unit variance before being included in the cluster analysis (without this step they completely dominate the cluster output).

4 RESULTS

4.1 Some Initial Univariate Analysis

4.1.1 Vertical Rhymes (Table 3)

Vertical end-rhymes were not heavily sought, but neither were they avoided. The most enthusiastic user of them is Lucretius in *De Rerum Natura*. Horace also has a propensity for this type, and some positive propensity is shown in the *Aeneid* and the *Metamorphoses*. None of the later epicists appear to favour end-rhymes although it is very interesting to note that Silius Italicus is the only hexameter author to show a negative propensity for the 'couplet' style (feature `aa -1`). In this he diverges sharply from the style of Vergil, whom he emulates in many other respects.[9] These preferences can be slight. For example Ovid in the *Metamorphoses* uses consecutive mid-rhymes (`aa mid`) with a Π of 1.13, which is to say that, over the course of about twelve thousand lines, he is approximately 13% more likely to employ such a rhyme than chance would suggest. It is entirely understandable that this preference might not be apparent to a human reader. On the other hand, the preferences of Lucretius for vertical rhyme (with Π of up to 1.25) are strong enough that they have been noted by readers unaided by a computer.[10]

In the results for Propertius, we see a negative propensity ($\Pi < 1$) for the feature `aa mid` when commencing at the pentameter. These rhymes, if present, would 'cross over' between two couplets. Compare this with his positive preference ($\Pi = 1.15, > 1$) for `aa -2` commencing at the hexameter (the penultimate words rhyme within the same couplet). This pattern was expected, because it is consistent with the couplet being handled as a unit. What was not expected was the *lack* of this same pattern in the other elegiac authors. Perhaps Propertius is 'tighter' with his couplets in which the pentameter is traditionally expected to respond to the hexameter (thesis-antithesis), or perhaps the use of rhyme is simply unrelated to that concept. This would be an interesting future study. Ovid, in fact, in the *Heroides*, displays a positive preference for the 'crossover' feature at the central caesura ($\Pi = 1.23$) which is surprising. Some of those occurrences are clearly deliberate (Fig. 2), and perhaps serve to either 'link' two couplets, or to undermine the unitary nature of the couplet itself (much as Ovid does with book boundaries in the *Metamorphoses*). This is an area in which further investigation seems warranted, and may improve our understanding of the various authors' attitudes to 'form vs function'.

Initial rhyme, which as mentioned was a particular area of study for Deutsch in her analysis of Lucretius, is another area that is worthy of broader comparative study. In hexameters, apart from Lucretius, it is really only used to a significant extent in Ovid's *Metamorphoses*. It is true that the *Apotheosis* of Prudentius also shows a significant Π of 1.49, but the work is small (just over one thousand lines) and the *Psychomachia* by the same author shows a negative preference for the same feature, so I do not make too much of it. More interesting is the marked difference in how initial rhyme is used in elegy. All of the elegiac authors show a strong propensity for the feature `aa 0`, and in all cases it is stronger when commencing at a hexameter—once again this means that line-initial rhyme is used more often to bind a couplet together than to cross two adjacent couplets. In many of these cases the 'rhyme' is actually a repeated word. While some studies have excluded these from their definition of rhyme, I believe strongly that a repeated word is really the most incontrovertible evidence of a deliberate sonic correspondence. To be sure it is a rhetorical technique[11] (and it is interesting to wonder how this fact might relate to the more frequent use in elegy) but so too is rhyme in general. In any case, this difference in the construction of elegy versus hexameter once again offers some insight into the technical aspects of verse-building as viewed by the classical poets.

Overall, there is strong support for the view that ornamentation via vertical rhyme *was* consciously used, but with restraint. In hexameter, Lucretius is the most significant user, but it is also a marked feature of the *Metamorphoses*. In elegiac couplets, vertical patterns were much more common, with every author showing some propensity for them, in particular at the line-initial position.

[9] Heitland (1896) claimed that 'no imitation of Vergil can be considered too servile for Silius'. Duckworth (1969, 109–10) showed that the broad distribution of hexameter variations (DSDD, SSDD etc.) in Silius is very close to that of Vergil.

[10] See for example Deutsch (1939, Ch. 6), and Herescu (1960, 175) '[rimes] semblent plus nombreuses chez Lucrèce' although it is not entirely clear whether he is simply relying on Deutsch.

[11] There is an extended discussion of rhyme, rhetoric and 'Gorgian figures' available in Guggenheimer (1972, 23–31).

Table 2: An example analysis for a single work (Prudentius' *Apotheosis*)

						Theoretical (Binomial)			Simulated		
Work	Metre	Test	Π	Signif.	Obs.	Exp.	Alt.	*P*-val	L_{95}	M_{50}	H_{95}
Apotheosis	H	`leo`	1.6667	***	90	53	greater	<0.0001	39	54	68
Apotheosis	H	`slant leo`	1.2368		47	-	-	-	27	38	50
Apotheosis	H	`aa 0`	1.5294	***	52	35	greater	0.0038	23	34	46
Apotheosis	H	`axa 0`	1.1667		42	35	greater	0.1341	24	36	48
Apotheosis	H	`axxa 0`	1.1622		43	35	greater	0.1012	26	37	49
Apotheosis	H	`aa -1`	1.0597		71	69	greater	0.4161	51	67	84
Apotheosis	H	`axa -1`	1.0882		74	69	greater	0.2782	56	68	86
Apotheosis	H	`axxa -1`	1.0441		71	69	greater	0.4099	54	68	83
Apotheosis	H	`aa -2`	1.1778		106	90	greater	0.0433	73	90	110
Apotheosis	H	`axa -2`	1.1957	*	110	90	greater	0.0161	73	92	111
Apotheosis	H	`axxa -2`	0.9785		91	90	greater	0.4514	76	93	110
Apotheosis	H	`aa mid`	1.1754		67	55	greater	0.0551	43	57	74
Apotheosis	H	`axa mid`	1.0741		58	55	greater	0.3431	41	54	68
Apotheosis	H	`axxa mid`	1.2143	*	68	55	greater	0.0408	43	56	70

