Assessing the Pace of Language Change via Estimated Loan Word Volumes: Implications for Irish

Dustin Bowers and Elliott Lash

May 26, 2024

Abstract Assessing the pace of language change in historical settings can be impeded by a lack of contemporary documents. Loan word adaptation can provide an additional window on this problem. Given a series of formerly productive phonological processes and a well studied donor language, a search algorithm equipped with a simple phonotactic probability model can estimate how many loans entered before each phonological period ended. The population of loans during a period is a plausible proxy for the duration of the period, so periods with few loans could have been subject to rapid change. Our approach is illustrated with the Latin loans in Irish, shedding light on a period that pre-dates substantial written records. This period includes the development of rhythmic syncope in Irish, a process that has garnered interest due to its resistance to analysis in parallel but not serial models of phonology (McCarthy 2008 *inter alia*). Strikingly, our model finds that few loans entered during the rhythmic syncope phase of Irish, which is consistent with the process quickly becoming unproductive, as has been found for other languages (Bowers 2019 *inter alia*).

1 Introduction

Gauging the relative timing and absolute pace of language change in historical periods is typically limited by the existence of contemporary records. A novel way to estimate the pace of language change is by estimating the flow of loanwords. If a succession of phonological processes arose, flourished, and then ceased to apply to new words, the result is that loanwords are partitioned into those that did or did not undergo each process. Importantly, words that matched the environment for a process are presumably borrowed alongside words that did not match the environment. If it is known how often the environment for the process occurs in the lexicon of the donor language, it is possible to fill in the loans that entered while the process was active, but that happened to be ineligible for it. This provides an estimate of how many words were borrowed during a particular phase in the phonological history of a language. If cultural factors like a break in contact can be discounted, periods with fewer loans presumably lasted for shorter times, which can be evidence that sound changes were closely spaced or overlapping, or even that an individual sound change itself was short lived. The primary contribution of this paper is a demonstration of how an algorithm equipped with knowledge of phonotactic trends can resolve ambiguous data to reveal likely timelines of borrowing.

We also illustrate the procedure with an in-depth application to the early Latin loans in Irish (Celtic, Ireland), which sheds light on a particularly dynamic period of language change. Our method allows us to estimate the approximate amount of time that no less than six phonological processes were active within a roughly century and a half span. The last of these processes was rhythmic syncope, the deletion of vowels in an even-odd pattern reminiscent of rhythmic stress. Rhythmic syncope has generated keen interest in phonological theory because serial theories of phonology, like Harmonic Serialism, can generate it (McCarthy

2008), while parallel or single level theories of phonology, like Classic OT, cannot (Kager 1997, Blumenfeld 2006, Hao and Bowers 2019). Strikingly, rhythmic syncope appears to be prone to rapid re-analysis and obsolescence, as seen especially clearly in Nishnaabemwin (Bowers 2019 and references therein), but also in Mojeño Trinitario (Rose 2019), Southern Pomo (Kaplan 2020, Kaplan 2022) and Eastern Slavic (Isačenko 1970). It is not currently known how often rhythmic syncope systems collapse, making Irish a valuable data point in understanding the trajectory of rhythmic syncope systems.

It is already known that rhythmic syncope did not survive to Modern Irish, and that it and other processes were in flux even in the earliest Old Irish manuscripts (Armstrong 1976, McCone 1985, 1997 pp. 164-169, 191 ff.). However, there is a roughly 150 to 200 year gap between when rhythmic syncope is thought to have arisen and the Old Irish manuscripts, which raises the possibility that rhythmic syncope could have been productive for several generations. Our simulations find that very few loans should be allocated to the rhythmic syncope period of Irish, which is consistent with rhythmic syncope being only a brief blip in the history of Irish. At the very least, the lack of loanwords during the rhythmic syncope period fails to corroborate the opposing view that rhythmic syncope is diachronically stable and easy to acquire.

A couple brief notes on terminology, exposition, and assumptions.[1] This paper treats the development and interaction of several phonological mappings over a period of time. For ease of understanding, we illustrate their application with traditional derivations reminiscent of rule based phonology (Chomsky and Halle 1968, Kenstowicz and Kisseberth 1979), and loan adaptations are illustrated in derivations proceeding from a faithful source language representation, though we apply Irish case suffixes and degeminate foreign consonants (see section A.1 and A.3.1, see alsoBoersma (1998) and Boersma and Hamann (2009) for a more realistic approach to loan adaptation). We do not claim that rule-based derivations are an adequate, or even preferable, model of phonological competence. In light of this, we also eschew the term 'rule', opting instead to use 'process' as an accessible term for the mappings that are presumably best treated in a constraint based approach.

This paper treats diachronic developments as they unfolded synchronically. Note that our derivations generally reflect the historical progression, but fealty to the historical developments may be sacrificed for expository clarity (especially with respect to palatalization, which we do not treat, see the opening section of the appendix). More importantly, there is the potential for confusion over whether we are discussing synchronic knowledge or diachronic events. To be clear, we assume that once a sound change occurs, it remains a part of synchronic knowledge as long as speakers have grammars that enforce its effects (see Bermúdez-Otero 2015). The activity of this grammar may be observed in loan word adaptation, paradigmatic alternations, phonotactic restrictions, or other aspects of linguistic behavior.

The persistence of diachronic changes as synchronic grammatical knowledge is in line with the analyses common in the Irish studies literature. These analyses are generally in the structuralist paradigm, and may not explicitly commit to representing the knowledge of speakers (as opposed to the contents of a corpus). Nonetheless, they accept that (predictable) allophonic distributions exist after a sound change operates, and often point out when former allophones become (unpredictable) phonemes. When discussing loan adaptation, authors allow that loans could be adapted "to the phonetic system of Irish at the time" (McCone 1996:89), or that loans could undergo "assimilation to the native allophonic distribution" (McManus 1983:56). This presumably would be carried out by speakers enforcing their knowledge of allophonic patterns.

Our method estimates the number of loan words that entered a language while a process applied to new words, which can be a proxy for how long a process remained in speakers' grammars. This depends crucially

[1] We use the following abbreviations for glossing examples: ADJ = 'adjective', ACC = 'accusative', AGEN = 'agentive', DIM = 'diminutive', FEM = 'feminine', IMPV = 'imperative', MASC = 'masculine', NOM = 'nominative', NEUT = 'neuter', PL = 'plural', PCL = 'proclitic', PST = 'past', SG = 'singular'. We mark reconstructed forms with †, and reserve * for ungrammatical forms.

on the processes of interest ceasing to apply to loan words at some point, which indicates that they ceased to be a part of speakers' grammars. Some processes, most notably palatalization, did not cease to apply to loans and so cannot inform our method (see also the introduction to the appendix). For most processes in our case study, a process illustrated at stage n of a derivation ceased to apply to loans at stage $n + 1$, allowing our model to sort loans into sequentially ordered bins, which correspond to individual phonological processes whose active periods in real time potentially partially overlapped (see section 6). One process (vowel shortening), appears to have applied to loans past stage $n+1$ (harmony) in the traditional presentation, plausibly ending with the development of compensatory lengthening (McManus 1983:56, 59). Since we assume that speakers continue to acquire a grammar that enforces the sound patterns of their language, each point where these processes evidently passed from synchronic knowledge requires explanation. In section 6 and the appendix, we typically tentatively ascribe the loss of processes to opacity, but we recognize that the psychological reality of opacity is an enduring question in phonological theory and we lack the space to litigate it here.

The paper will proceed as follows. Section 2 describes the method for allocating loans using phonotactic trends. Section 3 gives background on Irish and our collection of loans. Section 4 briefly sketches how the (non)-application of Irish phonological processes diagnoses the time of entry into Irish, with detailed discussion of the phonology appearing in the appendix. Section 5 describes the results of our simulations, and section 6 discusses their interpretation. Section 7 concludes.

2 Loan Allocation Method

While borrowing is primarily driven by a need for new words to express new concepts, the new words are essentially a random sample of the phonotactic space of the donor language, due to the arbitrary relationship between sound and meaning. Accordingly, the words that enter a language during a particular time should reflect how often various phonotactic traits appear in the donor language. At minimum, our method starts with a series of phonological periods in the borrowing language, a collection of loans, and how often the structural descriptions for the relevant phonological processess are observed in the donor language. We then proceed to apportion the loans between phonological periods so that the phonotactic properties in each period best reflect the rate at which they appear in the donor language.

An important requirement is that the phonological processes that define the periods must have stopped applying to loan words, dividing the loan vocabulary between those words that underwent a process, and those that did not. This allows us to determine a window of time when a loan could have possibly entered. For instance, anticipating our discussion of the Latin loans in Irish, if loans were adapted by mapping [p] to [k], then loans that undergo the change must have entered before the end of the [p]→[k] process, while loans that keep [p] faithfully must have entered after the end of it. By leveraging a suite of phonotactic properties, the phonotactic balance method can give a more precise estimate of how many loans entered at a particular time.

Attempting to plausibly balance multiple phonotactic traits with a large number of loans over several phonological periods is a daunting task to accomplish by hand.[2] To manage this, we apply the genetic

[2]For instance, in the Irish case study below, the full set of solutions is too large to directly compute all solutions and compare them against each other. The size of the set can be obtained by calculating the number of periods represented by a top-left to bottom-right diagonal in (11), exponentiating each diagonal by the sum of the values of the cells in the diagonal, and multiplying the exponentiated diagonals. This comes out to $1^{101} \times 2^{77} \times 3^{62} \times 4^{53} \times 5^{77} \times 6^{32} \times 7^{129} = 2.57 \times 10^{272}$. The more formidable obstacle to carrying this out by hand is deciding which words should be allocated to what periods in the face of potentially incompatible demands. This is a task that is well suited to a search algorithm equipped with an evaluation metric and the ability to consider large numbers of potential allocations.

search algorithm (Holland 1975, De Jong 1975, Yang 2021), a non-linear optimization procedure, to sift through random allocations of loans to phonological periods by scoring them for phonotactic balance. We provide a brief overview of genetic search in section 2.1, before working through a toy example in section 2.2, and giving a description of the specific aspects of our implementation in section 2.3.

2.1 Genetic Search Description

Genetic search (Holland 1975, De Jong 1975, Yang 2021) is an abstract characterization of biological evolution, where organisms consisting of genes with particular alleles are selected for fitness before passing their genes to the next generation. In our case, the organisms are complete allocations of all loans, or timelines, the genes are the range of possible dates associated with each word, and the alleles are the particular time periods the words are assigned to. A major benefit of genetic search is that it maintains multiple competing hypotheses and so simultaneously explores multiple regions of the search space. Genetic search has been widely applied to problems such as graph coloring, the travelling salesman problem, and multi-objective engineering optimization.

2.1.1 Search Procedure

Genetic search starts by creating a large gene pool of competing 'organisms', or timelines in our case, by randomly assigning all words to a specific date within their allowable time spans. The specimens in the gene pool are then scored by an evaluation metric, and the specimens in the gene pool serve as the basis for the next generation. In our setting, the evaluation metric measures the balance of phonotactic trends from the donor lexicon, as mentioned above and more formally described in section 2.3.1.

After initialization, genetic search alternates between 'mutation' and 'recombination' phases. In the mutation phase of our implementation, for every candidate timeline in the pool, a new collection of timelines is created by selecting sets of words with multiple possible dates of entry, and randomly picking an entry date from the possible dates of entry. If any of the mutated timelines are fit enough to join the n most fit specimens, they are added to the gene pool, and the least fit specimens are removed from the gene pool. This is how the algorithm explores new regions in the search space, by taking previous successes and randomly changing only a few of their genes.

In the recombination step, the specimens in the gene pool randomly swap alleles between each other, and once again the n most fit specimens are retained. Concretely, for each word where a pair of timelines differs in the assigned date, the new offspring will inherit one of the assigned dates from a randomly selected parent. Intuitively, the recombination step allows successes found in one area of the search space to propagate to other hypotheses. Recombination pushes the gene pool towards a single solution, as organisms/timelines become more similar to each other by sharing alleles/allocations from other hypotheses. The search proceeds by iterating between mutation and recombination phases until fitness no longer improves or a set number of generations has been reached.

2.1.2 Convergence Concerns

As a non-linear optimization algorithm, genetic search is not guaranteed to converge on a globally optimal solution. However, the maintenance of a pool of hypotheses that interact via recombination provides some resilience against getting stuck in a local optimum. To be concrete, a timeline is in a local optimum if it is in an area of the hypothesis space where any mutation of some subset of its genes will harm its performance on the evaluation metric, but if a larger subset were to be changed, performance would improve. Above all else, the presence of other hypotheses makes it possible that even if a hypothesis is trapped in a dead end, some

other hypothesis could be outside of the local optimum. Because the hypotheses share parameter settings during the recombination phase, hypotheses that lie outside of the local minimum can provide better alleles *en masse*, thereby allowing the descendants of the trapped hypothesis to escape the local minimum.

The following section gives a toy example to illustrate the application of the genetic algorithm to a loanword problem similar to our Irish case study.

2.2 Toy Example

Our toy example features two phonological time periods, where the first covers the active period for a process mapping [p] to [k], and the second covers the post-[p]→[k] period. We also assume that a second process leniting post-vocalic [t, k] to [θ, x] applies during the second period. Our borrowing language adapted four words from the donor language. One word entered during the [p]→[k] period, since it underwent [p]→[k], and another must have entered during the later period since it was eligible for [p]→[k] but failed to undergo it. Two further words could have entered during either period, because they are not eligible for [p]→[k], though one did undergo lenition. This distribution of loanwords is schematized in (1), where ✓ marks a loan that is eligible for a process and undergoes it, X marks a loan that is eligible for a process and does not undergo it, and — marks a loan that is not eligible for a process.

(1)

Source	Adapted	[p]→[k]	Lenition	Possible Periods
pil	kil	✓	—	1
pit	piθ	X	✓	2
lit	liθ	—	✓	1, 2
til	til	—	—	1, 2

We assume that half of the words in the source language have [p], and that half are eligible for lenition. Accordingly, the optimal allocation is one where half of the words in a period have [p], and half are eligible for lenition. Anticipating the fitness model to be described in sections 2.3.1 and 4.2, for each process we obtain the probability that there would be n words eligible for the process out of p total words in the period, given a rate of occurrence r (in this case 50% for each process). These probabilities are then multiplied to produce the fitness measure of the entire allocation. For convenience, we summarize the fitness measures of every possible allocation in (2), where a higher fitness value is better.

(2)

pil→kil	lit→liθ	til→til	pit→piθ	Fitness
1	1	2	2	0.063
1	1	1	2	0.035
1	2	2	2	0.035
1	2	1	2	0.012

Though the complete enumeration of hypotheses in (2) is small enough to be manageable, our sample run of the algorithm will not have access to it. In this toy example we limit the specimen pool to two hypotheses. During the mutation phase, each specimen produces one offspring with one mutated gene. During the recombination phase, the pair of specimens in the pool produces one offspring. We initialize the specimen pool as shown in (3):

(3) Initialization Phase

pil→kil	lit→liθ	til→til	pit→piθ	Fitness
1	2	2	2	0.035
1	2	1	2	0.012

Since initialization is effectively a mutation phase, in the first round the algorithm skips the usual mutation phase and moves straight to the recombination phase. The two specimens differ in whether [til]→[til] is assigned to period 1 or period 2. The recombination process randomly selects period 2 for this word. This offspring scores better than one of the specimens in the gene pool, and so it replaces the less fit ancestor. The gene pool now appears as in (4):

(4) Recombination Phase

pil→kil	lit→liθ	til→til	pit→piθ	Fitness
1	2	2	2	0.035
1	2	2	2	0.035

The algorithm now enters the mutation phase. When the first specimen is mutated, [til]→[til] is randomly selected as the mutation site, and period 1 is randomly selected as the value. This results in poorer performance on the evaluation metric than what is currently in the gene pool, so this specimen will not be added to the gene pool. For the second specimen, [lit]→[liθ] is the randomly selected mutation site, and it gets randomly assigned to period 1. This results in a more fit specimen, which is added to the gene pool. The gene pool now contains the specimens shown in (5):

(5) Mutation Phase

pil→kil	lit→liθ	til→til	pit→piθ	Fitness
1	1	2	2	0.063
1	2	2	2	0.035

In the subsequent recombination phase, the only word where the two specimens differ is [lit]→[liθ]. In the recombined offspring, [lit]→[liθ] is randomly assigned to period 1. This specimen is more fit than the second specimen in the pool, and so the updated pool is shown in (6):

(6) Recombination Phase

pil→kil	lit→liθ	til→til	pit→piθ	Fitness
1	1	2	2	0.063
1	1	2	2	0.063

At this point, no further changes will be made by further mutations or recombinations, since all specimens are maximally fit. With no new changes occurring in the subsequent round, the algorithm will announce that it has converged. The algorithm has ensured that the context for lenition and [p] are present in half of the words in both periods, producing an estimate that the same number of words entered during both periods, as would be expected given the observed adaptations.

It is important to interpret the estimate at the level of period vocabulary instead of the allocations of individual words. Two of the words (those without [p] in the source language) can logically enter during either period, and we can be no more certain than that on the level of individual words. Which period a particular word is assigned to depends on unpredictable properties of other words. It just so happens that period 1 has a word that was eligible for [p]→[k] but not lenition, which is best paired with a leniting word. Meanwhile, period 2 has a word that is eligible for [p]→[k] and lenition, so phonotactic balance is maximized by pairing it with a word that does not undergo lenition. To claim that a particular word with multiple possible entry dates had to enter at the time assigned by the simulation is to fail to recognize that the assignment is influenced by which phonotactic properties occur in other words in the period. Speakers presumably do not take such capricious factors into account when deciding to borrow a word. In contrast,

we only make the more restricted claim that in the aggregate, borrowed vocabulary is more likely to match the source language phonotactic frequencies than not.

We now turn to a technical description of our implementation for our case study.

2.3 Implementation Summary

In our implementation, the gene pool contains the 100 most fit allocations of 531 Latin loans distributed over seven phonological periods of Irish (described in section 4). The source code and data that we use for our simulations can be found at `https://github.com/bowersd/lat2sgaloans`.

In the mutation phase, each timeline was mutated 1,000 times.[3] During every round of the algorithm, the mutation phase produces 1,000*100=100,000 candidate allocations. These candidates and the gene pool are ranked by their score for the fitness measure (described in section 2.3.1), and the 100 most fit candidates are retained for the next phase. The mutation rate starts at 5% of words with multiple possible dates of entry, and the rate halves each time the mutation phase fails to add new hypotheses (i.e. allocations that are more fit than any pre-existing member of the gene pool). This gradual reduction in the mutation rate allows the algorithm to initially re-allocate broad swathes of words and progressively narrow its focus as it approaches a good solution.

In the recombination phase, each member of the pool creates 20 offspring with each other member of the pool by randomly swapping dates of entry between them. Since the pairing of specimen x with specimen y is symmetric (the same as pairing member y with member x), the recombination phase produces 50*99*20=99,000 candidate allocations. As in the mutation phase, these candidates and the gene pool are ranked by their score on the fitness measure (described in section 2.3.1), and the 100 most fit candidates are retained for the next phase.

The algorithm halts when new members cease to be added to the gene pool and the mutation rate is too low to change any dates. In our case study, this typically occurs between the 40th and the 60th generations.

2.3.1 Fitness Measure Calculation

The measure of timeline fitness evaluates phonotactic balance within each period. Informally, we need to measure the number of times each phonotactic property is observed in a period, and assess how well it corresponds to the expected number of times it should be observed, given the total number of words in the period and the rate at which the phonotactic property is observed in the donor vocabulary. We do this formally by equating the phonotactic probability Φ_p of each period p in the timeline T with the joint binomial probability of the various phonotactic properties. Joint binomial probability is the product of multiple binomial probabilities, which are computed using the number of words $n_f \in p$ bearing each phonotactic property f in the set ϕ of phonotactic properties, the total population $|p|$ of the period p, and the rate r_f at which phonotactic

[3] The reader should not worry that 1,000 mutations is an excessive number of samples for a 531 word corpus. This rate is indeed high towards the end of the search, when only one word is selected for mutation at a time and so each word will be sampled around twice per round. However, by this time the solution is near, so the large number of samples is merely inefficient, rather than a hindrance to the performance of the algorithm. By contrast, earlier in the search, up to 22 words are selected for mutation at once, and there is little chance that the same group of words will be mutated twice. We also tested the algorithm with 250, 500, and 2,000 mutant offspring per timeline, and found that while the highest attained value of the fitness measure was the same for all conditions across multiple runs of the search, it was most consistently achieved for the 1,000 mutant condition (8 of 10 runs), with second place going to the 500 mutant condition (6 of 10 runs).

property $f \in \phi$ is observed in the donor language. This is spelled out in the following formula.

$$\Phi_p = \prod_{f=1}^{|\phi|} \text{binomial}(n_f, |p|, r_f)$$

The fitness of a timeline T is the product of each probability Φ_p for all periods p.

For our simulations, we base the phonotactic set ϕ on the structural descriptions for the Irish processes that were applied to loans. We now shift our attention to Irish, first providing background on the historical context and data sources in section 3. In section 4 we provide an overview of the phonological processes at work in the Latin loans, these are also discussed in greater detail in the appendix. See especially section 4.2 for a description of how the Irish phonological processes are related to our phonotactic parameters.

3 Irish Historical Background

Our case study investigates the early Latin loans that entered prior to and during the Old Irish manuscripts. Irish is attested in a continuous tradition of writing in Latin letters dating to the seventh century CE (Thurneysen 1946:4-10), and still older stone inscriptions written in the Ogam alphabet (McManus 1991). The historical phonology of Irish that this study draws on is well understood. Most importantly, the manuscript record has a solid phonological interpretation, despite the vagaries common in pre-modern orthographic systems. This interpretation rests on various streams of evidence, such as (a) Old Irish metrical forms, which have strict rules for syllable counts as well as rhyme and alliteration systems that are based on groupings of consonants and vowels according to phonological features (Murphy 1961), (b) regular correspondences between Irish written in the Ogam and Latin alphabets, (c) comparison of Old Irish to the writing system and phonology of Modern Irish, and crucially (d) the distribution and orthography of initial consonant mutation, especially in early medieval Brittonic from which Old Irish borrowed much of its spelling system (Harvey 1990a:178–180). Further inferences about Irish historical phonology can be drawn via comparison with other Celtic languages, particularly the other Insular Celtic languages, which include Scots Gaelic and the Brittonic languages, i.e. Welsh, Cornish and Breton.

There are some minor controversies over the orthography, such as whether some cases of orthographic ⟨u⟩ represent 'u-coloring' of a vowel or labialization of a consonant (Hock 2019), but our discussion does not hinge on any non-standard or disputed interpretations of the orthography. Similarly, there is debate over whether Insular Celtic is a geographic or genetic grouping (Schmidt 1977, Koch 1992, de Bernardo Stempel 2006, McCone 1996, Schrijver 1995, Schumacher 2004, Sims-Williams 2007:1-42, esp. 24-34), but this does not affect our discussion. Our approach to the Latin loans in Irish follows the mainstream consensus in Irish historical linguistics, as represented by Jackson (1953) and McManus (1983), with some updates to the understanding of the phonology following McCone (1996).

Since our data is necessarily orthographic, we accompany phonological representations in [square brackets] with an attested orthographic forms in ⟨angle brackets⟩. We reserve /slashes/ for explicitly discussing underlying representations. Derivations of Irish loans start from a representation that is roughly faithful to Latin, though Irish case suffixes are substituted for Latin case suffixes, and Latin geminates are simplified (see the appendix for further discussion of suffix substitution and degemination). When providing citations for data, we provide both an author-year citation for the edition used and an abbreviation of the manuscript name with folio numbers.[4]

[4]Abbreviations for manuscripts are: Ml. = 'Milan Glosses', Sg. = 'St. Gall Glosses', and Wb. = 'Würzburg Glosses'.

For the reader who wishes to better understand Irish historical phonology, accessible student grammars of Old Irish include McCone (2005), Stifter (2006), Tigges and Ó Bearra (2006), and de Vries (2013). The standard reference and historical grammar remains Thurneysen (1946). For the interpretation of Old Irish and early medieval Brittonic orthography and its relation to the phonology, see Watkins (1966), Ó Buachalla (1982), Harvey (1989, 1990a, 1990b, 1991, 2011), Sims-Williams (1991), and Hamp (2000). References explicitly treating the phonological development of Irish include McCone (1996) and Jaskuła (2006). Section 4 briefly reviews the phonology relevant to dating loans, which is more comprehensively illustrated in the appendix.

3.1 Time period for borrowing

The Latin loan words we are most interested in are found in the manuscript record, but were adapted using phonological processes that predate it. Following Jackson (1953) and McManus (1983), these processes include adaptation of the foreign phone [p] by [k], consonant lenition, vowel harmony, vowel shortening, compensatory lengthening, and rhythmic syncope. These processes developed in roughly the order given, and will be more closely reviewed in section 4 and the appendix. We summarize these phonological events and their relationship to historical dates and the manuscript record in the timeline in Figure 1. The remainder of this section elaborates the reasoning supporting this timeline.

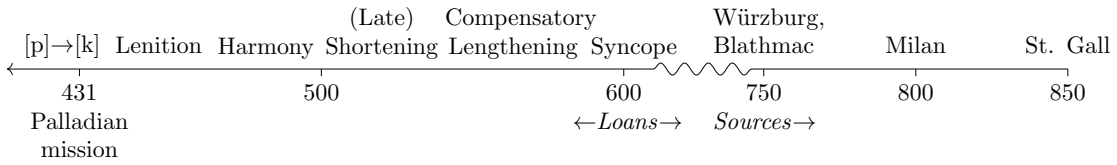

Figure 1: Timeline of key events and sources. Positions above the line reflect approximate dates.

Some of the Latin loans could have entered via trade (Fomin 2018), but the great majority are ecclesiastical terms, and must therefore be connected with the introduction of Christianity. This allows us to narrow down the beginning of the borrowing period to around the early fifth century CE. We know this because Prosper of Aquitaine's chronicle for the year 431/432 mentions that a missionary named Palladius was sent to a pre-existing Christian community in Ireland (Mommsen 1892). Over the following centuries, the connection to the Latin world via Christianity deepened (Flechner and Ní Mhaonaigh 2016), as evidenced by the beginning of the Irish monastic tradition in the sixth century, and the later Irish manuscripts found throughout Continental Europe as a result of the Irish missions to the continent during the sixth and subsequent centuries of the early medieval era (Flechner and Meeder 2017).

Prosper of Aquitaine's chronicle also allows us to tentatively fix a date to some of the earliest phonology we will consider. Many Christian ecclesiastical loans undergo lenition. Assuming these loans entered with the introduction of Christianity, lenition presumably emerged shortly thereafter. If Christianity was accelerating in 431/432, then putting the date for lenition at around 450 (McManus 1983) gives ample time for a body of ecclesiastical loans to accumulate before leniting.

Furthermore, a smattering of Christian ecclesiastical loans were adapted with Irish [k] for Latin [p], indicating that the [p]→[k] adaptation was active when they were borrowed. However, most Latin loans preserve [p] faithfully, indicating that [p] was borrowed into Irish. Strikingly, there are Latin loans that preserve [p] and undergo lenition (see section 4 for direct exemplification). These loans must have entered after [p] was legalized but still early enough to undergo lenition. Given these facts, we can conclude that

[p] was legalized early on during the conversion to Christianity, perhaps before 431/432 (see also McCone 1996:92 for a similar conclusion).

After [p]→[k] and lenition, Irish developed height harmony targeting short vowels (dubbed 'affection' in the Irish-studies literature), vowel shortening and compensatory lengthening. McManus (1991) gives evidence from Ogam inscriptions that vowel harmony preceded compensatory lengthening. Shortening is thought to have ended when compensatory lengthening developed (McManus 1983:56, 59), but it is thought to have begun before the end of vowel harmony (McCone 1996:110), since shortened vowels harmonize in the native vocabulary.

The last major milestone for loans is rhythmic syncope. Rhythmic syncope is generally thought to have emerged in the mid-to-late sixth century (Jackson 1953:143, McManus 1983:31), although there is potential evidence for the early sixth century (Sims-Williams 2003:346). Possible direct support for sixth-century syncope is found in early syncopated poetry traditionally attributed to Colmán mac Lénéni (Carney 1971), a poet who died in 606, although caution is required, since the poems could have been composed by a later author (Sims-Williams 2016:164, 172-174). Syncope also appears in stone inscriptions dating to the early seventh century (McManus 1986:2-4). This demonstrates that syncope could not have been initiated after the beginning of the seventh century.

Post-syncope loans into Irish continued to be adapted to the native phonological system, for instance, gaining the Irish distinction between between palatal/non-palatal consonants. However, these later loans are otherwise quite faithful to the Latin originals and do not reflect the progression of new Irish sound changes. This means that we must treat post-syncope loans as a uniform block, and can only give finer distinctions for pre-syncope loans.

In all, we have evidence for roughly a century to a century and a half elapsing between lenition and syncope, and at most a few decades of separation between any intervening processes.[5] We turn now to a closer examination of the manuscript sources that provide the data for this study.

3.2 Historical Data Sources

To get a meaningful picture of how many loans entered Irish at particular times in our period, we require a representative corpus of the early Latin loan vocabulary. Our primary source for this vocabulary is manuscripts containing Old Irish material. While there are multiple such manuscripts to choose from, most are in fact copies written much later than the Old Irish period. We set the tenth century as a cutoff point in order to exclude material that entered the language much later than syncope, and included all loans from the contemporary Old Irish manuscripts before that date.

Fortunately, the recently available Corpus Paleo-Hibernicum (CorPH, Stifter et al. 2021), a searchable web-based lexicon of pre-tenth century Irish, has made searching for loanwords during this period straightforward. From CorPH, we draw on the material in the Milan (Stifter et al. 2021; Stokes and Strachan 1901) and St. Gall (Stifter et al. 2021; Stokes and Strachan 1903) manuscripts, which contain Old Irish glosses on Latin texts and a large number of loanwords from Latin. They are standardly dated to the late eighth or early ninth centuries and the mid-ninth century, respectively. We also draw from fifty-eight so-called "minor" glossed manuscripts dated to the seventh to the tenth centuries (Lash 2021) and the mid-eighth-century poems of Blathmac (Barrett 2021, see Stifter 2015 on the dating of Blathmac). To round out the picture of securely pre-tenth-century loans, we draw on the Thesaurus Paleohibernicus (Stokes and Strachan 1901, Stokes and Strachan 1903) for manuscripts not found in CorPH, including the eighth-century Würzburg manuscript (of which Kavanagh 2001 provides a useful lexicon).

[5]Note that other sources provide narrow approximate dates for individual phonological developments (e.g. McManus 1983:30-31), while these are no doubt fairly accurate given the tight timeline, we refrain from speculating beyond the available evidence.

The above sources do not provide a complete sample of the early Irish loan vocabulary, because some loans in later sources have adaptations that clearly point to a pre-end-of-syncope entry date.[6] We draw many loans with early adaptations from McManus (1983), which is a thorough, albeit non-exhaustive, collection. One loan that we include from McManus (1983:65), Irish [saʟənd] ⟨salland⟩ 'act of singing (psalms)' from Latin [psalːendum], does not feature early adaptations. However, it could have entered Irish before syncope, and it appears in a securely dated Old Irish text, so it meets our other criteria for inclusion.

It may be possible that loans in later sources, but which were ineligible for early adaptations, nonetheless entered during our period. We choose to be conservative and do not include them. We leave the question of what our method would do on a data set that includes them to future research.

The contributions of each source to our corpus are shown in (7), where loans are only counted towards the earliest source in which they are attested.[7]

(7)

Source	Pre-syncope	Post-syncope	Either	Total
Würzburg	36	17	78	131
Blathmac	14	4	31	49
Milan	18	11	40	69
St. Gall	23	27	68	118
Minor Glosses	23	10	38	71
St. Gall Incantations	0	0	1	1
McManus	91	0	1	92
Total	204	70	257	531

3.2.1 Latin vs. Irish Perspective

The corpus contains loans without Irish derivational morphology. For example, Irish borrowed [korp] ⟨corp⟩ 'body' (Stokes and Strachan 1901:581, Wb. 3a4) from Latin [korpus], but we exclude Irish derivatives such as [korp-əx] ⟨corpach⟩ 'corporeal' (lit. 'body-ADJ') (Stokes and Strachan 1903:148, Sg. 125a5). We also exclude multiple case forms of the same loan.

There is however some ambiguity in how to determine what counts as a separate loan. For instance Irish borrowed [uṽəldoːdʲ] ⟨umaldóit⟩ 'humility' (Stokes and Strachan 1901:581, Wb. 13a17) from Latin [umilitaːtem]. From the perspective of Irish, [uṽəldoːdʲ] must be a separate borrowing from the borrowing [uṽəl] ⟨umal⟩ 'humble' (Stokes and Strachan 1901:532, Wb. 5d27), since there is no native suffix [-doːdʲ] that could create this noun. However, the Latin sources for [uṽəldoːdʲ] ⟨umaldóit⟩ and [uṽəl] ⟨umal⟩ are transparently related by regular morphology in Latin, making these words a single loan from the Latin perspective.

The conservative choice is to count loans from the Latin perspective, because our simulations rely on phonotactic frequencies drawn from the Latin nominal lexicon. For completeness, we also compiled the set

[6] An additional complication is that many of the loans in the early texts are literary and may have never been nativized or only existed in writing. A philological approach to such loans may be successful in determining when they entered Irish, but we do not attempt this here.

[7] There are several words in our sources that have occasionally been categorized as loan words from Latin but which we have rejected from the corpus because their etymology remains unclear to us. These are: [kolve] ⟨collbe⟩ 'pillar' (Lat. [kolumna]?), [diəθʲərʲ] ⟨diathir⟩ 'diameter' (Lat. [diametrus]?), [iðən] ⟨idan⟩ 'pure' (Lat. [idoːneus]?), [laɴ] ⟨lann⟩ 'thin plate' (Lat. [laːmina]?), [oxre] ⟨ochra(e)⟩ 'leggings' (Lat. [okreai]?), [regʲlʲeːs] ⟨reiclés⟩ 'oratory, small church' (Lat. [reklusum] or [ekːleːsia]?), [skʲovəðʲ] ⟨sciobaidh⟩ 's/he snatches' (Lat. [skoːpa] with an Irish verbal ending?), [skʲovoːl] ⟨scioból⟩ 'barn' (Lat. [skoːpaːrium]?), [teoθəs] ⟨Teothas⟩ 'Theodotion' (Lat. [teodotioː]?). Apart from these, biblical Hebrew names were excluded because though they were borrowed via Latin, they originate in a language with different phonotactic distributions than Latin.

of loans from the Irish perspective, resulting in 20 additional loans. The simulation results do not differ appreciably between these different collections.

3.2.2 Re-borrowed Loans

An additional wrinkle is that the same Latin lexeme could be borrowed multiple times. For instance, Latin [apostol-us] 'apostle-MASC.NOM.SG' appears as a very early loan in Irish [axsəl] ⟨axal⟩ 'apostle' (McManus 1983:48) and as a later loan in [abstəl] ⟨apstal⟩ 'apostle' (Stokes and Strachan 1901:527, Wb. 5b17). In such cases we included both Irish words as separate borrowings.

3.2.3 Hand Dating

Finally, 60 loans could not be dated purely mechanically by following the methodology laid out in section 4 and the appendix. This was usually because they had inconsistent phonological cues to their date of entry. A typical case is [uespəsʲiən] ⟨Uespisian⟩ 'Vespasian' (Barrett 2021, S0005-114), which has no orthographic cues to the vowel length in Latin [wespasiaːn-us] 'Vespasian-MASC.NOM.SG', and so possibly underwent shortening (a pre-syncope change), but which is also clearly unsyncopated, which would place it after syncope. For each such inconsistent form we provided our best guess for the dates of entry by hand. In the case of [uespəsʲiən] ⟨Uespisian⟩ 'Vespasian', we disregarded the putative shortening, attributing it the word being borrowed orthographically, since Latin orthography omitted length marking. Borrowing this word from a written form seems especially likely, since it is doubtful that a long-deceased Roman emperor was a frequent topic of oral conversation.

3.2.4 Local Summary

This concludes our overview of the history of Irish and the historical sources we rely on for loans. With these general preliminaries on Irish in hand, we now return to the main narrative. In the next section we illustrate how the processes that were or were not applied to loans reveal when they entered Irish. This provides the raw data for our simulations, and plays a major role in the ultimate quantification of how many words entered Irish at particular times.

4 Irish Phonology in Latin Loans

Early Latin loans can be dated using nine Irish phonological processes. Six of these processes demarcate the boundaries between seven periods in the phonological history of Irish (one period for each of the six processes, plus the post-syncope period), while three of the processes are best thought of as subsidiary to the six major processes. We sketch the key facts briefly in this section, and because the referenced sources can be difficult for non-specialists in Irish, we provide an explicit walk-through of the phonological developments in the appendix. The major milestones for dating the Latin loanwords in Irish are listed below with brief descriptions:

1. [p]→[k]: replacement of [p] with [k].

2. Lenition: in post-vocalic contexts, debuccalization of sibilants and weakening of [t, k, b, d, g, m] to [θ, x, v, ð, ɣ, ṽ], respectively.

3. Harmony: regressive left to right short vowel height harmony.[8]

4. Shortening: vowel shortening in non-initial syllables.[9]

5. Compensatory lengthening: loss of [θ, ð, x, ɣ] before [r, l, n, m] with compensatory lengthening of the preceding vowel.

6. Rhythmic syncope: loss of vowels from even-numbered non-final syllables when counting from left to right.

The subsidiary processes were primarily not independent sound changes of Irish, but presuppose one of the developments above. For instance, Irish never mapped [f]→[s] in the native vocabulary, but Irish [f] comes from debuccalized †[sʷ], so we associate Latin loans where [f] is replaced with [s] with lenition. Similarly, the native Irish vocabulary prohibited [ks] and nasal-voiceless obstruent clusters, but these were re-introduced into surface forms by syncope. As a result, repairs to these clusters via [ks]→[s], post-nasal voicing of stops or the simplification of [ns, nf] clusters, diagnose entry before rhythmic syncope. In contrast, [st]→[s] was a sound change of Irish that pre-dated lenition, but it applied to at least one post-lenition loan. Due to this wide ambit, we allow any loan undergoing it to enter at any point prior to compensatory lengthening. See the appendix for further discussion and exemplification of the subsidiary processes.