Figure 2: A playful example of `aa mid` crossing from pentameter to hexameter, from Ovid's *Heroides*.

```
20:17   Quique fuit numquam paruus, nunc tempore longo
20:18      Et spe, quam dederas tu mihi, creuit amor.
20:19   Spem mihi tu dederas; meus hic tibi credidit ardor;
20:20      Non potes hoc factum teste negare dea.
```

4.1.2 'Mosaic' Rhymes

This feature-by-feature analysis is not enough to paint the full picture of authorial style. Some of the most interesting rhymes occur when authors combine *multiple* rhymes in a dense passage of verse—what I will call 'mosaic rhymes'. Two examples of this type can be seen in Figs 3 and 4.

Figure 3: A dense mosaic quatrain from Lucan, *Pharsalia* (score=8.50)

```
5:280   Atque oculos morti clausuram quaerere dextram,
5:281   Coniugis illabi lacrimis, unique paratum
5:282   Scire rogum. Liceat morbis finire senectam;
5:283   Sit praeter gladios aliquod sub Caesare fatum.
```

Figure 4: Another mosaic, from Vergil's *Aeneid* (score=7.65). Note also the echo *quae me fuga – qui me mea*, which was beyond the scope of the automatic search.

```
10:669  Duxisti et talis uoluisti expendere poenas?
10:670  Quo feror? unde abii? quae me fuga quemue reducit?
10:671  Laurentisne iterum muros aut castra uidebo?
10:672  Quid manus illa uirum, qui me meaque arma secuti?
```

Herescu (1960, 139 ff.) gave some consideration to quatrain patterns based on vertical assonance, but his analysis of dense passages of rhyme (*qua* rhyme) is more based on 'horizontal' rhymes (p. 178). This accords with his general belief that 'rhyme occurs mainly in the final position among modern poets, and in the interior position among the ancients' (Herescu, 1960, 175).[12] I have chosen to consider mainly vertical rhymes, with just the leonine pattern for 'interior' (i.e. horizontal) rhyme. Future work might look for more powerful ways to connect these mosaic rhymes with authorial style. Herescu (1960, 178), for example, suggests that rhymes accumulate 'in passages with great sonic effect', but offers only *Aeneid* 1.85–8 to serve as an example. Unfortunately, mosaic quatrains are moderately rare, and so the statistical expectation for their counts is somewhat unreliable. To quantify this 'rarity', first recall that the quatrains are scored as a set, based on both the number and the strength of rhyming positions. Taking a quatrain score of 5.5 as a minimum threshold (see Fig. 5 for an example that barely meets the threshold), there are about 22 mosaic quatrains per thousand lines in the *Aeneid*, 34 per thousand in the *Metamorphoses* and 28 in the *Pharsalia*. Because there is no precise definition of these mosaic rhymes, probabilities cannot be calculated with the theoretical models, but simulation shows with more than 99% confidence that even the more modest number in the *Aeneid* did not occur by chance.[13] In terms of broad trends (and this can be seen to some extent in Fig. 7), the elegiac works contain significantly higher rhyme density than the hexameters, but the mean rhyme density is a different statistic to the count of mosaics. For hexameters, the highest overall density is in Lucan's *Pharsalia*, followed at some distance by the *Thebaid* and the *Metamorphoses*.

We may never have enough data to solidly connect these intricate ornamentations to ideas of theme or poetic function,[14] but there is no doubt that they are worthy of attention in criticism and

[12] 'La difference [est] dans la place qu'on lui assigne dans le vers; elle est surtout *finale* chez les Modernes, elle est surtout *interieure* chez les Anciens' (original emphasis)

[13] The greatest number in 101 simulated *Aeneidae* was 20.12 per thousand, median 16.87.

[14] As an experiment, I wondered whether rhyme density might be related to direct speech. I separated the *Aeneid* into quoted speech vs narration and compared the average rhyme density, but found no compelling statistical connection.

Table 3: Which vertical rhymes did classical Latin poets prefer? A table of works which show a statistically significant propensity (Π) for the given rhymes. Leonine features are not included because almost all works exhibit them, see Table 4 for that analysis. This includes complete works only, where the statistics are less variable.

						Theoretical (Binomial)			Simulated		
Work	Metre	Test	Π	Signif.	Obs.	Exp.	Alt.	*P*-val	L_{95}	M_{50}	H_{95}
Aeneid	H	aa -1	1.0810	**	774	725	greater	0.0323	669	716	766
Aeneid	H	axxa -1	1.0760	**	779	725	greater	0.0205	680	724	770
Apotheosis	H	aa -2	1.1398	*	106	90	greater	0.0433	73	93	107
Apotheosis	H	aa 0	1.4857	**	52	35	greater	0.0038	27	35	48
Apotheosis	H	axa -2	1.2222	*	110	90	greater	0.0161	74	90	110
Argonautica	H	axxa mid	0.8878	*	269	303	less	0.0209	267	303	335
Ars	H	aa 0	2.2632	***	86	37	greater	<0.0001	27	38	49
Ars	P	aa 0	1.3611	*	49	37	greater	0.0277	25	36	49
Ars	H	axa 0	1.5263	***	58	38	greater	0.0012	27	38	51
Ars	P	axa mid	1.1831	*	84	70	greater	0.0522	54	71	87
Cat64	H	axa -1	0.5714	**	16	28	less	0.0088	20	28	42
Cat64	H	axa mid	1.4800	*	37	24	greater	0.0069	16	25	37
DRN	H	aa -1	1.2459	***	679	565	greater	<0.0001	504	545	592
DRN	H	aa -2	1.0891	**	697	652	greater	0.0361	592	640	692
DRN	H	aa 0	1.2000	***	246	206	greater	0.0036	179	205	234
DRN	H	aa mid	1.1149	**	291	256	greater	0.0167	230	261	290
DRN	H	axa -1	1.1648	***	636	565	greater	0.0012	508	546	582
DRN	H	axa 0	1.1814	**	241	206	greater	0.0092	180	204	234
DRN	H	axxa -1	1.1384	***	625	565	greater	0.0051	489	549	597
DRN	H	axxa -2	1.0734	*	687	652	greater	0.0805	600	640	687
DRN	H	axxa mid	1.1401	**	293	256	greater	0.0121	220	257	292
Fasti	H	aa 0	1.3780	***	113	83	greater	0.0008	64	82	100
Fasti	P	aa 0	1.2410	*	103	83	greater	0.0168	70	83	103
Fasti	H	axa 0	1.3913	***	128	91	greater	0.0001	72	92	108
Fasti	H	axxa 0	1.2529	***	109	83	greater	0.0030	71	87	105
Georgics	H	axa -2	1.1520	***	235	205	greater	0.0173	176	204	231
Georgics	H	axxa 0	0.8136	*	48	59	less	0.0781	46	59	75
Hamartigenia	H	axa 0	1.2857	*	36	26	greater	0.0339	17	28	37
Hamartigenia	H	axxa 0	1.2963	*	35	26	greater	0.0493	16	27	37
Heroides	H	aa 0	1.9333	***	116	59	greater	<0.0001	46	60	76
Heroides	P	aa 0	1.4237	***	84	59	greater	0.0012	48	59	72
Heroides	H	aa mid	1.1667	*	126	105	greater	0.0221	90	108	127
Heroides	P	aa mid	1.2336	***	132	105	greater	0.0052	87	107	129
Heroides	H	axa 0	1.6500	***	99	59	greater	<0.0001	47	60	77
Hor. Sat.	H	axa -1	1.1951	*	147	131	greater	0.0770	102	123	147
Hor. Sat.	H	axxa -1	1.2823	***	159	131	greater	0.0069	103	124	148
Metamorphoses	H	aa -2	1.0684	**	1234	1147	greater	0.0038	1098	1155	1230
Metamorphoses	H	aa 0	1.1842	***	553	465	greater	<0.0001	418	467	506
Metamorphoses	H	aa mid	1.1252	***	692	606	greater	0.0002	562	615	660
Metamorphoses	H	axa -1	1.0608	**	959	888	greater	0.0073	845	904	954
Metamorphoses	H	axa 0	1.1061	*	511	465	greater	0.0169	424	462	512
Metamorphoses	H	axa mid	1.0689	*	652	606	greater	0.0299	560	610	654
Pharsalia	H	aa 0	1.0984	*	279	256	greater	0.0757	227	254	281
Pharsalia	H	axa -2	1.0830	***	926	846	greater	0.0021	792	855	911
Pharsalia	H	axxa 0	1.1732	**	298	256	greater	0.0047	223	254	296
Propertius	H	aa -2	1.1542	***	262	228	greater	0.0093	206	227	253
Propertius	H	aa 0	1.9200	***	96	51	greater	<0.0001	36	50	62
Propertius	P	aa mid	0.8226	**	102	122	less	0.0346	104	124	142
Propertius	H	axa -2	1.2538	***	247	195	greater	0.0001	178	197	228
Propertius	P	axa -2	1.1168	**	392	344	greater	0.0027	312	351	390
Propertius	H	axa 0	1.6909	***	93	53	greater	<0.0001	41	55	67
Propertius	P	axxa -2	1.0870	*	250	228	greater	0.0623	202	230	253
Propertius	P	axxa 0	1.3673	**	67	51	greater	0.0158	37	49	65
Psychomachia	H	aa 0	0.7037	**	19	26	less	0.0937	20	27	39
Psychomachia	H	axa 0	1.4815	***	40	26	greater	0.0056	16	27	37
Psychomachia	H	axxa -1	1.2388	*	83	66	greater	0.0171	49	67	85
Punica	H	aa -1	0.9328	**	860	925	less	0.0135	863	922	983
Punica	H	axxa mid	1.0706	*	576	535	greater	0.0369	490	538	576
Thebaid	H	axa -1	1.0592	*	787	736	greater	0.0274	693	743	795
Thebaid	H	axa -2	1.0543	**	1009	953	greater	0.0296	905	957	1007
Tibullus	H	aa 0	2.2353	***	38	17	greater	<0.0001	9	17	23
Tibullus	H	axa 0	2.2727	***	50	21	greater	<0.0001	13	22	32
Tibullus	P	axa mid	1.2353	*	63	49	greater	0.0240	38	51	66
Tibullus	H	axxa -2	1.2133	*	91	74	greater	0.0264	60	75	91
Tristia	H	aa 0	1.4237	***	84	58	greater	0.0006	43	59	73
Tristia	H	axa 0	1.5397	***	97	61	greater	<0.0001	49	63	78
Tristia	P	axa 0	1.2879	**	85	64	greater	0.0068	50	66	82
Tristia	H	axxa -2	1.1414	*	218	188	greater	0.0139	166	191	218
Tristia	H	axxa 0	1.2034	*	71	58	greater	0.0499	45	59	71