In the following sections, we demonstrate how these processes are exploited by our model. Section 4.1 shows how the (non)-application of a process can demarcate when a loan entered Irish, while section 4.2 explicitly ties these processes to the phonotactic statements used in the fitness measure described in section 2.3.1.

4.1 From Phonology to Date Ranges

In order to estimate how many Latin loans entered during the rhythmic syncope period, we follow the method established by Jackson (1953) and McManus (1983), which dates loans according to whether the processes listed above did or did not apply to them. When a process stopped applying to loan words, the result was an early group of loans that underwent the process, and a later group that did not undergo it. For instance, there are loans that underwent [p]→[k], such as Latin [pluːm-a] 'plumage-FEM.NOM.SG', which became Irish [kluːṽ] ⟨clúm⟩ (McManus 1983:48) by the derivation shown in (8). These loans must have entered before [p]→[k] ceased to apply.

(8)		
	pluːm-a	Latin
	/pluːm-aː/	Irish UR
	kluːmaː	[p]→[k]
	kluːṽaː	Lenition
	kluːṽ_	Apocope
	[kluːṽ]	SR
	⟨clúm⟩	Orthography

There are also numerous loans that retained Latin [p] faithfully. One such loan is Latin [pareːki-a] 'parish-FEM.NOM.SG', which avoided [p]→[k] but underwent lenition of [k] to [x] (among other processes),

[8]The diachronic literature on Irish typically treats vowel harmony as separate lowering and raising processes (sometimes called a/o affection and i/u affection, as in McManus 1983).

[9]Shortening began before the end of harmony and plausibly continued to be enforced until compensatory lengthening (McManus 1983:56, 59). We list it after harmony here to reflect that it only can only be treated as a distinct phonological period independent of the harmony period during the post-harmony phase of this process.

as seen in Irish [parʲxʲe] ⟨pairche⟩ (Stokes and Strachan 1901:632, Wb 21a12). Clearly, [parʲxʲe] ⟨pairche⟩ 'parish', must have entered between the end of [p]→[k] and the end of lenition. The full derivation of this loan is spelled out in (9). We use 'X' to mark processes that do not apply because the loan entered too late. We also include two counterfactual derivations illustrating the expected outcome if the borrowing had happened earlier (column 2) or later (column 3). Note that while alternating stress certainly was not developed immediately before syncope, to limit clutter in the derivation we introduce it late.

(9)	pareːki-a	pareːki-a	pareːki-a	Latin
	/pareːkij-a/	/pareːkij-a/	/pareːkij-a/	Irish UR
	X	kareːkij-a	X	[p]→[k]
	pareːxija	kareːxija	X	Lenition
	parexija	karexija	parekija	Shortening
	parexeja	karexeja	parekeja	Harmony
	parexe_	karexe_	pareke_	Apocope
	(ˈpare)(ˌxe)	(ˈkare)(ˌxe)	(ˈpare)(ˌke)	Footing
	(ˈpar_)(ˌxe)	(ˈkar_)(ˌxe)	(ˈpar_)(ˌke)	Syncope
	(ˈparʲ)(ˌxʲe)	(ˈkarʲ)(ˌxʲe)	(ˈparʲ)(ˌkʲe)	Other Processes
	[parʲxʲe]	*[karʲxʲe]	*[parʲkʲe]	SR
	⟨pairche⟩	⟨cairche⟩	⟨paircɛ⟩	Orthography

Less specific inferences about dates of entry can also be drawn. Remaining within the loans that retained Latin [p], there are cases where lenition was not applicable, but later processes were, so we conclude that the loan could have entered Irish after the end of [p]→[k] and before the end of whichever process applied. For instance, vowel harmony is partially responsible for Latin [stupː-a] 'flax-FEM.NOM.SG' appearing as Irish [sop] ⟨sopp⟩ 'wisp' (McManus 1983:37), forcing the conclusion that the loan entered after the end of [p]→[k] but before the end of vowel harmony. A roughly contemporaneous minor process of [st] cluster simplification (see appendix section A.4.2) also applied, as did the later process of apocope, as is illustrated in (10).

(10)	stupː-a	Latin
	/stup-aː/	Irish UR
	X	[p]→[k]
	supaː	[st] cluster simplification
	sopaː	Harmony
	sop_	Apocope
	[sop]	SR
	⟨sopp⟩	Orthography

It is of course also possible for a loan to not be bracketed by starting and ending information. For instance, the only useful dating criterion in Irish [ofʲ_ɾʲənd] ⟨oifrend⟩ 'office of the Mass' from Latin [ofːerendum] (McManus 1983:62) is syncope. In such a situation we can only conclude that the loan entered sometime prior to the process that applied. Furthermore, nearly a quarter of our data is like Latin [oleum], which was eligible for no informative changes en route to becoming Irish [ole] ⟨olae⟩ 'oil' (Stokes and Strachan 1901:410, Ml 121c4). Such loans are maximally undetermined, and so could have entered at any point during our timeline. We provide the distribution of loans across all possible date ranges in (11).

(11)

	Loans that entered from the end of…						
Until…(↓)	—	[p]→[k]	Lenition	Harmony	Shortening	Comp. Len.	Syncope
[p]→[k]	18						
Lenition	47	3					
Harmony	36	4	10				
Shortening	32	5	13	0			
Comp. Len.	17	1	1	1	0		
Syncope	5	1	8	0	2	0	
Post-Syncope	129	27	59	12	20	10	70

In the next section we describe how the structural descriptions of the Irish processes furnish the phonotactic frequency parameters for the fitness measure in our search algorithm.

4.2 From Phonology to Fitness Measure Parameters

Recall from section 2.3.1, that in the search algorithm the fitness measure evaluates the degree to which the loans assigned to each time period match the phonotactic trends of Latin. This is done by tabulating whether or not each Latin source word in a period matches each member of a set of phonotactic statements, and then calculating the probability that the number of matches would be observed, given the number of words in the period and the rate at which the phonotactic configuration appeared in Latin. The observed rates were calculated from a database of Latin nouns provided by Adam Albright, featuring the 1,965 nouns with a lemmatized frequency count of 5 or greater in a corpus of approximately 800,000 words (see Albright 2005:29-30).

In principle, we could track any phonotactic property of Latin in our fitness measure. However, our data is structured by the structural descriptions of Irish phonological processes, since the possible dates of entry for loans are determined by which Irish phonological processes the loans were eligible for. Consequently, it is best if the model at least tracks the phonotactic statements that diagnose membership in phonological periods. Failure to track these statements will make the model less sensitive to the fundamental factors for assigning loans to periods.

For the sake of simplicity, we track only these phonotactic statements. This results in a total of eleven parameters. Six of these parameters track the major phonological developments mentioned in section 4 ([p]→[k], lenition, harmony, shortening, compensatory lengthening and syncope). Three parameters track the minor processes ([f]→[s], [st→s], and modifications to clusters that were ultimately re-legalized by syncope). Two additional parameters accommodate sub-cases of [p]→[k] ([pt] clusters) and lenition (post-vocalic [b, d, g, m]) that required special treatment in assigning dates to loans, as discussed in the appendix.

4.2.1 Adjustments for Parameter Overlap

Ideally, the parameter set would be sufficient if it directly represented the structural descriptions of these processes. However, syncope, harmony, and shortening all have polysyllabic contexts, and thus are positively correlated with each other in Latin. Specifically, syncope occurs in roots of three or more syllables, while harmony and shortening occur in roots of two or more syllables.[10] This overlap means that words that match the structural description for one process are disproportionately likely to match for the other two.

[10]Strictly speaking, harmony can be detected in monosyllabic roots due to the original presence of suffixes that subsequently underwent apocope, but harmony is still heavily slanted towards polysyllables.

The search algorithm operates under the assumption that fitness parameters are independent of each other, so potential violations of this assumption must be addressed. We address this by creating an adjusted parameter set to be used for comparison with the unadjusted parameter set, which represents all structural descriptions faithfully. The next section will show that the adjusted parameter set addresses a real concern, but ultimately in the loan data excessive overlap in the unadjusted parameter set is not observed. Nonetheless, the difference between the adjusted and unadjusted parameter sets does produce minor differences in the estimates produced by the model, so both sets of results will be reported in section 5.

The adjusted set attempts to remove overlap between parameters. For instance, the sequence [agl] satisfies the structural description for lenition because it has a post-vocalic stop, and also satisfies the structural description for compensatory lengthening because the post-vocalic [g] precedes [l]. For the adjusted parameter set, we carve out exceptions from the more general structural description so that there is no overlap. Extending our example, post-vocalic stops preceding [l, n, r, m] are excluded from lenition, and are only counted towards compensatory lengthening. Additionally, the adjusted set broadens the parameters tracking harmony and shortening to look only for the targets of the processes (non-low short vowels in initial syllables for harmony, and long vowels for shortening), without imposing conditions on neighboring syllables. This ensures that only the syncope parameter directly tracks polysyllables.

4.2.2 Validation

With the parameters in hand, the appropriateness of the modeling strategy and the parameter sets can be assessed. Recall that the model rests on the central assumption that loan words may be treated as random draws from the phonological lexicon of the donor language, ignoring how borrowing is motivated by a need for new words for new concepts. If this is true, the phonotactic trends of the donor language should be mirrored in the loan vocabulary. As shown by Figure 2, the rates of attestation for the phonotactic parameters in the Latin lexicon closely predict the rates of attestation in the loan corpus. Indeed, the points in the graph frequently lie almost on the white dashed line representing perfect agreement with the rates in the Latin lexicon, though the rate in loans is slightly under the rate in Latin.

Figure 3 illustrates the correlations between parameters in the adjusted and unadjusted sets. Specifically, the figure plots the portion of words that match the conjunction of pairs of parameters against the expected portion of matches assuming independence between the parameters. The correlations in the Latin lexicon and the loan corpus are broken out into separate panels.

Examining the Latin lexicon (top panel of Figure 3), the concern over correlation in the unadjusted parameters is valid, and the adjustments to the parameter set are effective. As expected, a subset of the unadjusted parameters are positively correlated with each other, as shown by the upward bend in the solid line. This upward bend is not observed for the adjusted parameters, indicating that the adjustments were generally successful. The downward bend for the adjusted parameters at the right edge of the plot is driven by one pair of parameters, which is a tolerable idiosyncrasy for present purposes.

Despite the overlap seen in the Latin lexicon, this is not observed in the loan vocabulary. In the loan data (bottom panel of Figure 3), the upward bend in the unadjusted parameters is not present, and in general both parameter sets show slightly negative correlations. We suspect the trend towards negative correlations stems from the slight trend towards under attestation of the parameters in the loan data relative to the observed rates in the Latin lexicon (illustrated in section 4.2.2). While the loan vocabulary is not a perfect facsimile of the Latin lexicon, the fit is so close that no further modifications to our parameter set are necessary.

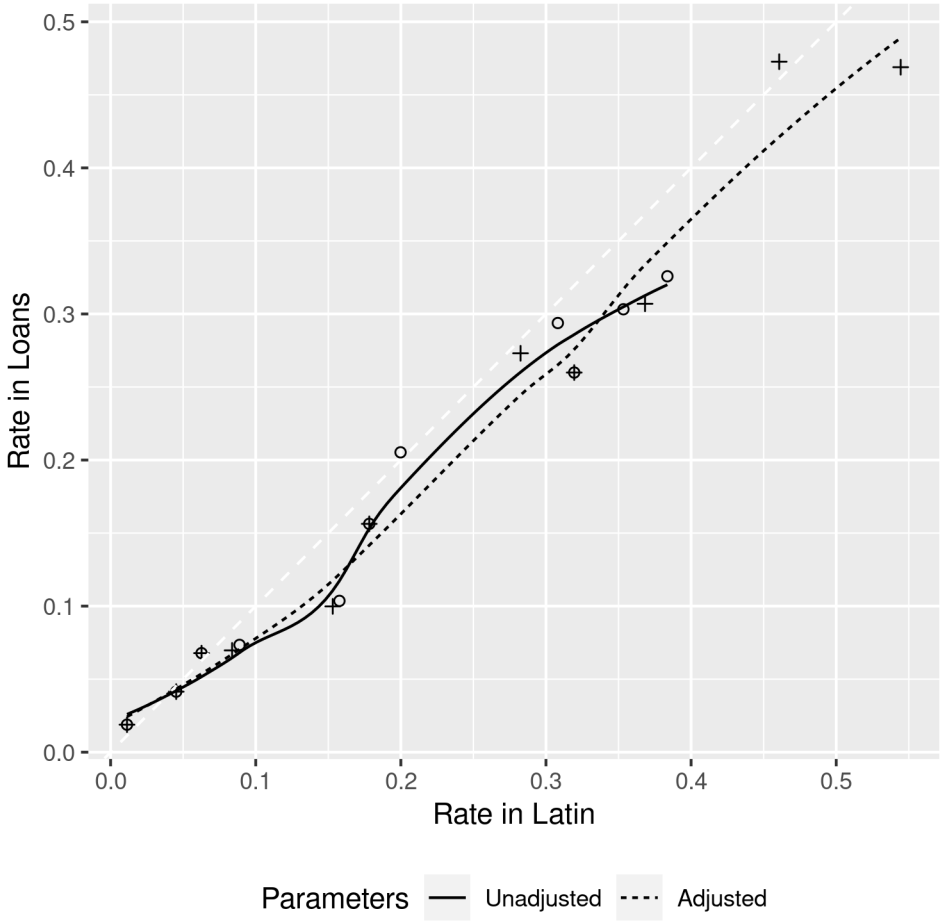

Figure 2: Portion of loan vocabulary that matches phonotactic statements in the loan vocabulary against the portion of matches in the overall Latin vocabulary, for each parameter set. Circles mark unadjusted parameters (summarized with a solid line), while crosses mark adjusted parameters (summarized with a black dashed line). The dashed white line marks perfect agreement between Latin and the loan vocabulary.

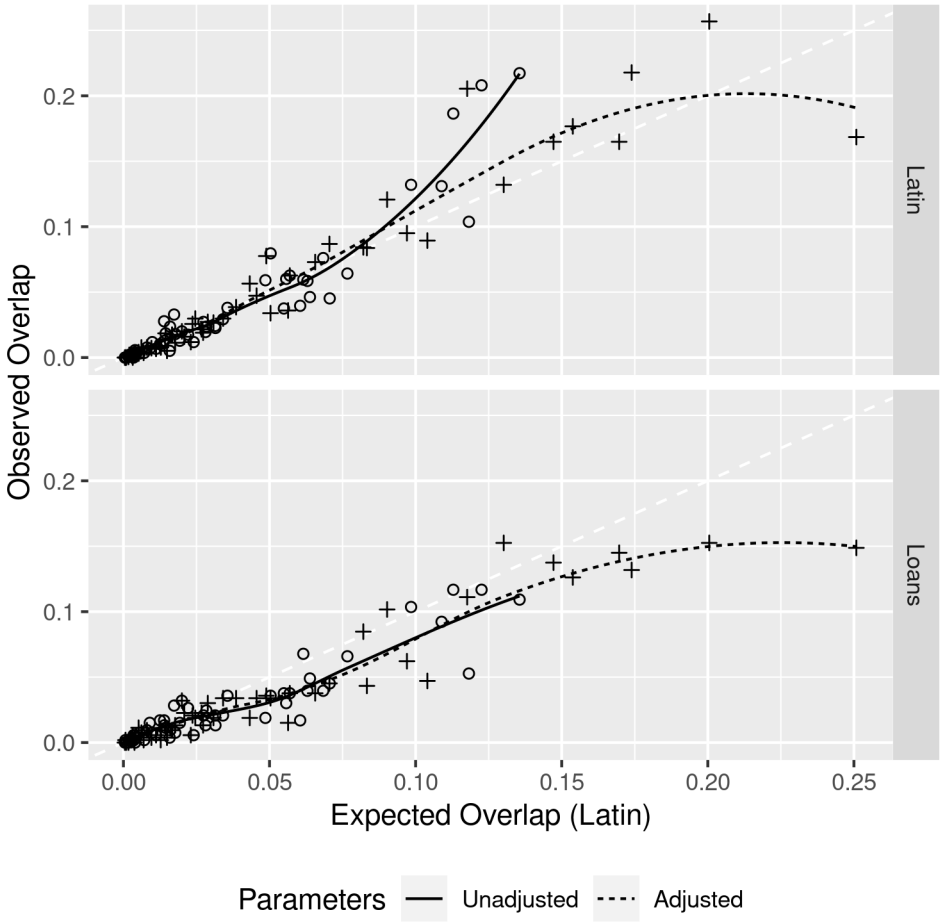

Figure 3: Portion of vocabulary matching both members of a pair of phonotactic expressions, for both the Latin nominal lexicon and the loan vocabulary, plotted against the expected amount of overlap given the raw probabilities obtained from the Latin nominal lexicon and the assumption that phonotactic expressions are independent of each other. Circles mark parameter pairs from the unadjusted parameter set (summarized with a solid line), while crosses mark parameter pairs from the adjusted parameter set (summarized with a black dashed line). The dashed white line marks perfect agreement between the expected amount of overlap and the observed amount of overlap.

5 Timeline Estimation Results

We report the results of 20 simulations, 10 simulations each for the adjusted and unadjusted parameters. The two sets of parameters behave similarly in the simulations. In simulations using the adjusted parameter set, a small number of words were shifted from the harmony period to the post-syncope period of the language, but the results were otherwise identical (see Figure 4). This is likely due to the relaxation of the harmony parameter in the adjusted parameter set, which made it possible to balance the population of the harmony period with fewer loans. Beyond the need for flexibility in gauging the duration of the harmony period and the post-syncope period, we assign no special significance to this divergence, and take the general agreement between the parameter sets to be an encouraging result.[11]

A more instructive comparison pits the estimates produced by the phonotactic balance model against a naive model, which evenly allocates loans between the periods in which they could have entered Irish. This results in a fairly equal allocation of loans to each period, as shown in (12). Such a result would be expected if the rate of borrowing was constant and all periods had the same duration.

(12)

Naive Baseline Allocation						
[p]→[k]	Lenition	Harmony	Shortening	Comp. Len.	Syncope	Post-Syncope
84.16	77.78	79.91	61.41	52.92	53.42	121.40

Figure 4 shows that the phonotactic model and the naive model diverge radically for the shortening, compensatory lengthening, and syncope periods, with only a very small number of loans being assigned to these periods under the phonotactic balance model. The likely reason that the simulations and the naive model diverge is that different periods have relatively more or fewer loans that must enter during or around that time. Most prominently, as shown in (11), 70 loans can only enter during the post-syncope period, primarily because they were eligible for syncope but failed to undergo it. Since around a third of the Latin vocabulary was eligible for syncope, balance on the syncope parameter is achieved if the post-syncope period receives around 140 loans that are not eligible for syncope. This is the the lion's share of the 257 loans that are eligible to enter before or during the post-syncope period. With such a strong claim being staked for so many loans, the remaining periods are left to search for scraps.