Figure 5: A mosaic which barely meets the threshold from the *Pharsalia* (score=5.50)

```
2:668    Decidat in fundum penitus stagnantis Auerni.
2:669    Ergo ubi nulla uado tenuit sua pondera moles,
2:670    Tunc placuit caesis innectere uincula siluis
2:671    Roboraque immensis late religare catenis.
```

philology. I remind the reader that the famous 'golden line'[15] is approximately ten times less common—there are just 34 in all ten thousand or so lines of the *Aeneid*—and yet they are a regular subject of teaching and commentary. This study is limited, in this area, by the four line 'window' used in all of the tests. This was purely for pragmatic reasons—as we widen our window for considering rhymes, it becomes difficult to tell the noise from the signal. Deutsch, in her examination of Lucretius, finds very long passages which are, in her analysis, part of a single, extremely complex scheme. Some of these schemes include rhymes (and, admittedly, very strong ones) which are ten or fifteen lines apart. There are similar analyses in Guggenheimer (1972, 149–76), and again in Herescu (1960, 176–8). To properly test these ideas would require more precise and quantifiable rules to include or exclude passages as 'extended rhyme schemes', but to automatically detect such extended matches would be difficult with the approaches described here, due to the number of false positives. This is not to say that it is out of the question, simply that the scoring and analysis would need to be more sensitive and complex than the basic approaches implemented so far.

4.1.3 Leonine Rhymes (Table 4)

Almost every work shows a statistical propensity for the 'leonine' rhyme. In this study I accept as leonine any rhyme that occurs between a word ending at a third-foot caesura (whether weak or strong) and the final word of the line. The first and most important thing to discuss is the idea that leonine rhymes occur 'naturally' due to agreement with nouns in the mid or final positions. Proponents of this view might present lines such as this one:

> et me saeuus *equis* Oriens afflauit *anhelis*
>
> and savage Morning breathes on me *with panting steeds*
>
> *Aen.* 5.739

Therefore, it is claimed, the leonine rhymes we see are not consciously sought; as argued by Wilkinson (1963, 34) they simply 'strike us more forcefully' due to the widespread use of this rhyme in regular forms in medieval verse.

Based on this proposition, we would expect natural 'inflation' in the number of leonine rhymes, since they are (the argument goes) a natural consequence of adjectives occurring near the nouns they modify. I do not believe this is enough to explain away the clear preference of almost every author, or indeed the very marked increase in propensity seen in elegy vs epic (even in the hexameter). I also note that we do *not* see a propensity for leonine rhyme in Lucretius' *De Rerum Natura* ($\Pi = 1.06$). If the leonine style of rhyme were indeed inevitable then it is unlikely that Lucretius should have produced almost six thousand lines of hexameter without displaying this feature—and so even if such inflation exists then it is slight.

Platnauer (1951, 49) claims that this ADJ-NOM agreement accounts for around 90% of the rhymes.[16] Based on a random sample of pentameters from the *Fasti* which I analysed by hand, and using my (probably more permissive) threshold for 'rhyme', I would suggest that his figure is a little high,[17]

but not sufficiently so as to invalidate his point. The only way to conclusively settle the matter would be to perform part-of-speech (POS) analysis of the entire corpus being analysed, and to determine how often this ADJ-NOM agreement takes place. However while automatic POS analysis for Latin has taken some great leaps recently,[18] even perfect POS tagging would not completely solve the problem—it may be that a pair of words 'match' grammatically (i.e. in number, gender, and case) and yet the adjective actually modifies a different substantive altogether. So, with some regret, this investigation is deferred to future work.

What *was* possible was a very coarse workaround. The test `slant_leo` simply scans for leonine rhymes *except* those in which both words end with a common nominal suffix (-os, -is, -as, etc.). This test would not match *equis–anhelis* in the line quoted above. The hypothesis is then that authors who show a clear preference for both `leo` and `slant_leo` really are exhibiting a significant tendency. Note that this test does not exclude *all* of the '90%' of rhymes claimed by Platnauer, since it does not reject words where the grammatical correspondence is revealed by a single letter (in particular, ablatives and genitives ending -a, -i, -o), but rejecting those rhymes entailed too many false positives.

Personally, I take at face value the statistics in Table 4—showing that leonine rhyme occurs more frequently than chance would suggest throughout classical Latin verse. In any case, despite any inevitable inflation, there is still great value in the comparative study of the style of the various poets, and also in considering the diachronic development of the pattern. Leonine rhyme is strongest in the elegists and, in those, more so in the pentameter (although note the difference between say Propertius, strongly leonine in both metres, and Tibullus who shows a more traditional hexameter). In pure hexameter, the most enthusiastic users of the leonine pattern are Valerius Flaccus in the *Argonautica* and the *Satires* of Juvenal. One might begin to wonder if this is simply a trend that grew more common over time—and indeed

[15] A five word line with a central verb, and two initial adjectives modifying two final substantives, i.e. abVAB. Consult Winbolt (1903, 219–22) for several examples and some typical analysis. Amusingly, study of this form is entirely modern, emerging from the English philological tradition; on this, see Mayer (2020).

[16] Platnauer only considered the pentameter, but as can be seen in Table 4, Ovid and Propertius both use this feature in their hexameters as well, where the metre is more flexible. The central caesura in the pentameter is obligatory, and an ADJ-NOM agreement with a rhyme is often used to 'balance' a line, but this should hardly be seen as accidental.