Approaching the question from the opposite angle, (11) shows that only three loans are constrained to enter during the span encompassing the post-harmony shortening period and the syncope period, while the [p]→[k], lenition and harmony periods are much better attested. In the competition for limited loans, the earlier periods thus won out over the post-harmony shortening, compensatory lengthening and syncope periods.

6 Discussion

Figure 4 shows something of a zigzag pattern, with many loans entering during the [p]→[k], harmony and post-syncope periods, and vastly fewer loans entering during the lenition, post-harmony shortening, compensatory lengthening and syncope periods. Setting aside the small number of loans in the lenition period, which have a benign explanation (see section 6.1.1), this revives a view of the Latin loans that

[11] Other variations of these simulations were run with little effect on the results. Since we excluded some potential loans featuring productive Latin morphology that does not exist in Irish (see section 3.2.1), we constructed an alternative corpus that included these words. The result was that the post-syncope period received more words. Another variation changed the dating criteria to allow words featuring Brittonic lenition to enter alongside, instead of after, loans showing Irish lenition (see the appendix section A.3). This resulted in the lenition and harmony periods having roughly equal numbers of loans assigned to them.

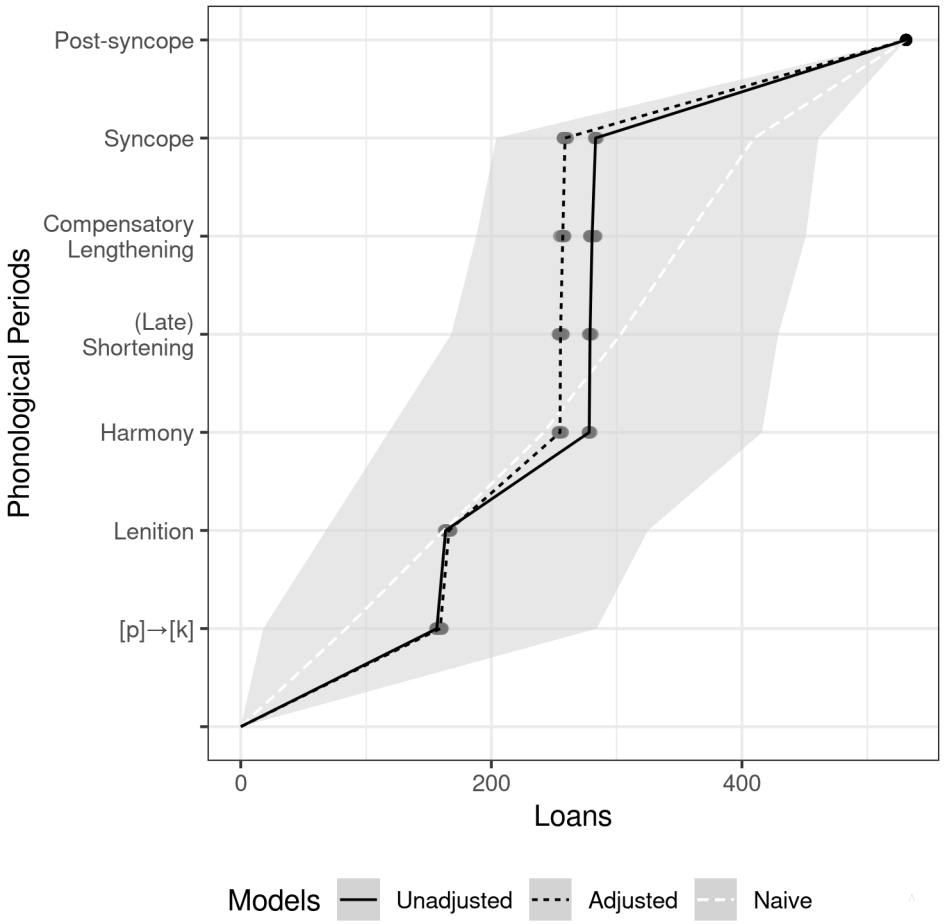

Figure 4: Phonological periods over number of accumulated loans. Lines connect the mean value over 10 simulations for each period in the adusted and unadjusted models; the naive model values (white dashed line) were obtained by direct calculation in (12). Points represent allocations for individual simulations, and are semi-transparent to overcome overplotting. The gray background shape demarcates the possible space of loan allocations.

was thought to be defunct. Early work recognized two groups of loans, roughly a pre-syncope and a post-syncope group (Sarauw 1900, MacNeill 1931, Thurneysen 1946:565-576, Jackson 1953:122 ff.). McManus (1983:32), citing historical evidence of continuous contact and the existence of loans that entered before some processes but after others, argued for continuous borrowing, which could be compatible with more or less equal numbers of loans entering at any particular time. Our simulations follow McManus's phonological methodology but they still find a gap between two groups of loans by dint of greater computational effort and sensitivity to phonotactic trends in Latin.

Any period with few loans attributed to it can be explained by (a) a reduced rate of borrowing from Latin, (b) the period having a short duration relative to the more well populated periods, or (c) a combination of the two. We refer to the first explanation as the 'reduced rate' hypothesis, and the second as the 'brief blip' hypothesis.

The reduced rate and brief blip hypotheses are difficult to conclusively disambiguate. Nonetheless, the available evidence points to consistent, and increasing, contact between Irish and Latin, as the Christian community expanded, founded monasteries and churches, and Irish settlements were formed in Britain (see Bauer 2015:5-8 for a recent review of the Irish presence in Britain). This leads us to emphasize the brief blip hypothesis.

6.1 Brief Blip Hypothesis

A period can be a brief blip either because part of its active period overlapped with the prior period, or because the process itself only lasted for a short time. Overlaps are possible because we can generally only detect whether a loan enters before or after the end of a period. Concretely, a loan that underwent lenition, like Irish [baxə̲l] ⟨bachall⟩ 'staff', from Latin [bakul-um] entered some time before lenition ceased, while a loan like Irish [par$^{\text{j}}$x$^{\text{j}}$e] ⟨pairche⟩ 'parish' from Latin [pareːkia] entered after [p]→[k] but before the end of lenition. In contrast, no loan can bear signs that would disentangle when lenition began relative to the end of [p]→[k]. As a result, our periodization only truly marks the end of a period and the end of the next. Unless the onset of one process terminates the application of the prior process, we do not have information on the beginning of a period. The phonological periods that we discuss are thus best understood as the periods where a process applied independently of the prior process, leaving open the possibility that the process and the prior process overlapped for some amount of time.

On the other hand, a process may simply be short lived, possibly because it is difficult to learn. Implicit in this reasoning is the idea that language change may inform phonological theory, since phonological theories differ in what patterns are predicted to be difficult (McCarthy 2007, Bakovic 2007; 2011). However, the external evidence of what patterns are not learned can be mixed. Opaque phonology is often argued to be difficult to learn (Kiparsky 1971, Sanders 2003, Zhang, Lai and Sailor 2009, 2016; 2019, Kawahara 2015; 2015, Nagle 2020), but learners have also evidently made errors with transparent phonology (Hale 1973; 1991) and there are documented cases of robust opacity (Jurgec 2019, Andersson 2018).

In light of this controversy, explanations via overlap should have preference over appeals to brief duration, all else being equal. This is the case for the low numbers of loans assigned to the lenition period and the post-harmony shortening period, as we will show in section 6.1.1. However, for the compensatory lengthening and the rhythmic syncope periods, overlap is tenuous or impossible to maintain, forcing an explanation via brief duration in section 6.1.2.

6.1.1 Brief Blips via Overlap

The low population of loans in the lenition period is easily explained by overlap with the [p]→[k] period. As shown in Figure 4, the population of the lenition period is dwarfed by the population of the [p]→[k] period. There is nothing that weighs against lenition existing for some time while [p]→[k] was still active. In this scenario, [p]→[k] overshadowed lenition, getting credit for loans that entered while both processes were active. If lenition only applied independently for a short while after [p]→[k] ceased, it would not have had substantial time to accrue loans to its own account.

Lenition was a chain shift (see the appendix), and a chain shift in Modern Bengali has been shown to be underlearned (Nagle 2020). This could certainly have helped bring about the end of lenition, but we do not know how quickly or in what circumstances this underlearning is manifested. If such details can be determined, it may be possible to estimate how long lenition was active in Irish.

Overlap is also the likely reason that the shortening period has few loans attributed to it. It is already believed that shortening began before the end of harmony, since there are long vowels that underwent shortening and thus became eligible for harmony. As discussed in the appendix, harmony applied to these shortened vowels, which would be expected if shortening overlapped with harmony.

The only additional stipulation suggested by the model results is that the post-harmony shortening period must have been short. Assuming that the development of compensatory lengthening ended shortening (McManus 1983:56, see the appendix for more discussion), this is tantamount to moving the onset of compensatory lengthening and the end of harmony towards each other.

One benefit of the overlap scenario is that it relaxes the tight timeline of phonological developments, which had several major processes developing within approximately 100 years (see Figure 1). With leniting loans being overwhelmingly assigned to the [p]→[k] period and the end of lenition coming shortly after the end of [p]→[k], it may be possible to move the estimated date of lenition closer (or even prior) to the Palladian mission of 431 CE, instead of the current estimated date of 450 CE. Though approximately twenty to thirty years is a modest adjustment on an absolute scale, this is a substantial portion of our period. See Figure 5 below for an illustration of how the loan populations may be mapped to period durations in absolute time.

6.1.2 True Brief Blips

This section establishes that compensatory lengthening and rhythmic syncope cannot be brief blips due to overlap, and so they must have been only a flash in the pan. In the case of compensatory lengthening, this could have been due to syncope creating clusters that were eligible for compensatory lengthening, but that failed to undergo it. As for rhythmic syncope, subsequent opacity is also not out of the question, but recent literature has shown that a rapid rise and fall may be a trait of rhythmic syncope systems.

The low number of loans assigned to compensatory lengthening and rhythmic syncope cannot be attributed to overlap with a prior period. This is because the nearest populated period before these processes is the harmony period, but compensatory lengthening and rhythmic syncope cannot be easily made to overlap with the harmony period. At best, as discussed in the appendix, the beginning of compensatory lengthening may have overlapped with the end of shortening, and since harmony overlapped with the beginning of shortening, it is logically possible that compensatory lengthening and harmony may have overlapped. Nonetheless, this tenuous overlap between compensatory lengthening and harmony could not have covered the bulk of the compensatory lengthening period, since compensatory lengthening must have persisted after the end of shortening. Since rhythmic syncope occurred later still, overlap also cannot explain the dearth of loans attributed to rhythmic syncope.

The rapid onset and decline of compensatory lengthening could be due to a dearth of alternations to support learning the process or the rapid arrival of counterevidence from syncope. Compensatory lengthening may have been difficult to learn, since there were few alternations in Irish to support the existence of an underlying cluster after a surface long vowel (see the appendix for further discussion).[12] Compensatory lengthening could also have been ended abruptly by rhythmic syncope developing shortly after it. Rhythmic syncope created a large number of consonant clusters in surface forms that matched the target for compensatory lengthening but were not simplified. Children encountering this data would thus have had apparent counterevidence against compensatory lengthening and could have failed to learn it.

Rhythmic syncope may have begun and ended quickly of its own accord, since it has been a brief blip in other languages. The modern Algonquian language Nishnaabemwin began rescinding rhythmic syncope alternations within the space of a generation (Bowers 2019 and references therein). Furthermore, in Mojeño Trinitario, rhythmic syncope developed sometime between 1898 and 1957, but it is no longer productive in the modern language and it fails to apply to approximately 40% of eligible vowels (Rose 2019).[13] Isačenko (1970, see especially pp. 95-6) argues that rhythmic syncope in Eastern Slavic collapsed immediately after it arose. In Southern Pomo, dates for the development of rhythmic syncope are not available, but Kaplan (2020; 2022) highlights innovative deletion patterns that suggest speakers carried out a re-analysis. It is not known whether all cases of rhythmic syncope are intrinsically unstable and only persist for the blink of an eye, but Irish would be in good company if rhythmic syncope were only a flash in the pan.

If the quick collapse of parallel rhythmic syncope cases is not accepted as evidence that Irish syncope was intrinsically short lived, it is also possible to attribute the collapse of syncope to subsequent opacity. After syncope occurred, epenthetic vowels were inserted before sonorants that were not adjacent to vowels. This can be seen in the native word †[forkʲedl] 'teaching', which became [forkʲədəl] ⟨forcedal⟩ (Thurneysen 1946:70) and did not undergo syncope to become *[(ˈforʲkʲ_)(ˌdʲəl)] ⟨forcdal⟩. Examples such as these may have undermined rhythmic syncope in time to prevent many words from being borrowed during the syncope period.[14]

6.1.3 Local Summary

The lack of loans in the lenition and shortening periods can be plausibly explained by overlap with preceding periods, while compensatory lengthening and rhythmic syncope must be true brief blips. This has important implications for the absolute timeline of developments in this period. Figure 5 integrates these interpretations into a single timeline where loan population is mapped directly to period duration, with the end of [p]→[k]

[12]Despite being a subjectively natural sound change, compensatory lengthening requires reference to a deleted entity and so is not amenable to surface oriented parallel evaluation. Rather, it requires either step-wise derivations (Samko 2011, Torres-Tamarit 2016), or possibly direct reference to underlying forms in the spirit of Chandlee, Heinz and Jardine (2018). A similar, but not identical, state of affairs holds for rhythmic syncope (see Hao and Bowers 2019, or the less technical discussion in Bowers and Hao 2020). If these properties strain or exceed the capacities of human language learners, it is possible that compensatory lengthening and rhythmic syncope are intrinsically difficult to learn.

[13]The failure of rhythmic syncope to apply in large swaths of the Mojeño Trinitario vocabulary is reminiscent of what is reported for the Tonkawa lexicon in Hoijer (1949). Strikingly, Hoijer's (1933; 1946) description also suggests that the morae of deleted vowels were preserved via consonant lengthening, in much the same way as Rose (2019) proposes for Mojeño Trinitario. See also Rose (2014) for a robust class of morphological exceptions to syncope. Note that further research has shown that classifier suffixes in Mojeño Trinitario are not wholly immune to syncope, contrary to what is claimed in the paper (Françoise Rose, p.c.).

[14]There is a multitude of examples showing that this epenthesis also targeted sonorants that were in clusters created by syncope as well. For instance, we find an epenthetic vowel in the loan [egʲəlʲsʲ-e] ⟨egilse⟩ 'church-GEN' (Thurneysen 1946:70) from syncopated †[(ˈegl_)(sʲ-e)], borrowed from Greek via Latin [ekleːsi-a] 'church-FEM.NOM.SG. Syncope would have had to have been already defunct for epenthesis in this environment to materialize. However, we do not know whether epenthesis into word final clusters triggered the end of syncope before epenthesis spread to word medial clusters, or if both environments were targeted in one fell swoop, which would be possible if syncope were intrinsically short lived.

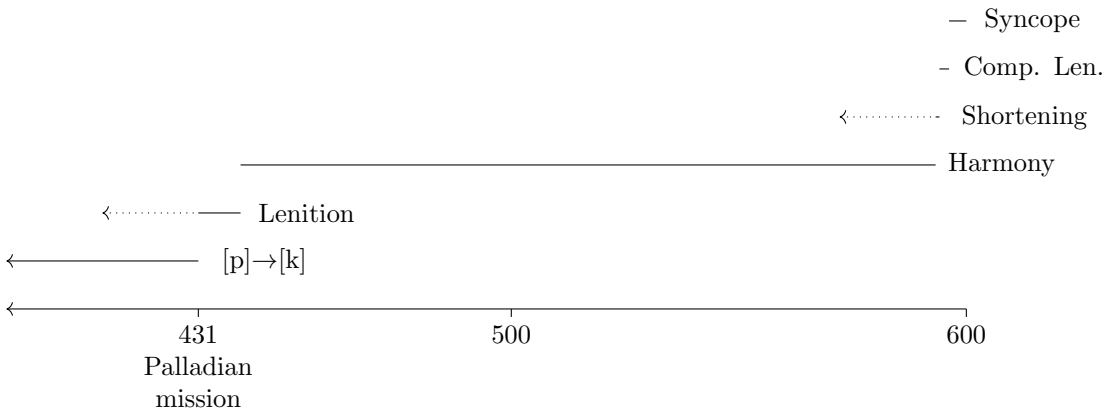

Figure 5: Timeline of phonological period duration if loan allocations from the unadjusted model correspond only to period duration. The end of [p]→[k] and syncope are arbitrarily set to 431 and 600 CE, respectively. Dotted lines mark periods where we explicitly posit overlap with a prior process, solid lines mark periods of independent application.

and syncope being arbitrarily set to 431 CE and 600 CE, respectively.

The dates in Figure 5 are not certainties, and they could be revised to reflect the adjusted parameter set, different termination dates, the development of apocope, the reduced rate hypothesis, or other factors. However, they should not be rejected out of hand. In particular, allocating a mere breath of time to the rhythmic syncope period is not out of the realm of possibility if it touched off a learner-driven morphophonological restructuring as in modern Nishnaabemwin (Bowers 2019, Rhodes 1985). To be clear, the innovation of rhythmic syncope involves a cohort of speakers with such severe reduction that it is prone to be analyzed as categorical deletion. Under the strongest reading of the modern Nishnaabemwin events, once severe reduction crossed into incipient rhythmic syncope, a cohort of speakers with restructured grammars emerged. In our Irish case, recent loans where accessible Latin originals were still in circulation would be prone to be adapted without syncope by these speakers with restructured grammars. As a result, the mark of syncope in the loan data would end scarcely after it started, even while the speakers with incipient rhythmic syncope were still alive. At the risk of redundancy, similar instability for compensatory lengthening need not be assumed, since the short duration of compensatory lengthening could be a consequence of rhythmic syncope developing shortly after it.

Importantly, these conclusions are only as strong as our confidence that the rate of borrowing was constant. The next section discusses whether there is reason to believe that the rate of borrowing dropped.

6.2 Reduced Rate Hypothesis

The overriding concern at this juncture is whether the lack of loans during the syncope and compensatory lengthening periods can be explained without recourse to the potentially controversial brief blip hypothesis, since the shortening and lenition periods can be benignly attributed to overlap. Of course, the number of loans that enter during a period depends on the rate of borrowing as well as the duration of the period. A reduced rate of borrowing can occur due to a break in cultural contact, or saturation of the vocabulary needs of the borrowing language. More insidiously, borrowing may carry on unperturbed but the loan

words may simply not be nativized, making their entry undetectable by our phonological method. The availability of both the brief blip and the reduced rate hypotheses introduces a fundamental uncertainty into the interpretation of loan word allocations. We cannot fully resolve the ambiguity, but every potential reduced rate scenario has at least some difficulties. As a result, we advocate for cautious acceptance of the brief blip hypothesis.

6.2.1 Lack of Contact

Lack of contact with Latin was dismissed by McManus (1983:32), and there is no need to revise his argument. The available evidence shows that Ireland enjoyed increasing cultural contact with the Latin speaking world through the fifth, sixth and later centuries (Moore 1970, Thomas 1971, Laing 2006). During this time, Christianity spread in Ireland, monasteries were founded and increasing numbers of students were formally trained in Latin.

It may be tempting to point to the traditional date for the fall of of the Western Roman empire in 476 CE as sufficient evidence of cultural turmoil during the shortening-syncope period. However, this is a red herring, primarily because Ireland was outside the Roman empire and Irish contact with Latin was through the Christian church. Importantly, the Christian church was relatively untroubled by the military breakup of Rome (Brown 1989). Furthermore, the actual dates for the decline of the Roman empire in the neighborhood of Ireland do not align well with this period, since imperial Roman authority ceased in Britain in 410 CE, and was tenuous in Gaul even before it catastrophically collapsed in 455 CE.

6.2.2 Vocabulary Saturation

One possibility is that demand for loans became saturated. That is, once all of the new words that were useful for a growing Christian community had been borrowed, there would be no need for additional terms (see McManus 1983:25 for discussion of similar speculation on when particular concepts would need to be borrowed). The chief obstacle to this explanation is that both the pre-syncope and post-syncope loans are predominately ecclesiastical, indicating that demand for Christian words was not satisfied. Indeed, the most remarkable thematic division occurs within the earliest loans, where a number of terms for trade items can be found (McManus 1983:43-45).

6.2.3 Non-Nativization

A close cousin of changes to the supply or demand for loans is a failure to nativize loans. Since non-nativized words escape diagnostic phonology, they would be especially likely to be assigned to the final period in the simulation, even if they potentially entered earlier. This scenario quite likely applies at least to some extent for the Latin loans in Irish. The post-syncope loans are predominately literary, and most likely entered Irish through formal scholastic settings using written Latin. The cultural setting also matches the lull in borrowing around the syncope period, since monastic communities were established throughout the sixth century.

However, it is not completely straightforward to assume that putatively post-syncope loans entered during or before the syncope period. This is because the later loans were not completely immune to native phonological processes. An especially prominent adaptation that features throughout the later loans is palatalization, which dates from the pre-harmony era and is an enduring feature of even Modern Irish. The later loans are also rife with vowel quality reduction, a probable post-syncope development. It would be remarkable for loans to enter during the heyday of rhythmic syncope and undergo contemporary or later processes, but still escape syncope. A more cogent view is that the apparently post-syncope loans entered

after syncope, phones were mapped into the palatalization system as they entered, and once vowel quality reduction developed, it applied to the new loans.

Assuming that the compensatory lengthening and rhythmic syncope periods were not brief blips but were actually populated by non-nativized loans also comes at a cost. The simulation results divide the loans roughly equally into a pre-syncope and a post-syncope group, and the pre-syncope and post-syncope borrowing periods both cover around 200 years (see Figure 1). This would be consistent with a generally stable rate of borrowing. Padding the compensatory lengthening period and the syncope period with apparently post-syncope loans necessarily reduces the number of loans attributed to the post-syncope period. If the padding is used to move the start dates of compensatory lengthening and syncope earlier, there must be a corresponding explanation for why borrowing decreased during the post-syncope period. If the padding is used to extend the end dates of compensatory lengthening and rhythmic syncope later, the analysis must contend with evidence from the manuscript record indicating that these processes were prone to apparent exceptions and had lost productivity (Thurneysen 1946:68-69), including in texts dating from the 7th century (see for instance McManus 1986:2-4, fn. 5 on the name *Fechureg*).

7 Conclusion

We have defined a procedure using simple phonotactic statements to estimate the number of loans that entered a language during a sequence of phonological periods. The results can be interpreted under the brief blip hypothesis, which concerns the learnability and productivity of phonological processes, and so can inform phonological debates. It is dogged by the reduced rate hypothesis, a competing, but not mutually exclusive, explanation for a lack of loans in a period. Depending on the availability of further cross-linguistic or cultural evidence, these hypotheses enable rough conclusions to be drawn about the intensity of contact or the duration of the phonological periods in a language. We expect that this methodology could be productively applied to other cases of sustained contact, including Sanskrit or Mandarin loans into neighboring languages.

The loan allocation procedure was illustrated with the Latin loans in early Irish. The model spreads an early group of loans over several periods, before entering a pronounced lull during the shortening-rhythmic syncope phase, and finally resuming borrowing in the post-syncope period. The small numbers of loans placed in the compensatory lengthening period and especially the rhythmic syncope phase are especially noteworthy for phonological theory. These small numbers suggest that compensatory lengthening and rhythmic syncope quickly ignited and burned out, either due to subsequent opacity or intrinsic instability. Importantly, the reduced rate hypothesis could still be true despite the objections raised to the various scenarios in sections 6.2.1-6.2.3, since we do not have direct evidence of what occurred in early medieval Ireland. Nonetheless, it is worth noting that the opposite result does not hold, where large numbers of loans were allocated to rhythmic syncope and the other processes. Such a result would have been a strong sign that these processes persisted for an appreciable amount of time.

A Major Processes in Loans

This appendix provides a more thorough description of the processes that provide dates for Latin loans. We give special attention to loans that can be limited to a single period because the corresponding process applied even though the immediately preceding one did not apply. These loans are important because they establish that the bins used in our simulations are discrete.

This is not an exhaustive treatment of Old Irish phonology, or even the phonology that developed during the period between [p]→[k] and syncope (see the sources referenced in section 3 for fuller discussion). We limit ourselves to the phonology that has a clear division between application and non-application in loans. Processes that did not cease to apply during the loan period cannot be used to obtain dates of entry and so are not relevant for our simulations. In particular, palatalization and apocope (whether Irish apocope or the more aggressive British apocope) applied in all loans and so do not distinguish classes of loans from each other. For our purposes, we have elected to simply ignore palatalization and apocope, though a more sophisticated approach may be possible. More generally, while it is clearly of great interest to understand why some phonological processes cease to apply while others continue, such questions lie beyond the scope of this paper. We simply apply the evidence supplied by the loans to draw inferences about the existence of discrete phonological periods and the number of loans that accrued during the periods.

This appendix is organized as follows. Section A.1 gives a brief overview of our practice of replacing Latin case suffixes with Irish ones. The rest of the appendix proceeds essentially chronologically, with sections A.2-A.7 discussing the [p]→[k] process, lenition, harmony, shortening, compensatory lengthening and syncope.

Our data reflects additional processes besides the relevant ones discussed here (see McCone 1996 ch. 3-4), most prominently palatalization and the later reduction of word-medial syllables or closed word-final syllables. These orthogonal processes are included in derivations to preserve the relationship with the observed orthography, but further attention will not be given to them.

A.1 Suffix Substitution

One of the initially more surprising aspects of the Latin loans in Irish is that roots, rather than whole inflected words, were borrowed. We know this because many loans show phonological effects that would only be possible if Latin suffixes were removed and Irish suffixes applied in their place (McManus 1984). The key phonological process responsible for this is a harmony process targeting vowel height, described in further detail in section A.4. The evidence for suffix substitution setting up the harmony environment is somewhat indirect because by the time these loans were captured in writing, an apocope process had been developed, which counter-bled the harmony process by removing the suffix.

By way of example, the original Latin form [kipː-us] 'stump-MASC.NOM.SG' is harmonic for vowel height, so we would not expect to see any changes to the root vowel if it was borrowed into Irish with the Latin suffix. However, vowel harmony appears to have lowered the root vowel in Irish, as seen in [kʲep] ⟨cepp⟩ (McManus 1983:37). The solution to this is that Irish speakers applied the native case suffix [-as] or its later lenited variant [-ah] to this word. The result was a disharmonic sequence †[kip-as] or †[kip-ah] 'stump-MASC.NOM.SG'. The disharmonic sequence was repaired as illustrated in (13). In light of examples like these, we substitute Latin suffixes with the appropriate Irish suffix in examples.

(13)

kipː-us	Latin
/kip-as/	Irish UR
kipah	Lenition
kepah	Harmony
kep_	Apocope
kʲep	Other Processes
[kʲep]	SR
⟨cepp⟩	Orthography

Ultimately, suffix substitution reveals an ability to morphologically parse Latin words and assign new

words to declension classes. We do not attempt to explain which morphological classes loans were assigned to in this paper, though this is an interesting question worthy of further pursuit. The ability to parse Latin words may not be highly surprising, because early Irish was an obviously close cousin of Latin, Greek and Sanskrit. More to the point, however, it is well known that educated Irish speakers of the early medieval period were steeped in grammatical learning and possessed a highly developed literacy in Latin (Law 1982, 1997, Esposito 1988, Johnston 2013, Hayden and Russell 2016). This deep engagement with Latin and the general interest in linguistic modes of analysis on the part of the Irish probably played a role in the suffix substitution phenomenon.

More importantly, the evidence for morphological effects potentially clouds our ability to assign loans to particular time periods. As a reviewer suggests, the phonological analysis of loan adaptation presented here could be recast into a morphological one where Latin [kipː-us] 'stump-MASC.NOM.SG' was adapted to Irish [kep] to satisfy a constraint banning short [i] in the masculine singular of o-stem words (the class of words that took †[-as] as a masculine singular nominative case suffix as shown in (13)). While this is a cumbersome analysis, something like it may explain harmony alternations observed in the manuscript record, long after harmony had lost productivity under our account. The upshot for the current topic is that under a morphological account of loan adaptation, the application or non-application of harmony could often be due to morphological class assignment regardless of time of entry. Note that the morphological proposal predicts the same set of forms as a phonological analysis where underlying /kip-as/ underwent harmony. Absent a compelling reason in favor of the morphological account, we use the apparently simpler phonological analysis.

A.2 [p]→[k]

Several sound changes characteristic of Celtic languages resulted in Irish completely lacking /p/ prior to contact with Latin. As a result, Latin [p] was illegal in Irish and was replaced with [k] for some time, as illustrated by the adaptation of Latin [paːsk-a] 'Easter-NEUT.NOM.PL' in example (14), drawn from McManus (1983:48).[15] Eventually /p/ became a marginal phoneme of Irish (presumably due to sustained exposure to Latin, McCone 1996:129-130) and the [p]→[k] replacement was no longer enforced.

(14)	paːsk-a	Latin
	/paːsk-aː/	Irish UR
	kaːskaː	[p]→[k]
	kaːsk_	Apocope
	[kaːsk]	SR
	⟨cásc⟩	Orthography

When determining timelines, we conclude that a loan entered during this first period if Latin [p] is adapted as [k], its lenited variant [x] (except before [t], where [p] also changed to [x] in Vulgar Latin), or [ɣ], which is a later variant of [x] in unstressed syllables. Latin [p] that is adapted as [p] indicates that the loan entered after the [p]→[k] period.

A.3 Lenition

The adaptation of Latin loans was affected by a confluence of consonant lenitions that originated not only in Irish, but also in Brittonic and even Proto-Celtic (McCone 1996:81-98 and references therein, see Iosad

[15] The replacement of [p] with [k] is standardly analyzed as involving the following stages: [p]→[k^{w}]→[k]. In the shift from [k^{w}] to [k], the labial feature may be transferred to following short vowels. For details, see McCone (1996:118).

2022 for discussion of the modern morphological lenition systems of Celtic languages). Lenition in the Celtic family appears to have developed in three waves. The first wave mapped post-vocalic voiced singleton stops [b, d, g, m] to [v, ð, ɣ, ṽ] in an early ancestor of several attested Celtic languages. The second wave debuccalized post-vocalic [s, s^w] to [h] and †[h^w] in only Irish and Brittonic (†[h^w] ultimately became [f] in Irish and [xw] in the descendants of Brittonic). During the third wave, postvocalic voiceless stops [t, k] were spirantized to [θ, x] in Irish. In Brittonic, the stop inventory included [p] from †[k^w], and postvocalic [p, t, k] were voiced to [b, d, g] by the third wave of lenition.

The lenition of voiceless stops is the most useful for dating loans, since that is the only phase that not only is unique to Irish but is certainly contemporary with the period of contact with Latin. Irish spirantizing lenition is observed in many loans, as in example (15), which illustrates the adaptations of Latin [bakul-um] 'staff-NEUT.NOM.SG' to Irish [baxəl] ⟨bachall⟩ (Bieler and Kelly 2004 [1979]:176§13.5) and Vulgar Latin †[siːtul-a] 'vessel-FEM.NOM.SG' to Irish [s^jiːθəl] ⟨síthal⟩ (Lash 2021, S0050-82).

(15)	bakul-um	siːtul-a	(Vulgar) Latin
	/bakul-aː/	/siːtul-aː/	Irish UR
	baxulaː	siːθul-aː	Lenition
	baxolaː	siːθolaː	Harmony
	baxol_	siːθol_	Apocope
	baxəl	s^jiːθəl	Other Processes
	[baxəl]	[s^jiːθəl]	SR
	⟨bachall⟩	⟨síthal⟩	Orthography

In each section discussing a particular process below, it will be our practice to provide a derivation demonstrating that the process was active after the earlier processes. The separation between lenition and [p]→[k] was already shown by the derivation of [par^{j}x^{j}e] ⟨pairche⟩ 'parish' from Latin [parːekia] in (9), so we will not repeat it here.

Our general practice is to count loans that underwent Irish spirantizing lenition of [k]→[x] or [t]→[θ] as entering before the end of lenition, while loans that failed to undergo lenition of [t, k, b, d, g, m] are counted as entering after the end of lenition. This divergent treatment is primarily due to complications introduced by loans showing Brittonic lenition instead of Irish lenition, which we discuss in the next section. The divergent treatment is also required by the orthographic ambiguity between lenited and unlenited [m], which were often both written as ⟨m⟩, while unlenited [m] could be written as ⟨mm⟩. This means that it is only possible to detect some post-lenition cases of [m].

A.3.1 Loans with Brittonic Lenition

Even more prominent in the loan data is the application of Brittonic voicing lenition, as in Latin [paːtrikius] 'Patrick-MASC.NOM.SG', which appears as [paːdrəg^j] ⟨Pátraic⟩ (McManus 1983:69), with Latin [t] and [k] being mapped to [d, g], respectively. The appearance of Brittonic lenition in Latin loans to Irish is standardly attributed to Irish borrowing Latin loan words from British varieties of Latin. Because so many loans show Brittonic voicing lenition and because other evidence of close cultural contact is so strong (see Bauer 2015:5-8 and references therein), most Latin loans in Irish probably arrived via British Latin, though borrowing from Continental Latin can be difficult to rule out in all cases.

Since Brittonic lenition was not an Irish process, we cannot conclude that a loan showing its effects entered Irish before any particular point in Irish history. We can only be certain that loans showing Brittonic voicing lenition arrived in Irish after lenition happened in Brittonic. However, since Brittonic lenition redirected Latin [p] to [b], in order for [p]→[k] to be able to apply in Irish, we conclude that loans with

Brittonic lenition arrived after [p]→[k]. McCone (1996:92) further concludes that loans with Brittonic lenition entered after Irish lenition ceased to apply in loans. As the next sections will show, whether loans with Brittonic lenition entered Irish after [p]→[k] or after lenition is somewhat contingent on the status of geminates in Irish.

To foreshadow the ultimate result, simulations reflecting both a post-[p]→[k] and a post-lenition entry for words with Brittonic lenition were run. Simulations that assumed a post-[p]→[k] entry had an even allocation of loans between the harmony and lenition periods, and simulations that assumed a post-lenition entry had a small number of loans assigned to the lenition period, as reported in the main paper.

A.3.2 Late Brittonic Lenition Scenario

A straightforward interpretation of loans with Brittonic lenition of voiceless stops is that Irish lenition ceased to apply productively to new vocabulary, and that these loans were borrowed during the aftermath of Irish lenition. This accounts for the striking failure of the post-vocalic voiced stops [d, g] derived by Brittonic lenition to lenite further to [ð, ɣ] in Irish. That is, under this interpretation of loans with Brittonic lenition, the development of Latin [nota] through British Latin †[noda] and ultimately Irish [nod] ⟨not⟩ 'mark, sign' (Stokes and Strachan 1903:52, Sg. 3b17) follows the left-hand column of (16) instead of the counter-factual right hand column.

(16)	not-a	not-a	Latin
	nod-a	nod-a	British Latin
	/nod-aː/	/nod-aː/	Irish UR
	X	noðaː	Lenition
	nod	noð	Apocope
	[nod]	*[noð]	SR
	⟨not⟩	⟨nod⟩	Orthography

The plausibility of this interpretation rests on when post-vocalic singleton obstruents became legal in Irish. It is possible that Irish lenition was a chain shift, whereby singleton stops became fricatives and geminate stops simplified to singletons. Under this view, post-vocalic singleton obstruents were legal as soon as lenition developed. Importantly, if this happened, British Latin loans like [paːdrəgʲ] ⟨Pátraic⟩ 'Patrick' would not violate any phonotactic bans once lenition occurred.

However, that situation is ultimately speculative, since it is not known when original geminates degeminated. We can only be certain that by the early 20th century former geminate obstruents were no longer phonetically long (Wheatley and Iosad 2021). Unfortunately, the spellings in the manuscript record cannot distinguish original singletons from original geminates, as single or double consonants could be used to represent both categories (Sims-Williams 1990).

Note that data from modern languages shows that even if a chain shift occurs in the alternation system of a language, it is liable to be underlearned (Zhang, Lai, and Sailor 2009; Zhang 2016; Zhang 2019; Nagle 2020). Even if loan adaptation occurs by applying native phonology to a representation that is essentially faithful to the source language, as argued by La Charité and Paradis (2002, 2005 *et seq*), this underlearning means that a lenition chain shift may not be enforced in loan words once it developed. So long as loans with Brittonic lenition entered after an Irish lenition chain shift began, the voiced stops from Brittonic lenition should not be expected to be modified in Irish.

A.3.3 Early Brittonic Lenition Scenario

Given that we only have evidence that loans with Brittonic lenition entered after [p]→[k], it is also possible that loans with Brittonic lenition entered before or during Irish lenition.[16] Because post-vocalic voiced singleton stops had been mapped to fricatives by the first wave of lenition, the post-vocalic voiced singleton stops from Brittonic lenition would violate an exceptionless phonotactic constraint in Irish prior to the degemination of voiced geminates. Since the British Latin singleton voiced stops did not spirantize in Irish, we must conclude that if they entered before degemination, then they must have been adapted as geminate voiced stops. That is, instead of British Latin †[paːdrig] 'Patrick' being faithfully borrowed as [paːdrig], it would have been borrowed as [paːdːrigː].

While degemination could have been part of Irish lenition, it was not necessarily so, and later dates have been proposed.[17] For instance, Stifter (2017:1199) lists degemination as occurring after syncope. However, Stifter's claim does not concern the date of an actual phonetic sound change, but when the ancestral geminate/singleton contrast must give way to the Old Irish unlenited/lenited contrast at the structuralist morphophonological level (David Stifter p.c.).[18] We are not wholly convinced of a post-syncope date for degemination, since there are syncopated loans with unlenited [m] like Latin [kamisi-a] 'shirt-FEM.NOM.SG', which appears as Irish [kamʲsʲe] ⟨caimmse⟩ (McManus 1983:39) or Latin [memori-a] 'death.monument-FEM.NOM.SG', which appears as [memre] ⟨membræ⟩ (Lash 2021:S0027-20).[19] These loans presumably entered after lenition and before syncope.