[17] See also the figures from several other sources collected in Wilkinson (1963, 33 in note) which vary considerably, and measure a variety of slightly different things.

[18] Of particular interest are the joint learning framework PIE (Manjavacas, Kádár, & Kestemont, 2019) and the model and Python API that is pre-trained for Latin by Clérice (2020).

Table 4: An analysis of the (almost universal) propensity (Π) for Leonine rhyme. The test `slant_leo` considers only rhymes that do *not* share common noun endings, like '-us', '-os', '-as' etc. Since the theoretical probability for `slant_leo` is impractical to calculate, the binomial test is not performed and no *P*-value is calculated. This table includes complete works only, where the statistics are less variable.

						Theoretical (Binomial)			Simulated		
Work	Metre	Test	Π	Signif.	Obs.	Exp.	Alt.	*P*-val	L_{95}	M_{50}	H_{95}
Aeneid	H	leo	1.1961	***	549	459	greater	<0.0001	420	459	504
Aeneid	H	slant leo	1.1091		376	0	–	–	309	339	380
Apotheosis	H	leo	1.6667	***	90	53	greater	<0.0001	40	54	69
Apotheosis	H	slant leo	1.2368		47	0	–	–	28	38	50
Argonautica	H	leo	1.6817	***	523	310	greater	<0.0001	282	311	343
Argonautica	H	slant leo	1.3487	***	321	0	–	–	211	238	274
Ars	H	leo	1.6765	***	114	67	greater	<0.0001	54	68	84
Ars	P	leo	2.0411	***	149	71	greater	<0.0001	57	73	86
Ars	H	slant leo	1.6154	***	84	0	–	–	40	52	65
Ars	P	slant leo	1.4182	***	78	0	–	–	43	55	70
Cat64	H	leo	1.5417	**	37	24	greater	0.0060	15	24	35
Cat64	H	slant leo	1.2222		22	0	–	–	11	18	28
DRN	H	leo	1.0599		336	324	greater	0.2632	287	317	353
DRN	H	slant leo	0.9440		219	0	–	–	203	232	266
Fasti	H	leo	1.7234	***	243	138	greater	<0.0001	121	141	161
Fasti	P	leo	2.1625	***	346	158	greater	<0.0001	140	160	185
Fasti	H	slant leo	1.4623	***	155	0	–	–	91	106	122
Fasti	P	slant leo	1.3443	***	164	0	–	–	102	122	143
Georgics	H	leo	1.3303	***	145	110	greater	0.0005	91	109	123
Georgics	H	slant leo	1.3188	**	91	0	–	–	56	69	83
Hamartigenia	H	leo	2.0227	***	89	45	greater	<0.0001	31	44	57
Hamartigenia	H	slant leo	1.3333		40	0	–	–	21	30	43
Heroides	H	leo	1.4312	***	156	107	greater	<0.0001	93	109	134
Heroides	P	leo	1.8231	***	237	126	greater	<0.0001	104	130	147
Heroides	H	slant leo	1.2118	*	103	0	–	–	67	85	106
Heroides	P	slant leo	1.1771	*	113	0	–	–	75	96	113
Hor. Sat.	H	leo	1.2473	**	116	99	greater	0.0492	74	93	108
Hor. Sat.	H	slant leo	1.1642		78	0	–	–	55	67	81
Juv. Sat.	H	leo	1.5849	***	252	165	greater	<0.0001	132	159	180
Juv. Sat.	H	slant leo	1.3583	**	163	0	–	–	97	120	143
Metamorphoses	H	leo	1.3323	***	878	646	greater	<0.0001	605	659	702
Metamorphoses	H	slant leo	1.1267	***	587	0	–	–	479	521	559
Pharsalia	H	leo	1.2718	***	627	489	greater	<0.0001	457	493	543
Pharsalia	H	slant leo	1.0384		379	0	–	–	337	365	407
Propertius	H	leo	2.3968	***	302	126	greater	<0.0001	108	126	153
Propertius	P	leo	2.4538	***	319	128	greater	<0.0001	107	130	150
Propertius	H	slant leo	1.7778	***	144	0	–	–	67	81	101
Propertius	P	slant leo	1.5957	***	150	0	–	–	76	94	111
Psychomachia	H	leo	1.4130	***	65	46	greater	0.0031	34	46	61
Psychomachia	H	slant leo	0.9394		31	0	–	–	22	33	47
Punica	H	leo	1.3151	***	818	626	greater	<0.0001	580	622	659
Punica	H	slant leo	1.1229	***	539	0	–	–	438	480	518
Thebaid	H	leo	1.4540	***	775	534	greater	<0.0001	503	533	574
Thebaid	H	slant leo	1.1785	***	482	0	–	–	380	409	450
Tibullus	H	leo	1.2051		47	39	greater	0.1090	27	39	49
Tibullus	P	leo	2.0000	***	80	40	greater	<0.0001	30	40	52
Tibullus	H	slant leo	1.0323		32	0	–	–	21	31	42
Tibullus	P	slant leo	1.1724		34	0	–	–	20	29	38
Tristia	H	leo	1.4239	***	131	91	greater	<0.0001	77	92	116
Tristia	P	leo	2.0513	***	240	114	greater	<0.0001	94	117	140
Tristia	H	slant leo	1.0580		73	0	–	–	56	69	86
Tristia	P	slant leo	1.3804	***	127	0	–	–	73	92	111

this may well be the case. The fly in that particular ointment is the much earlier Catullus 64; with a Π of 1.54, it is more leonine than any classical work except the two just mentioned. It is, however, only 406 lines long, and so we might simply be looking at random variation. For the sake of interest, I included a few fourth century (CE) works by Prudentius, and they are, indeed, more leonine than all of the classical hexameter. The *Apotheosis* displays a Π of 1.67 and the *Hamartigenia* 2.02 (both poems contain about 1000 lines of hexameter, roughly the same as a single book of classical epic). At the end of the day, the evidence comes from a relatively small number of texts. All the same, it may be worth investigating additional Late Antique verse to see if this trend might continue. It does seem only natural that the regular leonine pattern 'invented' by Gottschalk in the ninth century should be more of an evolution than a sudden innovation—another area for future work.

4.2 Multivariate Analysis and Visualisation

For the multi-variate analysis, each work was represented by the vector containing its Π scores for each test, along with the global scores `rhyme amount` and one for `rhyme score`, as discussed above in Section 3.7. There is a small procedural wrinkle, here, because works that are in elegiac couplets have two scores for each test (one for the rhyme test commencing at a hexameter line, e.g. `H-aa -1`, and one for the same test commencing at a pentameter line, `P-aa -1`) whereas hexameter works are written in a single metre. Since the vectors to be considered must all contain the same number of components, the hexameter vectors were 'doubled in length' by simply repeating the scores for the hexameter tests. This might create an artificial difference between works written in hexameter and works in elegiac couplets—and so the fact that the elegiac works cluster together is perhaps not entirely an artefact of authorial style. From a careful inspection of the univariate results, however (Tables 3 and 4) it is clear that elegiac works were genuinely different; in particular in the number of leonine rhymes and also the propensity towards rhymes (or repeats) in the initial position (`aa 0`, `axa 0` etc.). The final vector for each work has 30 components—28 Π scores for 14 different rhyme tests (see Table 2) and two global scores for general rhyminess. As a reminder, the Π scores are left unchanged, but the global rhyme scores are standardized to a zero mean and unit variance using the scikit-learn `StandardScaler` (Pedregosa et al., 2011).

4.2.1 UMAP (Manifold Projection) Clustering (Fig. 6)

For the first analysis, the works were analysed with unsupervised clustering using UMAP (McInnes, Healy, & Melville, 2018). UMAP is a manifold projection tool, which (roughly) means that when we project down to a two-dimensional figure, it attempts to preserve small-scale local distances between points in the high dimensional space as best it can. Conceptually it is somewhat similar to t-SNE (in that it considers local distances instead of trying to determine centroids like *k-means*) but UMAP is easier to tune and works well for a quick visualisation. In Fig. 6, each work is plotted separately, and scaled by size. Nearby works are 'close' to each other, but relative distances for distant works should probably be treated with caution, i.e. it is not necessarily true that Juvenal's *Satires* are *more* similar to the *Punica* than Lucan's *Pharsalia*, but it is fair to say that the *Metamorphoses* and the *Thebaid* are close.

Based on a number of experiments (which are omitted for brevity) and also on the PCA analysis in the following section, the most important general differentiator (moving from right to left) is the overall rhyme density—the *Satires* of Juvenal and Horace being the least dense, Lucan's *Pharsalia* the densest of the epics and then the elegiac works the densest of all. In this figure, however, the most useful things to think about are the local relationships between the works. There are a number of interesting observations.

There is a clearly visible division between the three broad genres: elegy, satire and epic. This is particularly interesting in terms of Ovid, who wrote in several different modes: 'epic' (if one can be forgiven for so broadly characterising the *Metamorphoses*), love elegy (the *Ars* and the *Heroides* although again an over-simplification), and didactic elegy (the *Fasti*) just to take a few examples. Despite the different tone of Ovid's elegiac works, they cluster tightly together, whereas the *Metamorphoses* sits somewhere in the middle of the spread of 'traditional' epic. Unfortunately, Ovid is the only author who was this flexible—the rest wrote elegy or epic, but not both.[19] Never the less, it is reasonable to conclude that there is some sort of link between the way in which rhyme was handled and the mode of the verse being written. This further underlines the fact that there was a conscious awareness of rhyme.

Within the broad clusters, authorial style can vary a great deal. In some cases like the *Argonautica* and *Pharsalia*, individual books cluster fairly closely to the vectors representing the entire work (shown larger in the figure). In others, and probably most obviously with the *Punica* it is clear that there is very significant variation from book to book. The feature space used for this project seems to *broadly* separate works, but a significant amount of text would be required before attempting tasks like authorship attribution or forgery detection. This is not to say that the approach evaluated here would be useless for such tasks, but more to suggest that it would not be suitable in isolation, but better as a part of broader, multi-mode expression of style.

The final thing I will note is that there is no clear temporal signal in Fig. 6. The elegiac works, in any case, were written within a fairly short historical period, but the hexameters of the *Aeneid* and the *Punica* cluster nearby, despite being separated by roughly a century. What is more, Vergil's earlier *Georgics* appear in that zone, as well as the *Psychomachia* of Prudentius, one of the three Late Antique works from the fourth century CE. The *Argonautica* and the *Thebaid* are reasonably close (two of the three works of Flavian epic) but so are the *Satires* of Horace and Juvenal, once again written more than a century apart. This should probably be no surprise, of course, since Horace was almost certainly one of Juvenal's influences. And so, these features do not seem particularly well-matched to questions of dating or priority. Having said that, and as mentioned before, it may be possible that *individual* features (such as the use of leonine rhyme) became more or less common over time—but

[19]This is unfair to Horace, of course, who was extremely flexible in moving between the Greek metres and the dactylic hexameter of his *Satires*, as was Catullus with hendecasyllables versus his hexameter epyllion Cat. 64, but the point stands with respect to the two metres that were analysed in this study.