Nonetheless, not wishing to prejudice the case, we ran simulations reflecting both scenarios. In late Brittonic lenition simulations, the timeline is fairly neat, with loans that undergo Irish lenition entering before the end of Irish lenition and loans undergoing Brittonic voicing lenition (or that otherwise fail to lenite) entering after Irish lenition. In early Brittonic lenition simulations, loans that undergo Brittonic voicing lenition, or otherwise fail to lenite, may enter before Irish lenition, but not before the end of [p]→[k]. Ultimately, early Brittonic lenition simulations produced time lines where the lenition period and the harmony period had roughly equal numbers of loans, a minimal difference from what is reported in the main body of the paper.

[16] Allowing loans with Brittonic lenition to enter during the Irish lenition period would seem to be incompatible with post-[p]→[k] loans showing Irish lenition, like [parʲxʲe] ⟨pairche⟩ 'parish'. Such a problem can be avoided by positing that such forms were borrowed from Continental varieties of Latin.

[17] McCone (1996:89) also tersely speculates that degemination was likely later than lenition, though ultimately it appears his proposal requires the same post-degemination entry for loans with Brittonic lenition as our initial proposal. To be concrete, McCone seeks to enforce Irish lenition of voiceless stops in ecclesiastic loans while assuming that Irish lenition happened much earlier than the first known formal Christian presence in 431/432 CE. That is, if Latin [parekia] entered long after Irish lenition ended, there must be an explanation for why it appears in Irish as [parʲxʲe] ⟨pairche⟩ (Stokes and Strachan 1901:632, Wb. 21a12), instead of *[parʲkʲe]). McCone's proposed solution is that degemination occurred some time after Irish lenition, so that at the time Latin [parekia] was encountered, post-vocalic [k] was illegal, but [x] and [kː] were not. Presumably because the perceptual distance was shortest between [k] and [x], voiceless singletons were adapted as fricatives instead of geminates.

Clearly, a different story must be told for the voiced stops from Brittonic lenition, which remained stops in Irish. Beyond simply stipulating that [x] was a better alternative to [kː] for [k], while [gː] was a better alternative to [ɣ] for [g], we can state that loans with Brittonic lenition entered after degemination. That is, before degemination Latin [k] was better adapted as [x] than as [kː], then degemination happened and British Latin [g] can be perfectly adapted as [g] instead of [ɣ]. This is equivalent to our original proposal that loans with Brittonic lenition were borrowed after lenition ceased to apply in loan words, albeit with stronger assumptions about the underlying timeline.

[18] The reasoning for post-syncope degemination at the structuralist morphophonological level goes as follows. Prior to apocope and syncope, the original morphophonological opposition between geminates and singletons can still be posited. This is because lenition has a well defined surface post-vocalic environment, and so belongs to the phonetic/allophonic level. Once apocope and syncope occur, lenited phones lose their well defined surface distribution, and so must be treated at the morphophonological level. Without singletons to oppose geminates, the historical gemination contrast is no longer tenable, and so degemination is held to have occurred at the morphophonological level.

[19] Note that Latin [memori-a] was also borrowed before lenition, as seen in Irish [mʲeβʲur] ⟨mebuir⟩ 'memory' (Stokes and Strachan 1901:626, Wb. 20a5).

For the sake of simplicity, further discussion will proceed under the assumption of the late Brittonic lenition scenario.

A.3.4 [f]→[s]

Eleven loans with [f] in Latin appear in Irish with [s], as in Irish [suːst] ⟨súst⟩ 'flail' (McManus 1983:29), from Latin [fuːstis]. These adaptations could have arisen by Latin [f] being mapped to Irish †[s^{w}], which had [f] as a lenited allophone, and which was eventually delabialized to [s].[20] These adaptations could also have been the result of [f] being directly mapped to [s].

Unfortunately, the current understanding of lenition as a gradually developed process makes it very difficult to date these loans. Recall that the lenition of [s] and †[s^{w}] is common to both the Brittonic languages and Irish. Taking these shared traits as evidence of inheritance puts the lenition of [s] to [h] and †[s^{w}] to †[h^{w}] in the ancestor of Irish and Brittonic.[21] After this common development, there were many Irish-specific sound changes, many of which were not applied to Latin loans and so presumably happened before Irish began to borrow from Latin.

The upshot of this is that the lenition of sibilants was too remote to give precise dates for these loans. While it is plausible that there were active alternations between †[s^{w}] and [f], or only static restrictions on where [f] could occur during the time of contact with Latin, we only know that mapping [f] to a sibilant could have been early. In fact, the best move is to limit [f]→[s] loans to the early portion of our timeline. This is because all three of the eleven [f]→[s] loans that were eligible for lenition or harmony, underwent those processes.[22] Accordingly, we treat loans that underwent this adaptation as entering no later than the immediately post-harmony period described in section A.5.

A.4 Vowel Harmony

The next major process after lenition was vowel harmony (see section A.5 for discussion of shortening, which at least overlapped with harmony, and may have begun before harmony). Vowel harmony applied from left to right across the word, causing non-low short vowels to agree with the following syllable for the feature [HIGH]. There were two restrictions on this process. First, [e, eː] did not trigger agreement in the preceding syllable. Second, [i, iː, u, uː] only triggered agreement in initial syllables, and could be blocked by an intervening voiceless consonant or consonant cluster (McCone 1996:110).[23] Harmony is illustrated in (17), which shows the mapping from Latin [pult-em] 'porridge.FEM-ACC.SG' to [kolt] ⟨colt⟩ (McManus 1983:48).[24]

[20] If [f]→[s] loans were borrowed with †[s^{w}], at some point they joined the [s]→[h] morphological lenition pattern along with all but one of the native words that originally began with †[s^{w}], i.e. ⟨siur⟩ 'sister' (with the lenited form ⟨fiur⟩) from †[s^{w}esuːr]. See Iosad (2022) for a comprehensive discussion of morphological lenition.

[21] The controversy over whether Irish and Brittonic form an Insular Celtic subgrouping does not affect the existence of a common ancestor for Irish and Brittonic.

[22] That is, Latin [furn-us] 'oven-MASC.NOM.SG' and [feːri-a] 'holiday-FEM.NOM.SG' were evidently borrowed as †[s$^{(w)}$urn-as] and †[s$^{(w)}$eːrij-aː] before undergoing harmony and apocope to become the attested forms [sorn] ⟨sorn⟩ (McManus 1983:28) and [sʲeːrʲe] ⟨séire⟩ (McManus 1983:55), while Latin [flokːus] 'fluff-MASC.NOM.SG' may have become Vulgar Latin †[floːk-us] (Petersson 1913) and become Irish †[s$^{(w)}$loːk-as] en route to undergoing lenition and apocope to become the attested form [sloːx] ⟨slóch⟩ 'snowflake' (McManus 1983:55).

[23] McCone (1996:110) recognizes that the full account of which consonant sequences block vowel raising has not been worked out. Thurneysen (1946:47-49) gives a list of clusters that did not block raising: [nd, mb, ṽl, ṽr, ðv, dr, or gl]. Thurneysen also writes that intervening ⟨cc⟩ (= [k]) permits raising, but the evidence for this is equivocal at best. In cases where a vowel fails to raise, we only conclude that this is due to post-harmony borrowing if the intervening consonant is voiced, or a member of Thurneysen's list.

[24] McManus (1983:48) erroneously claims that [kolt] ⟨colt⟩ 'porridge' comes from Latin [pult-a] 'knock-2SG.IMPV'.

(17)	pult-em	Latin
	/pult-an/	Irish UR
	kultan	[p]→[k]
	koltan	Harmony
	kolt_	Apocope
	[kolt]	SR
	⟨colt⟩	Orthography

The fact that harmony applied iteratively from left to right, while targets were to the left of their triggers, meant that it was a self-counterfeeding process. In particular, high vowels in initial syllables could be followed by derived cases of the lowering trigger [o]. For example, an ancestral stage of Irish is thought to have had a form †[berur-as] 'watercress-NOM.SG' (cf. Welsh [berur] ⟨berwr⟩), which developed to the observed form [birər] ⟨biror⟩ (Russell, Arbuthnot, and Mórán 2017:Y.121) as shown in (18).

(18)	/berur-as/	UR
	berurah/	Lenition
	birorah/	Harmony
	biror/	Apocope
	birər/	Vowel Reduction
	[birər]	SR
	⟨biror⟩	Orthography

Somewhat paradoxically, the left-to-right application of the harmony process produced a disharmonic form †[birorah], as opposed to the ungrammatical (but fully harmonic) *[beroras]. Note that the subsequent development of apocope further opacated harmony by deleting many harmony triggers, as shown in (17-18).

As mentioned in the main body of the paper, a substantial literature discusses whether opacity is underlearned (Sanders 2003; Kawahara 2015a; Andersson 2018; Jurgec 2019), and Kaplan (2008) argues specifically that self-counter-feeding opacity is unattested as a phonological phenomenon. However, we refrain from asserting that this self-counter-feeding opacity triggered underlearning of all aspects of the harmony process. That said, even if it was fully learned, Irish speakers had to permit some disharmonic sequences in surface forms. As was the case for lenition, the presence of surface disharmonic sequences opens the door to not adapting disharmonic loans that entered while harmony was being developed. For the sake of simplicity, we treat all disharmonic sequences as being faithfully adaptable at the same time, and do not assume that [i/u…o] sequences were accepted before other disharmonic sequences.

Due to the later application of vowel reduction in word-medial syllables, only initial syllables and word-final open syllables (after apocope) are informative for whether a word underwent vowel harmony.[25] To be concrete, we conclude that a loan was borrowed before the end of harmony if the conditions for harmony were met in the initial or final syllable (after apocope) and harmony applied. If the conditions for harmony were met, but harmony did not apply, we conclude that the loan was borrowed after the end of harmony. Because Latin case suffixes were replaced by Irish case suffixes, Latin monosyllabic stems may or may not have met the harmony environment once Irish suffixes were applied. If harmony applied in Irish to monosyllabic stems, we assume that the environment for harmony was met. If, however, harmony did not apply in a monosyllabic stem, we assess the morphological paradigm of the loan to determine whether the environment for harmony could have been met, and date the loan accordingly.

[25] See McManus (1991:94) for evidence from Ogam inscriptions that vowel harmony applied in word-medial syllables.

A.4.1 Separating lenition and harmony

Loans with Brittonic lenition began to enter Irish before harmony was completed. For instance, Latin [kokʷiːn-a] 'kitchen-FEM.NOM.SG.' was adapted as [kugən̲] ⟨cucann⟩ (McManus 1983:59). We can explain the raising of Latin [o] to Irish [u] as being the result of the harmony process enforcing raising due to the following high vowel.

The derivations in (19) illustrate the development of Irish [kugən̲] ⟨cucann⟩ 'kitchen', as well as the counterfactual derivations illustrating the expected outcome if the word had been borrowed before lenition (column 2), or after harmony (column 3). These derivations follow the assumption that Brittonic voicing lenition only appeared in loans borrowed after Irish lenition (see section A.3.1). If that assumption is abandoned, then we can only conclude that loans of this type entered Irish after [p]→[k] and before harmony.

(19)				
	kokʷiːn-a	kokʷiːn-a	kokʷiːn-a	Latin
	kogiːn-a	kokiːn-a	kogiːn-a	British Latin
	/kogiːn-aː/	/kokiːn-aː/	/kogiːn-aː/	Irish UR
	X	koxiːnaː	X	Lenition
	kogina	koxina	X	Shortening
	kugena	kuxena	X	Harmony
	kugen_	kuxen_	kogin_	Apocope
	kugən̲	kuxən̲	kogən̲	Other Processes
	[kugən̲]	*[kuxən̲]	*[kogən̲]	SR
	⟨cucann⟩	⟨cuchann⟩	⟨cocann⟩	Orthography

Note that the shortening of Latin [iː] to Irish †[i] is not informative for dating this word, because shortening began before the end of harmony (McCone 1996:110-115), and continued through harmony and apocope before being ended by the development of compensatory lengthening (McManus 1983:56, see section A.5). The long duration of shortening is also the reason that in the second counterfactual derivation shortening has been applied in the apocope stage.

A.4.2 [st]→[s]

In the native vocabulary, inherited †[st] clusters became †[sː] and were subsequently degeminated to [s]. Many Latin loans were adapted similarly, as in Irish [kasʲəl] ⟨caisel⟩ 'castle', from Vulgar Latin †[kastilːum] (McManus 1983:58), or Irish [sraθər] ⟨srathar⟩ 'pack-saddle' (Stokes and Strachan 1903:290, Sg. 229a), from Vulgar Latin †[stratuːra]. Though it would be natural to date such words as entering before lenition, Latin [straːt-a] 'street-FEM.NOM.SG' appears as Irish [sraːdʲ] ⟨sráit⟩ (McManus 1983:54), with simplification of [st] to [s] but showing the potentially post-Irish lenition feature of Brittonic lenition of the stem-final consonant.

In order to preserve the intuition that [st] → [s] simplification was early, while not limiting these loans to entering before lenition, this trait is taken as evidence of adaptation before harmony in the simulations. Faithful maintenance of [st] clusters is not taken as evidence of any date of entry (McManus 1983:54).

A.5 Shortening

Vowel shortening targeted vowels in non-initial syllables except before [h] (McCone 1996:110-112). This process pre-dates the end of vowel harmony and is usually presented before it in derivations, since Latin long vowels were shortened and harmonized as in (19). Despite this early beginning, vowel shortening is

thought to have persisted until compensatory lengthening re-introduced long vowels in word medial syllables (McManus 1983:56, 59).

A.5.1 Separating shortening and harmony

The fact that nothing stood in the way of shortening continuing to apply until compensatory lengthening appeared raises the possibility that some loans could have entered too late for harmony to apply, but early enough for shortening to have applied. The only uncontroversial loan that could exemplify this is Irish [komən] ⟨comman⟩ (McManus 1983:29, 59) 'communion', from Latin [komːuːnio]. This word must have entered after harmony, since the mid vowel in the initial syllable was eligible for harmony due to the following high vowel, but harmony did not apply.[26] Moreover, the [uː] was shortened, indicating that the word entered while shortening was still active. The progression of this word is spelled out in (20) as well as counterfactual derivations illustrating the expected outcome if the word had been borrowed before or after shortening.

(20)	komːuːni-oː	komːuːni-oː	komːuːni-oː	Latin
	/komuːn /	/komuːn /	/komuːn /	Irish UR
	X	kumuːn	X	Harmony
	komun	kumun	X	Shortening
	komən	kumən	—	Other Processes
	[komən]	*[kumən]	*[komuːn]	SR
	⟨comman⟩	⟨cumman⟩	⟨commún⟩	Orthography

Two further examples potentially could establish a post-harmony shortening period beyond a doubt. These are Irish [iðənʲ] ⟨idain⟩ 'pure.PL' (Stokes and Strachan 1901:700, Wb. 31c13), which is potentially from Latin [idoːneus], and Irish [fʲirʲmʲənʲtʲ] ⟨firmint⟩ 'firmament' (Stokes and Strachan 1901:115, Ml. 42b22), from Latin [firmaːmentum]. Unfortunately, proceeding under that assumption would be controversial. Despite McManus (1983:59) attributing a Latin origin to [iðənʲ], this is not a widespread conclusion (cf. the entry for ⟨idan⟩ in eDIL (2019) at `https://www.dil.ie/27179`, accessed July 27, 2022). Regarding ⟨firmint⟩, it is noteworthy that the more common form is [fʲirməməntʲ] ⟨firmimint/⟩ (Stokes and Strachan 1901:116, Ml. 42b24; cf. also (2019) at `https://www.dil.ie/22208`, accessed February 17, 2023), with the preserved medial vowel suggestive of a post-syncope loan. A reviewer helpfully points out that the Milan glosses contain several cases of apparent haplology, which raises the possibility that ⟨firmint⟩ is a copying error, or at least an idiosyncrasy of the scribe. If true, this form would provide no evidence for post-harmony shortening.

A.6 Compensatory Lengthening

After the development of vowel harmony, Irish deleted dental and velar fricatives before consonantal sonorants [r, l, m, n], and lengthened the preceding vowel, as in the native word [kʲenʲeːl] ⟨ceneel⟩ 'race' (Stokes and Strachan 1901:681, Wb. 28b1), from †[kenеθl] (where the †[θ<t] has a reflex in Old Welsh [kenedl] ⟨kenetl⟩ McCone 1996:122). Example (21) illustrates this in the loan vocabulary for Latin [sign-um] 'sign-NEUT.NOM.SG.' (Lash 2021:S0022-78).

[26] If [komːunio] entered during the harmony period, harmony would be unlikely to be blocked by the restriction on intervening consonant clusters. The Latin geminate [mː] in [komːunio] 'communion' was presumably mapped to a singleton [m], and even if it were not, [mː] is presumably in a natural class with [mb], a cluster that did not block raising.

(21)

sign-um	Latin
/sign-an/	Irish UR
siɣnan	Lenition
seɣnan	Harmony
seɣn_	Apocope
seːn	Compensatory Lengthening
sʲeːn	Other Processes
[sʲeːn]	SR
⟨sén⟩	Orthography

Only about 4% of Latin loanwords met the environment for compensatory lengthening. Compensatory lengthening is instead a major milestone for dating Latin loans because it overrode vowel shortening. Latin loans that preserve vowel length must have entered during or after this development.[27] For instance, Latin [altaːre] 'altar', after undergoing the later Brittonic change of [aː] to [ɔː] (Stifter 2017:1200), maintained vowel length when it was adapted into Irish as [altoːrʲ] ⟨altóir⟩ (Stokes and Strachan 1901:527, Wb. 5b6).

A.6.1 Separating Shortening and Compensatory Lengthening

In previous sections the loan vocabulary directly established a separation between two periods. We cannot provide such an example here, most likely due to the rarity of compensatory lengthening. A relevant example would require a form that underwent compensatory lengthening and was eligible for shortening, but failed to undergo it. Since only about 4% of loans were eligible for compensatory lengthening alone, it is not surprising that there are no examples that were eligible for both compensatory lengthening and shortening.

However, there is evidence beyond the loan vocabulary for the position of compensatory lengthening in our timeline. The Ogam stone inscriptions establish that compensatory lengthening occurred after harmony (see McManus 1991:94-95, who refers to compensatory lengthening as "the vocalization of fricatives before resonants"). Since compensatory lengthening began after harmony, which plausibly began after the beginning of shortening (as discussed above), compensatory lengthening probably also began after shortening. Furthermore, because shortening and compensatory lengthening had opposite effects on vowel length, the fact that lengthened vowels exist in the native vocabulary is evidence that compensatory lengthening chronologically followed shortening. Under the alternative sequence of events, where shortening developed after compensatory lengthening, we would expect there to be no lengthened vowels in non initial syllables. Our earlier example, [kʲenʲeːl] ⟨ceneel⟩ 'race', shows the alternative version of events to be false.