Figure 6: UMAP Cluster of works, scaled by size and coloured by work. Nearby works are stylistically similar in the way they use rhyme. Long works are shown as whole units (larger) and also in their individual books, to highlight the stylistic variation that can occur.

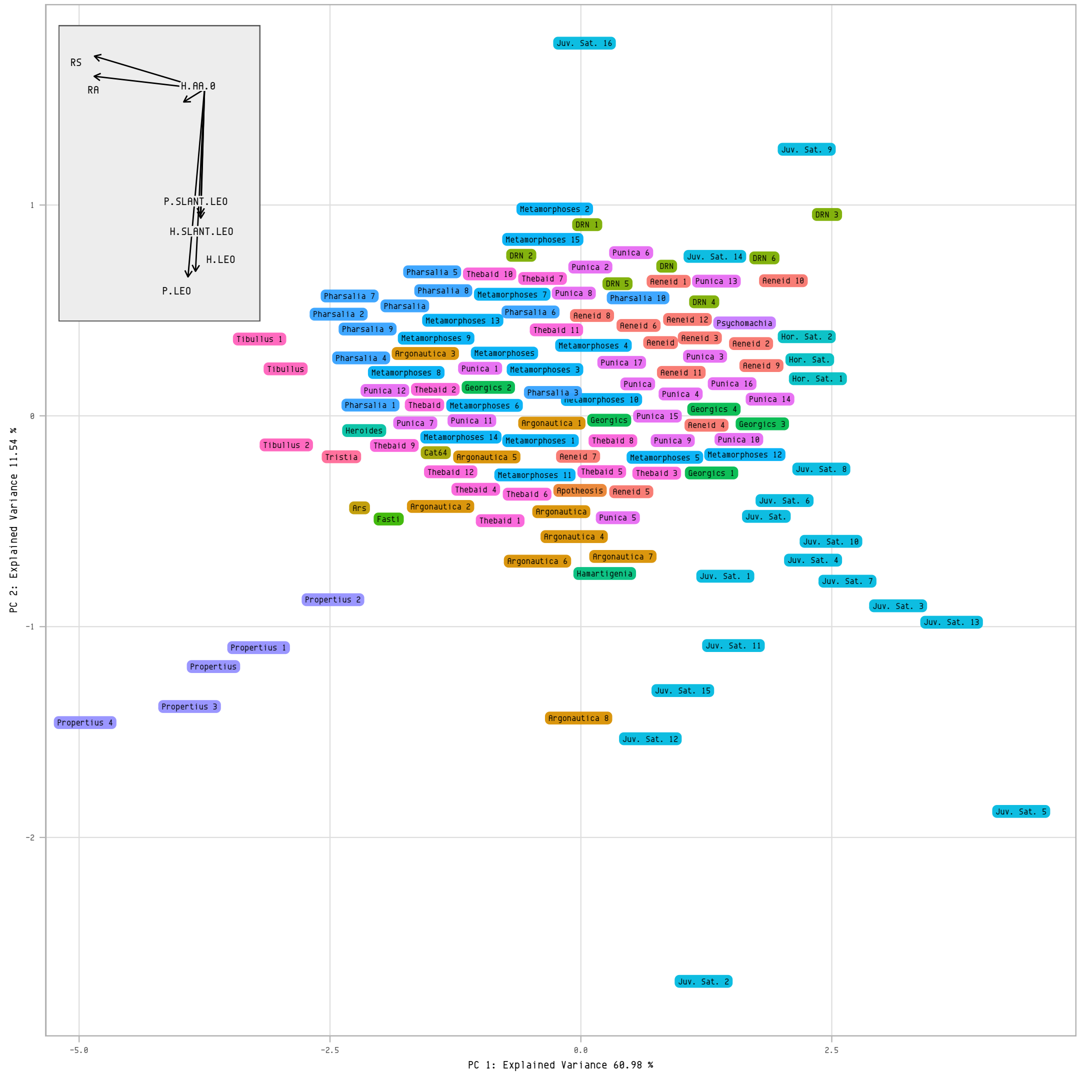
that should be analysed via the univariate statistics. This is not to say that the apparent division in the epic works is useless—it appears that a case could be made for a 'traditional' model based on Vergil (to whom Silius owed a great stylistic debt) and a more progressive model encompassing Ovid, Statius, Lucan and Valerius Flaccus. The following analysis via PCA has more to say on this subject but essentially the idea, although interesting, requires more investigation.

4.2.2 A Principal Component Analysis (PCA) (Fig. 7)

A standard visualisation technique to explore multi-variate relationships is Principal Component Analysis (PCA). While the previous section tried to give insight into the way the various works relate to each other, PCA can often provide some understanding as to how the data is separated by the individual features. This is not the place for a full explanation of the technique, but some broad intuition may assist the reader. The 'principal components' (hence PCs) are *composite* features; each PC comprises some element of several of the 'true' features. Because of the nature of the mathematical construction, the full set of PCs separate the data well in high dimensional space, but the real value of them in terms of visualisation is that the PCs are *ordered* in terms of how well they perform this separation. So, by plotting the data against the first two PCs, we often obtain a useful projection of high dimensional data in a two-dimensional plot. In this case the PCA is very informative—the first two PCs account for 72% of the observed variation (so they are very descriptive) and they are each dominated by essentially a single feature (so they are easy to understand). In Fig. 7, `PC1` is dominated by the two features describing rhyme density (scores < 0 have more rhyme overall) and `PC2` is dominated by the propensity for leonine rhyme (scores < 0 are more leonine). So, for the sake of orientation, Propertius 4 is both unusually rhymey and leonine, Juv. *Sat.* 9 is unusually free of both, Juv. *Sat.* 5 is very leonine but with low rhyme density, etc. Hopefully, for a reader armed with that information, the figure may now speak for itself, but here are a few observations of my own.