There may have been a transitional period when fricative-sonorant cluster simplification occurred, but shortening overrode the nascent compensatory lengthening. The evidence for this comes from anomalous syncope of vowels in the compensatory lengthening context. Ordinarily, vowels in the context for compensatory lengthening do not syncopate, as in [gavaːl-e] ⟨gabálae⟩ 'taking-GEN.SG', from †[gavagl-e], or [kʲenʲeːl-əvʲ] ⟨cenélaib⟩ 'races', from etymological †[kʲenʲeθl-ovʲ] (McCone 1996:123). However, some vowels that historically preceded voiced fricatives may also fail to appear, as can be seen in [do=riɣeːni] ⟨do:rigéni⟩ 'has done', from †[de=roɣeɣni], which has a syncopated variant [do=riɣ_ni] ⟨do:rigni⟩ (McCone 1996:123).

[27] A reviewer asks if the low number of loans dated to the compensatory lengthening period in (11) could be due to Latin simply not having many words with fricative-sonorant sequences matching the environment for compensatory lengthening. This is unlikely, because as mentioned above, loans that failed to undergo shortening are dated to during or after compensatory lengthening. Long vowels in non-initial syllables are much better attested than fricative-sonorant clusters in Latin. Indeed, besides compensatory lengthening, the phonological processes that diagnose period membership usually match 30-40% of the Latin vocabulary (with the exception of [p]→[k], which matches around 18%).

Because syncope is the endpoint of increasingly extreme reduction, we are reluctant to claim that syncope directly removed long vowels (which would also require optionality or analogy to explain unsyncopated long vowels). Rather, the vowels that were deleted should have gone through a phase where they were short before finally succumbing to complete occlusion. Since shortening was active at least immediately before compensatory lengthening, a simple analysis is that voiced fricative-sonorant clusters began to simplify while shortening was active. This would produce short vowel variants that would be susceptible to syncope, while long vowel variants would emerge after shortening was overridden by lengthening. Under this account, the fact that voiceless fricative-sonorant cluster simplification only gave rise to long vowels is explained by voiceless fricatives deleting later than voiced fricatives, i.e. once shortening was no longer active. This accords well with voiceless obstruents being phonetically stronger than voiced obstruents.[28]

Other timelines have been proposed to account for these data. Instead of positing that compensatory lengthening and shortening overlapped, McCone (1996:123-124) proposes that syncope developed in the middle of the compensatory lengthening period. Under this account, syncope developed after the simplification of voiced fricative-sonorant clusters, but before the simplification of voiceless fricative-sonorant clusters. The long vowels that were left by voiced fricative-sonorant cluster simplification are assumed to have been eligible to delete, and those that did not delete are assumed to have been restored by analogy. Meanwhile, the vowels before voiceless fricative-sonorant clusters are argued to have been protected from syncope by constraints on permissible consonant clusters. This approach has the advantage of explaining an apparent case of rhythmic syncope applying out of turn before voiceless fricative-sonorant cluster simplification. However, it also falsely predicts that voiceless fricative-sonorant clusters created by syncope would simplify. For this reason, we do not modify the relative order of compensatory lengthening and syncope, and leave a full account of the interaction of compensatory lengthening and syncope for further research.

A.6.2 Recoverability of Compensatory Lengthening

If speakers of Irish did not recover the deleted fricative at the time of compensatory lengthening, vowel length would need to be specified in inputs, and faithfulness constraints to protect vowel length would need to be promoted. A second, more restrictive possibility, would only protect underlying vowel length before sonorants. On the other hand, if Irish speakers were aware of the deleted fricative, they could have maintained a grammar that enforced shortening and restricted long vowels to arising via compensatory lengthening.

It is unlikely that Irish speakers recovered the underlying fricatives and maintained productive compensatory lengthening. The primary paradigmatic context that speakers could use to recover the process was quite specialized. Some verbs beginning with stop-sonorant clusters formed the past tense via initial consonant reduplication, which set up a CVCR sequence that triggered compensatory lengthening to CV:R. This can be seen in the past tense of [krɛ-n-əðʲ] ⟨crenaid⟩ ‘s/he buys’, which in the first person past tense became [kɛ:-r] ⟨cér⟩ ‘I bought’ (Thurneysen 1946:428). The historical progression leading to [kɛ:r] ⟨cér⟩ ‘I bought’ is laid out in (22).

[28] Some short vowel variants would have been in strong metrical positions. These short vowels would not have been targeted by syncope and thus would be expected to have surfaced as short vowels. We cannot be sure whether this did or did not occur, since vowel length was not consistently marked in manuscripts, though poetic forms that tracked vowel length could possibly furnish positive examples.

(22)

kikra	Pre-lenition
kixra	Lenition
kexra	Harmony
kexr	Apocope
keːr	Comp. Len
⟨cér⟩	Orthography

By the time of the Old Irish manuscripts we find innovative reduplicated forms. These provide concrete evidence that compensatory lengthening was not acquired, and thus that vowel length outside the initial syllable must have become contrastive. For instance, the reduplicating verb meaning 'dig' appears without consonant loss or a long initial syllable, so that /RED-klað-adar/ appears as [kexləðədər] ⟨cechladatar⟩ 'they dug' (Stokes and Strachan 1901:526, Wb. 5a24), instead of compensatorily lengthened *[keːləðədər] or its syncopated version *[keːldədər].[29]

Unfortunately, we do not know whether the process was abandoned before or after the development of rhythmic syncope, which created a cavalcade of surface fricative-sonorant clusters. We only know that compensatory lengthening had progressed far enough before syncope that there are pre-syncope Ogam stone inscriptions which have solitary sonorants in place of etymological fricative-sonorant sequences (McManus 1991:96). These inscriptions establish that syncope and compensatory lengthening did not happen at exactly the same time, but they cannot tell us what the contrastive status of vowel length was in the grammars of speakers.

However, following our decisions to preserve granularity by recognizing a post-harmony shortening period and placing the entry of loans with Brittonic lenition after Irish lenition, we assume that Irish speakers had grammars that enforced a length contrast in all word medial syllables before syncope. That is, we analyze word-medial vowels that undergo shortening as entering the language before compensatory lengthening. Furthermore, we conclude that a loan was borrowed before compensatory lengthening if the Latin original meets the environment for compensatory lengthening and it is carried out. Meanwhile, loanwords that maintain vowel length word-medially are thought to have entered after compensatory lengthening restored the vowel length contrast. If a Latin original has a cluster that was made illegal by compensatory lengthening, and that cluster is not simplified, we conclude that it was borrowed after compensatory lengthening. That is, such a loan must have entered during or after the syncope period, which re-created these consonant clusters.

A.7 Syncope

Rhythmic syncope in Irish removed even-numbered non-final syllables when counting from left to right. Primary stress was assigned to the first syllable (Thurneysen 1946:27-31, Stifter 2006:21-22). Initial stress, and the alternating character of deletion, are consistent with left-aligned trochaic feet. In familiar phonological terms, syncope targeted the weak branch of all non-final feet. See McCarthy (2008) for a thorough discussion of how phonological rhythmic syncope should be implemented. The derivation in (23) illustrates the application of syncope to Latin [apostol-us] 'apostle-MASC.NOM.SG.' to create Irish [axsəl] ⟨axal⟩ (McManus 1983:48).

[29] The form [ke-xləðədər] ⟨cechladatar⟩ also illustrates how the rhythmic syncope system had broken down by the time of the Old Irish manuscripts. If syncope had been applied to the reformed reduplicated form starting in [kex…], we would expect to find *[kexldadar] or possibly *[kexəldədər] with regular epenthesis before stranded sonorants.

(23)	apostol-us	Latin
	/apostol-as/	Irish UR
	akostolas	[p]→[k]
	axostolah	Lenition
	axosolah	[st]→[s]
	axosol_	Apocope
	(ˈaxo)(ˌsol)	Footing
	(ˈax_)(ˌsol)	Syncope
	(ˈax_)(ˌsəl)	Other Processes
	[axsəl]	SR
	⟨axal⟩	Orthography

The first verbal proclitic, if any, was omitted from the stress calculation, which set up paradigmatic alternations in the native vocabulary. In these examples, we mark proclitic boundaries with '='. For instance, consider the native verb /to=ro=xar-adar/ 'they fell' (Bieler and Kelly 2004 [1979]:176§13.7) and its form with a further proclitic /ko^{+voi}=to=ro=xar-adar/ 'until they fell' (Stokes and Strachan 1901:93, Ml. 36d13), which surfaced as illustrated in (24).[30]

(24)	/ko^{+voi}=to=ro=xar-adar/	/to=ro=xar-adar/	UR
	ko^{+voi}=(ˈtoro)(ˌxara)(ˌdar)	to=(ˈroxa)(ˌradar)	Stress
	ko^{+voi}=(ˈtor_)(ˌxar_)(ˌdar)	to=(ˈrox_)(ˌradar)	Syncope
	ko=(ˈdor_)(ˌxər_)(ˌdər)	do=(ˈrox_)(ˌrədər)	Other Processes
	[ko=ˈdorxərdər]	[do=ˈroxrədər]	SR
	⟨con torchartar⟩	⟨dorochratar⟩	Orthography

Notice that the addition of a proclitic at the leading edge of the stress domain causes a ripple of deletion and non-deletion throughout the word. Such paradigmatic alternations are the calling card of rhythmic syncope.

There were few phonotactic factors that influenced syncope. Syncope was blocked before /xt/ clusters, as seen by the imperviousness of the second syllable in [kuṽəxtax] ⟨cumachtach⟩ 'mighty' *[kuṽ_xtəx] (Thurneysen 1946:67). When /xt/ clusters blocked deletion of a preceding vowel, the following syllable was apt to delete, as in [kuṽəxtx-u] ⟨cumachtchu⟩ 'mightier'. McCone (1996:123) suggests that clusters of [θ, x] followed by [l, r, n] also may have blocked syncope of a preceding vowel, but this is contingent on a controversial analysis of compensatory lengthening section (see section A.6.1). Without further evidence, we do not implement these additional blocking conditions in our model.

In simulations, we take the removal of vowels from even-numbered non-final syllables as evidence that a word entered Irish before or during the syncope period. Vowels may be deleted from other syllables, as in /kon=to-ro-xar-adar/ → [kon=torxradar] ⟨con-torchratar⟩ 'they fell together' (discussed in section A.7.3), or more commonly, may fail to be removed from the expected syllables. Either of these deviations are taken as evidence of entry after the syncope period. See section A.7.2 for further dating criteria using the adaptation of consonant clusters.

[30] The 'other processes' invoked at the end of (24) are the so-called nasalization mutation triggered by the proclitic [ko^{+voi}=], in which a voiceless obstruent receives a floating voicing feature left over from an original nasal (viz. orthographic ⟨n⟩ in ⟨con torchartar⟩), an independent process voicing /to=/ when domain initial and unstressed (Stifter 2014), and a vowel reduction process.

A.7.1 Separating syncope and other processes

At least two loans may have entered between the beginning of compensatory lengthening and before the end of syncope. Latin [kandel-aːri-us] ‘candle-AGEN-MASC.NOM.SG.’ appears in Irish as [kanʲdʲlʲoːrʲ] ⟨caindl(e)óir⟩ ‘candle-bearer’ (Stokes and Strachan 1901:703, Wb. 24b32). This word shows both syncope and the retention of the long vowel [aː], which had been rounded to [ɔː] in Brittonic before becoming Irish [oː]. The adaptation of this word is illustrated in (25), alongside counterfactual derivations for early (column 2) and late (column 3) entry. We use ↓ to mark a possible point of entry where the listed process does not apply.

(25)	kandelaːri-us	kandelaːri-us	kandelaːri-us	Latin
	kandeloːr	kandeloːr	kandeloːr	British Latin
	/kandeloːrʲ/	/kandeloːrʲ/	/kandeloːrʲ/	Irish UR
	X	kandelorʲ	X	Shortening
	↓	—	X	Comp. Len
	(ˈkande)(ˌloːrʲ)	(ˈkande)(ˌlorʲ)	X	Stress
	(ˈkand_)(ˌloːrʲ)	(ˈkand_)(ˌlorʲ)	X	Syncope
	(ˈkanʲdʲ)(ˌlʲoːrʲ)	(ˈkanʲdʲ)(ˌlʲərʲ)	kandəloːrʲ	Other rules
	[kanʲdʲlʲoːrʲ]	*[kanʲdʲlʲərʲ]	*[kandəloːrʲ]	SR
	⟨caindleóir⟩	⟨caindler⟩	⟨candalóir⟩	Orthography

However, this case is controversial, because [kanʲdʲlʲoːrʲ] ⟨caindleóir⟩ may have been formed within Irish from borrowed morphemes, rather than the whole word being borrowed directly from Latin. That is, Latin [kandeːla] ‘candle’ was borrowed into Irish as [kanʲdʲəl] ⟨caindel⟩ (Lash 2021, S0027-57), where the shortening of Latin [eː] indicates that it entered Irish before compensatory lengthening. Furthermore, the suffix [-oːrʲ] ‘AGEN’ was extracted from other Latin loans and was applied even to native roots, such as the word [foxʲlʲ-oːrʲ] ⟨foichleóir⟩ ‘curator’ from [foxʲəl] ⟨fochell⟩ ‘attention, heed, caring for’ (Thurneysen 1946:172).[31] Concatenating /kanʲdʲel/ and the suffix /-oːrʲ/ produces /kanʲdʲel-oːrʲ/, which would undergo syncope to become [kanʲdʲ_lʲ-oːrʲ] ⟨caindleóir⟩. Although our model does not treat Irish-internal neologisms, in this case the distinction between borrowing and neologism is so faint that we include this word in our simulations.[32]

The second loan that could have entered in this time span is Latin [deprekaːtioː] ‘deprecation’, which appears either as Irish [dʲebrʲəgoːdʲ] ⟨deprecóit⟩ (McManus 1983:68) or [dʲibʲərgoːdʲ] ⟨dibercoit⟩ (eDIL 2019 `https://www.dil.ie/15240`). Though at first blush neither form would seem to comply with the expected output of syncope, the vocalism of the latter is the expected outcome of epenthesis repairing sonorants stranded between consonants by syncope (Thurneysen 1946:70). Furthermore, similar variation is seen in the clearly pre-syncope loan of the Latin name [paːtriki-us] ‘Patrick-MASC.NOM.SG’, which appears both as [koθrəɣʲe] ⟨Cothrige⟩ (Thurneysen 1946:571) and [kaθʲərʲɣʲe] ⟨Cathirge⟩ (McManus 1983:62, fn. 122). We date [dʲebrʲəgoːdʲ] ⟨deprecóit⟩ ‘deprecation’ to either the syncope or compensatory lengthening periods.[33]

[31] This suffix remains productive even in the modern language.

[32] There are three other potential loans that lack a Latin vowel and retain a long vowel. Latin [triːnitaːt-em] ‘trinity-FEM.ACC.SG’ appears as [triːndoːdʲ] ⟨tríndóit⟩ (attested in a different case form ⟨tríndóti⟩ in Stokes and Strachan 1901:9, Ml. 2d2), Vulgar Latin [antitaːt-em] ‘antiquity-FEM.ACC.SG’ became Irish [andoːdʲ] ⟨andóit⟩ ‘mother church’ (McManus 1983:61), and Latin [feːriaːl-is] ‘pertaining to a weekday-MASC/FEM.NOM.SG’ appears as [feːroːlʲ] ⟨féróil⟩ (Lash 2021, S0058-40). However, syncope of front vowels in Irish triggers palatalization on the neighboring consonants (as seen in examples 9 and 25). The lack of palatalization of the medial consonant or clusters in these words indicates that the missing Classical Latin vowel was lost in either British Latin or Vulgar Latin.

[33] Two further loans have a similar consonant configuration but without the variation in vocalism. These are Irish [mʲedrəbəlʲ]

A.7.2 Juxtaposed Consonants

The deletion of vowels via syncope created consonant clusters, some of which had been illegal in Irish and were repaired when they appeared in loanwords. McManus (1983:60-62) points out that some loanwords do not undergo these repairs, which is plausibly attributable to syncope having legalized them. Specifically, faithful adaptation of [ns, nf, ks] diagnoses entry after syncope, while a repair of Latin [nf] to Irish [v] diagnoses a pre-syncope loan. However, Irish and Vulgar Latin both repaired [ns, ks] to [s], making it impossible to determine anything about date of entry from these repairs.

Importantly, nasal-voiceless stop clusters [ŋk, nt] were often repaired by voicing the stop (see McManus 1983:61 for discussion). We analyze cases of voicing as evidence that a word entered the language before syncope. We cannot draw any conclusions from the failure of voicing to apply, because there are early loans that do not show voicing. For instance, Latin [intelːekt-us] 'intellect-MASC.NOM.SG' appears in Irish as [inʲtʲlʲuxt] ⟨intliucht⟩ (McManus 1983:62), instead of *[inʲdʲlʲuxt]. Syncope has applied to this form (as has another pre-syncope process known as u-coloring or u-affection (Hock 2019, McCone 1996:111-112)), so it must have entered before the end of syncope, despite not having voiced the [t] in the cluster.

In addition to the consonant clusters discussed by McManus (1983), syncope re-legalized the consonant clusters that were simplified by compensatory lengthening. Latin originals with these clusters are extremely rare in our loan data, but if they were faithfully adapted, it would be evidence for adaptation that occurred after syncope.

A.7.3 Evidence of Non-productivity

In prior sections we have been able to show that a process ended during the borrowing period by adducing loans that failed to undergo the process but underwent later processes. As the last process in our sequence, this option is not available. Nonetheless, there is evidence that rhythmic syncope lost productivity at some point. Old Irish manuscripts contain indications that rhythmic syncope was no longer productive at the time they were written (Thurneysen 1946:68, Armstrong 1976, McCone 1985)). The vast majority of these manuscripts were composed some time after syncope began, and so cannot reveal how quickly syncope decayed.

That rhythmic syncope was eventually abandoned in Irish is well established. Even a casual overview of the textual record highlights the decline of syncope in Irish. The Old Irish manuscripts, composed from the seventh to tenth centuries, largely abide by rhythmic syncope patterns, though numerous exceptions occur. Middle Irish, generally held to have begun in the mid-tenth century, also attests many prominent deviations from the historically expected syncope patterns (see McCone 1997:163ff. for a general overview of Middle Irish verbs). Finally, in the twelfth century the classical modern literary standard emerged, which featured widespread paradigm leveling to remove rhythmic syncope alternations. Indeed, "there are very few genuine survivals" of many characteristic Old Irish alternations, including rhythmic syncope alternations, in any variety of the modern language (McCone 1997:191).