In the UMAP visualisation (Fig. 6), the elegiac works clustered tightly overall, showing a fundamental difference in the way rhyme was handled between elegy and epic. In the PCA figure, we can begin to tease apart the styles of those authors. Tibullus and Propertius are both towards the high end for rhyme density, but are quite different in the degree to which they use leonine rhymes. This can also be seen in the descriptive statistics in Table 4—in particular, Tibullus is much more sparing of this ornamentation in his hexameters. Ovid, we now see, appears to use the leonine style more in the *Ars* and *Fasti* than the *Heroides* or the *Tristia*. In a similar vein, the *Satires* of Horace and Juvenal, which exhibit a high degree of self-similarity in the UMAP clusters, can be differentiated once again by their handling of leonicity—but in contrast to elegy they both have low rhyme density. As an aside, it seems counter-intuitive for Juvenal to have such a strong Π for leonine rhymes but a low overall density; the explanation appears to be that this is the only rhyming ornament that Juvenal employs with any regularity—

Figure 7: Principal Component Analysis (PCA) plot of the same data from Fig. 6. `PC1` and `PC2` account for 72% of the explained variance. In order to preserve legibility it was necessary to avoid over-plotting, so some works may be closer to the origin than they appear, but the relative direction of their displacement is preserved. Inset: the relative direction of the most important features.



the 'mosaic' rhymes employed to a varying degree by the epicists are rare in Juvenal.[20]

Works near the centre of the plot are not strongly characterised. The PCA gives more weight to features which *separate* works, and in this case that task is dominated by the two features we have just discussed (leonicity and rhyme density). The individual tests for various kind of vertical rhyme, as seen in Table 3 are drowned out in this figure, even when the Π scores are clearly significant. Neither this figure nor the the UMAP plot is wholly satisfactory, which is why it is useful to consider the data through a number of different visualisations. And, of course, the visualisations that can be printed on paper are only simplified projections of data models that exist in high-dimensional space, so it is inevitable that some information be lost.

5 CONCLUSIONS

The primary goal of this paper has been to break a small area of new ground in the computational study of Latin verse. By providing an initial set of tools and algorithms for the detection and statistical analysis of rhyme it is hoped that future work will have an easier path to follow. The tools, data and replication information are available from the associated code repository (Nagy, 2021). This study shows that, for classical Latin verse, the baseline levels for rhyme are heavily affected by positional constraints. To this end it introduces a Propensity Index, Π, which facilitates comparative analysis in a way that percentages cannot. Incremental advances to the technical approaches would be valuable, and the way is now (more) open for studies that aim to verify, dispute, deepen or extend the rich tradition that

[20] Using the same threshold as in Section 4.1.2 there are 16.6 per thousand, compare the *Aeneid* 21.8, *Metamorphoses* 34.1, and *Pharsalia* 28.4. This number is close to the simulated median, suggesting no detectable propensity (nor a detectable aversion).

exists in Classical scholarship. The analysis presented has been mostly aimed at establishing some fundamental claims, using a corpus whose breadth, finally, can be claimed to be generally representative.

The key result of the analysis, which will seem tiresomely obvious to some, is that rhyme *is* part of the authorial fingerprint for classical Latin verse. Far from the idea that authors avoided rhyme, or even the idea that 'rhyme simply happened by chance' it is clear that rhyme was used differently by different authors and differently in different genres. This finding should validate and encourage further study into the particulars; why is the Tibullan hexameter less leonine than the Propertian? Why does Propertius 'unify' his couplets with vertical rhyme where Ovid is more inclined to link them? Why is line-initial rhyme more favoured in elegy than epic? What literary effects are supported by these technical devices?

The study of concentrated 'mosaic' rhymes (Section 4.1.2) is a nascent attempt to apply formal quantitative analysis to the idea of 'extended schemes' typified by Deutsch (1939) and Guggenheimer (1972). The initial work here is limited by the four-line window, which seeks to find individual mosaics that 'stand out' from larger passages of text. Different approaches will be needed to consider the long, extended schemes, and it is not yet clear how far this can be taken. Deutsch (1939, 148), at one point, concludes that 'the whole of Lucretius is one great scheme of rhyme' and that it is 'difficult to appreciate completely the close interweaving of similar words and sounds, unless the entire passage can be read aloud' (p. 147). This is probably true for computational analysis as well—there is only so much a computer can do, and still an irreplaceable role for the ear of a human critic. Never the less there is an obvious benefit to using automated tools to quickly scan long works for candidate passages. With respect to Deutsch's 'close interweaving of similar words and sounds', and based on a fairly shallow exploration of the literature, an interdisciplinary approach that incorporates related work on rap lyrics appears to show potential; their problems are very much like the ones faced here.

In terms of computational stylometry, the authorial signal that can be identified with the methods described here is not very strong. No attempt was made to classify works, but based on the unsupervised clustering methods, comparatively large samples would be needed. Even when taking entire books as observations (a book of hexameter epic is typically 4–5000 words) there is a great deal of stylistic variation. In some cases, good results may be possible for one-vs-one determinations, but in general it appears more sensible to consider adding rhyme as one component to a multi-faceted representation of style. Perhaps, in the final assessment, this paper poses more questions than it is able to conclusively answer. None the less, it is hoped that these findings and new tools might justify and support further research into an area of Latin poetics that has hitherto been consigned to the fringes of the field.

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