It would be a mistake to read the general adherence to rhythmic syncope patterns in Old Irish manuscripts as evidence that rhythmic syncope was still active in the seventh through tenth centuries. The Würzburg and Milan glosses (Stokes and Strachan 1901) are strongly representative of the standardized language of the

⟨metrapoil⟩ 'metropolis' (Stokes and Strachan 1901:361 Ml. 106d6) from Latin [meːtropolis] and Irish [akrʲəsʲəndəvʲ] ⟨acrisiondaib⟩ (Stokes and Strachan 1903:85 Sg. 32b25). The latter is a dative plural adjective derived within Irish from a Latin proper name [akrisioneː]; it is also a *hapax legomenon* from a mid-ninth-century (well after the time of syncope) gloss on a Latin text containing the clearly unsyncopated Latin form. This could therefore be an instance of a literary loan (cf. section 3.2). Nonetheless, we lack direct evidence of syncope and subsequent vowel epenthesis for these words, but we recognize the possibility that the observed forms could have been developed this way with subsequent metathesis. Accordingly, we allow these words to enter during both the pre-syncope and post-syncope periods.

eighth century (Lash 2017:147-151). Nonetheless, they contain a number of deviations from the expected norm (Armstrong 1976). For instance, in (26) we align the segments of [ko=dor_xər_dər] ⟨con torchartar⟩ 'until they fell' (repeated from example 24) with a related form [kon=tor_x_rədər] ⟨con-torchratar⟩ 'they fell together' (Stokes and Strachan 1901:148, Ml. 48c28) with a divergent vocalism.

(26)

		σ_1		σ_2		σ_3		σ_4		σ_5	
ko=	d	o	r		x	ə	r		d	ə	r
kon=	t	o	r		x		r	ə	d	ə	r

While [ko=dor_xər_dər] ⟨con torchartar⟩ 'until they fell' follows the expected pattern of rhythmic vowel loss, [kon=tor_x_rədər] ⟨con-torchratar⟩ 'they fell together' has deletion in adjacent syllables and an unexpected vowel in the fourth syllable of the stress domain. This vocalism cannot be derived by application of rhythmic syncope.

According to McCone (1985, 1997), these deviations are in fact early instantiations of innovative patterns that flourished in Middle Irish, and that were ultimately standardized in Modern Irish. This strongly suggests that Old Irish records partially reflect an 'artificially fostered learned and literary standard' (McCone 1997:167). It is impossible to know what the living spoken language of the Old Irish period was, but it is not beyond the realm of possibility that the innovations were already displacing the old patterns or had even become regular.

References

Albright, Adam (2005). "The Morphological Basis of Paradigm Leveling". In: *Paradigms in Phonological Theory*. Ed. by Laura Downing, Tracy Hall, and Renate Raffelsiefen. Oxford University Press.

Andersson, Samuel (2018). "Rorövovarorsospoproråkoketot: Language Games and Swedish Phonology". In: *Papers of the Annual Meeting on Phonology (2017)*.

Armstrong, John (1976). "Phonological Irregularity in Compound Verb Forms in the Würzburg Glosses". In: *Ériu* 27, pp. 46–72.

Bakovic, Eric (2007). "A Revised Typology of Opaque Generalizations". In: *Phonology* 24.2, pp. 217–259.

— (2011). "Opacity and Ordering". In: *The Handbook of Phonological Theory*. Ed. by John Goldsmith, Jason Riggle, and Alan Yu. Second. Wiley-Blackwell.

Barrett, Siobhán (2021). *Poems of Blathmac Database*. Version 2.0. URL: `http://chronhib.maynoothuniversity.ie`.

Bauer, Bernhard (2015). "Intra-Celtic Loanwords". PhD thesis. Universität Wien.

Bermúdez-Otero, Ricardo (2015). "Amphichronic Explanation and the Life Cycle of Phonological Processes". In: *The Oxford handbook of Historical Phonology*. Ed. by Patrick Honeybone and Joseph C Salmons. Oxford University Press.

Bernardo Stempel, P. de (2006). "Indogermanish und keltisch 'geben', kontinentalkelt. Gabiae, gabi/gabas, keltib. Gabizeti, altir. Ro-(n)-gab und Zugehoeriges". In: *Historische Sprachforschung* 118, pp. 185–200.

Bieler, Ludwig and Fergus Kelly, eds. (2004 [1979]). *The Patrician texts in the Book of Armagh*. Dublin: School of Celtic Studies, Dublin Institute for Advanced Studies.

Blumenfeld, Lev (2006). "Constraints on Phonological Interactions". PhD thesis. Stanford.

Boersma, Paul (1998). *Functional phonology: formalizing the interaction between articulatory and perceptual drives*. The Hague: Holland Academic Graphics.

Boersma, Paul and Silke Hamann (2009). "Loanword adaptation as first-language phonological perception". In: *Loan phonology*. Ed. by Andrea Calabrese and Leo Wetzels. Amsterdam: John Benjamins, pp. 11–58.

Bowers, Dustin (2019). “The Nishnaabemwin Restructuring Controversy: New Empirical Evidence”. In: *Phonology* 36.2, pp. 187–224. DOI: 10.1017/S0952675719000113.

Bowers, Dustin and Yiding Hao (2020). “Rhythmic Syncope in Subregular Phonology”. In: ed. by Nari Rhee and Ryan Budnick. Vol. 26. University of Pennsylvania Working Papers in Linguistics 1. Philadelphia, PA: Penn Graduate Linguistics Society.

Brown, Peter (1989). *The World of Late Antiquity: AD 150-750*. London: Thames and Hudson Ltd.

Carney, James (1971). “Three Old Irish Accentual Poems”. In: *Ériu* 22, pp. 23–80.

Chandlee, Jane, Jeffrey Heinz, and Adam Jardine (2018). “Input Strictly Local Opaque Maps”. In: *Phonology* 35.2, pp. 171–205.

Chomsky, Noam and Morris Halle (1968). *The Sound Pattern of English*. Harper and Row.

De Jong, K. (1975). “Analysis of the Behavior of a Class of Genetic Adaptive Systems”. PhD thesis. University of Michigan.

de Vries, Ranke (2013). *Student’s Companion to Old Irish Grammar*. Forgotten Scholar Press.

eDIL: An Electronic Dictionary of the Irish Language, based on the Contributions to a Dictionary of the Irish Language (Dublin: Royal Irish Academy, 1913-1976) (2019). URL: http://www.dil.ie.

Esposito, Mario (1988). *Latin learning in mediaeval Ireland*. Ed. by Michael Lapidge. Variorum Collected Studies Series 285. London: Variorum Reprints.

Flechner, Roy and Sven Meeder, eds. (2017). *The Irish in Early Medieval Europe: Identity, Culture and Religion*. London: Palgrave Macmillan.

Flechner, Roy and Máire Ní Mhaonaigh (2016). *The Introduction of Christianity into the Early Medieval Insular World: Converting the Isles I*. Turnhout: Brepols.

Fomin, Maxim (2018). “Multilingual practices and linguistic contacts in pre-Patrician Ireland and late Roman Britain”. In: *Studia Celto-Slavica* 8, pp. 151–172.

Hale, Kenneth (1973). “A Note on Subject-Object Inversion in Navajo”. In: *Issues in Linguistics: Papers in Honor of Henry and Renée Kahane*. University of Illinois, pp. 300–309.

— (1991). “Remarks on Sanders ”Levelling in the History of Polynesian Passive Formations””. In: *The Journal of the Polynesian Society* 100.1, pp. 99–101.

Hamp, Eric P. (2000). “Reading Old Irish Writing: Making Complex Mechanisms Effortless - Well, Somewhat”. In: *Ériu* 51, pp. 59–62.

Hao, Yiding and Dustin Bowers (Aug. 2019). “Action-sensitive Phonological Processes”. In: *Proceedings of the 16th SIGMORPHON Workshop on Computational Research in Phonetics, Phonology and Morphology*, pp. 218–228.

Harvey, Anthony (1989). “Some significant points of early Insular Celtic orthography”. In: *Sages, saints and storytellers: Celtic studies in honour of Professor James Carney*. Ed. by Donnchadh Ó Corráin, Liam Breatnach, and Kim McCone. Maynooth monographs 2. An Sagart: Maynooth, pp. 56–66.

— (1991). “Retrieving the pronunciation of early Insular Celtic scribes: the case of Dorbbēne”. In: *Celtica* 22, pp. 48–63.

— (2011). “Reading the genetic code of early medieval Celtic orthography”. In: *LautSchriftSprache. Beiträge zur vergleichenden historischen Graphematik*. Ed. by Elvira Glaser, Seiler Anna, and Michelle Waldispühl. Medienwandel - Medienwechsel - Medienwissen 5. Zürich: Chronos, pp. 155–166.

— (1990b). “Notes on Old Irish and Old Welsh consonantal spelling”. In: *Celtic linguistics / Ieithyddiaeth Geltaidd: readings in the Brythonic languages. Festschrift for T. Arwyn Watkins*. Ed. by Martin J. Ball et al. Amsterdam Studies in the Theory and History of Linguistic Science 4.68. Amsterdam: John Benjamins, pp. 403–410.

— (1990a). “Retrieving the pronunciation of early Insular Celtic scribes: towards a methodology”. In: *Celtica* 21, pp. 178–190.

Hayden, Deborah and Paul Russell, eds. (2016). *Grammatica, gramadach and gramadeg: vernacular grammar and grammarians in medieval Ireland and Wales*. Studies in the History of the Language Sciences 125. Amsterdam: John Benjamins.

Hock, Hans Henrich (2019). "Old Irish consonant quality re-examined". In: *Historical Linguistics 2015: Selected papers from the 22nd International Conference on Historical Linguistics, Naples, 27-31 July 2015*. Ed. by Michela Cennamo and Claudia Fabrizio. Current Issues in Linguistic Theory 348. Amsterdam/Philadelphia: John Benjamin Publishing Company.

Hoijer, Harry (1933). *Tonkawa: An Indian Language of Texas*. Vol. 3. Handbook of American Indian Languages. Columbia University Press.

— (1946). "Tonkawa: An Indian Language of Texas". In: *Linguistic Structures of Native America*. Ed. by C Osgood. Vol. 6. Publications in Anthropology. Viking Fund.

— (1949). *An Analytical Dictionary of the Tonkawa Language*. Vol. 5. University of California Publications in Linguistics 1. University of California Press.

Holland, J. (1975). *Adaptation in Nature and Artificial Systems*. Ann Arbor, MI, USA: University of Michigan Press.

Iosad, Pavel (2022). "Mutation in Celtic". in press.

Isačenko, Alexander (1970). "East Slavic Morphophonemics and the Treatment of the jers in Russian: A Revision of Havlık's Law". In: *International Journal of Slavic Linguistics and Poetics* 13, pp. 73–124.

Jackson, Kenneth (1953). *Language and History in Early Britain: A Chronological Survey of the Brittonic Languages First to Twelfth Century A.D.* Edinburgh University Press.

Jaskuła, Kzrysztof (2006). *Ancient Sound Changes and Old Irish Phonology*. Wydawnictwo KUL.

Johnston, Elva (2013). *Literacy and identity in early medieval Ireland*. Studies in Celtic History 23. Woodbridge: Boydell.

Jurgec, Peter (2019). "Opacity in Šmartno Slovenian". In: *Phonology* 36, pp. 265–301. DOI: 10.1017/S0952675719000137.

Kager, Rene (1997). "Rhythmic Vowel Deletion in Optimality Theory". In: *Derivations and Constraints in Phonology*. Ed. by Iggy Roca. Oxford University Press, pp. 463–499.

Kaplan, Aaron (2008). "Noniterativity is an Emergent Property of Grammar". PhD thesis. University of California, Santa Cruz.

Kaplan, Max (2022). "Metrical Opacity, Stratal Derivation and Restructuring in Southern Pomo". University of California, Santa Cruz ms.

Kaplan, Maxwell (2020). "Southern Pomo Syncope is Metrically Conditioned: Metrical Opacity and Stratal Derivation". In: *Proceedings of the Linguistic Society of America*, pp. 584–598.

Kavanagh, Séamus (2001). *A Lexicon of the Old Irish Glosses in the Würzburg Manuscript of the Epistles of St. Paul*. Ed. by Dagmar Wodtko. Mitteilungen der Prähistorischen Kommission 45. Vienna: Verlag der Östereichischen Akademie der Wissenschaften.

Kawahara, Shigeto (2015a). "A Catalogue of Phonological Opacity in Japanese: Version 1.2". In: *Reports of the Keio Institute of Cultural and Linguistic Studies*. Vol. 46, pp. 145–174.

— (2015b). "Can we Use Rendaku for Phonological Argumentation?" In: *Linguistics Vanguard* 1.1, pp. 3–14.

Kenstowicz, Michael and Charles Kisseberth (1979). *Generative Phonology*. Academic Press.

Kiparsky, Paul (1971). "Historical Linguistics". In: *A Survey of Linguistic Science*. Ed. by W. O. Dingwall. University of Maryland Press, pp. 576–649.

Koch, John (1992). "'Gallo-Brittonic' vs 'Insular Celtic': The Inter-relationships of the Celtic Languages Reconsidered". In: *Bretagne et pays celtiques - langue histoire, civilisation. Mélanges offerts a la memoire de Léon Fleuriot*. Ed. by G Le Menn. Saint-Brieuc/Rennes, pp. 471–495.

LaCharité, Darlène and Carole Paradis (2002). "Addressing and disconfirming some predictions of phonetic approximation for loanword adaptation". In: *Langues et linguistique* 28, pp. 71–91.
— (2005). "Category preservation and proximity vs. phonetic approximation in loanword adaptation". In: *Linguistic Inquiry* 36, pp. 223–58.
Laing, Lloyd (2006). *The Archaeology of Celtic Britain and Ireland c. AD 400-1200*. Cambridge: Cambridge University Press.
Lash, Elliott (2017). "A quantitative analysis of e/i variation in Old Irish etar and ceta". In: *Ériu* 67, pp. 141–167.
— (2021). *The Minor Glosses Database*. Version 1.0. URL: `http://chronhib.maynoothuniversity.ie`.
Law, Vivien (1982). *The Insular Latin grammarians*. Studies in Celtic History 3. Woodbridge: Boydell.
— (1997). *Grammar and grammarians in the early Middle Ages*. Longman Linguistics Library. London and New York: Longman.
MacNeill, Eoin (1931). "Archaisms in the Ogham Inscriptions". In: *Proceedings of the Royal Irish Academy* 39, pp. 33–53.
McCarthy, John (2007). *Hidden Generalizations: Phonological Opacity in Optimality Theory*. Equinox Publishing.
— (2008). "The Serial Interaction of Stress and Syncope". In: *Natural Language and Linguistic Theory* 26, pp. 499–546.
McCone, Kim (1985). "The Würzburg and Milan Glosses: Our Earliest Sources of 'Middle Irish'". In: *Ériu* 36, pp. 85–106.
— (1996). *Towards a Relative Chronology of Ancient and Medieval Celtic Sound Change*. Maynooth: The Cardinal Press.
— (1997). *The Early Irish Verb*. Nass: The Leinster Leader.
— (2005). *A First Old Irish Grammar and Reader Including an Introduction to Middle Irish*. Medieval Irish Texts 3. Maynooth: Department of Old and Middle Irish.
McManus, Damian (1983). "A Chronology of the Latin Loan-Words in Early Irish". In: *Ériu* 34, pp. 21–71.
— (1984). "On Final Syllables in the Latin Loan-Words in Early Irish". In: *Ériu* 35, pp. 137–162.
— (1986). "Ogam: Archaizing, Orthography and the Authenticity of the Manuscript Key to the Alphabet". In: *Ériu* 37, pp. 9–31.
— (1991). *A Guide to Ogam*. An Sagart.
Mommsen, Theodor (1892). "Prosperi Tironis epitoma chronicon ed. primum a. CCCCXXXIII, continuata ad a. CCCLV". In: *Chronica minora saec. IV, V, VI, VII*. Ed. by Theodor Mommsen. Vol. 1. MGH Scriptores. Auctores antiquissimi 9. Berlin: Weidmann, pp. 341–499.
Moore, Donald (1970). *The Irish Sea Province in Archaeology and History*. Cardiff: Cambrian Archaeological Society.
Murphy, Gerard (1961). *Early Irish metrics*. Dublin: R.I.A., Hodges Figgis.
Nagle, Traci (2020). "Perception, Production and the Implementation of Phonological Opacity in the Bangla Vowel Chain Shift". PhD thesis. Indiana University.
Ó Buachalla, Breandán (1982). "Scribal practice, philology and historical linguistics". In: *Papers from the 5th international conference on historical linguistics*. Ed. by Ahlqvist Anders. Maynooth monographs 2. Amsterdam: John Benjamins, pp. 425–432.
Petersson, Herbert (1913). "Lateinische und griechische Etymologien". In: *Glotta* 4.3, pp. 294–299.
Rhodes, Richard (1985). "Lexicography and Ojibwa Vowel Deletion". In: *The Canadian Journal of Linguistics* 30.4, pp. 453–471.

Rose, Françoise (2014). “When Vowel Deletion Blurs Reduplication in Mojeño Trinitario”. In: *Reduplication in Indigenous Languages of South America*. Brill, pp. 375–399. DOI: https://doi.org/10.1163/97890004272415_015.
— (2019). “Rhythmic Syncope and Opacity in Mojeño Trinitario”. In: *Phonological Data and Analysis* 1.2, pp. 1–25.
Russell, Paul, Sharon Arbuthnot, and Pádraic Mórán (2017). *Early Irish Glossaries Database*. Available online at https://www.asnc.cam.ac.uk/irishglossaries/, cf. https://www.asnc.cam.ac.uk/irishglossaries/texts.php?versionID=9&ref=&page=13&perPage=10&readingID=.
Samko, Bern (2011). “Compensatory Lengthening in Harmonic Serialism”. UCSC MS.
Sanders, Robert Nathaniel (2003). “Opacity and Sound Change in the Polish Lexicon”. PhD thesis. University of California, Santa Cruz.
Sarauw, Christian (1900). *Irske Studier*. Copenhagen.
Schmidt, Karl Horst (1977). “Der Beitrag der keltiberischen Inschrift von Botorrita zur Rekonstruktion der protokeltischen Syntax”. In: *Word* 28, pp. 51–62.
Schrijver, Peter (1995). *Studies in British Celtic Historical Phonology*. Amsterdam and Atlanta: Rodopi.
Schumacher, Stefan (2004). *Die keltischen Primaverben*. Innsbruck: IBS.
Sims-Williams, Patrick (1990). “Dating the Transition to Neo-Brittonic: phonology and history, 400-600”. In: *Britain 400-600: Language and History*. Ed. by Alfred Bammesberger and Alfred Wollman. Heidelberg: Carl Winter, pp. 217–261.
— (1991). “The emergence of Old Welsh, Cornish and Breton orthography, 600–800: the evidence of Archaic Old Welsh”. In: *Bulletin of the Board of Celtic Studies* 38, pp. 20–86.
— (2003). *The Celtic inscriptions of Britain: phonology and chronology, c. 400-1200*. Publications of the Philological Society 37. Oxford/Boston: Blackwell.
— (2007). Aberystwyth: CMCS Publications, pp. 1–42.
— (2016). “Dating the Poems of Aneirin and Taliesin”. In: *Zeitschrift für celtische Philologie* 63.1.
Stifter, David (2006). *Sengoídelc: Old Irish for Beginners*. Syracuse, New York: Syracuse University Press.
— (2014). “The history of the Old Irish preverb to-”. In: *Linguistic and philological studies in Early Irish*. Ed. by Elisa Roma and David Stifter. Lewiston, NY/Lampeter: Edwin Mellen Press, pp. 203–246.
— (2015). “The language of the poems of Blathmac”. In: *The poems of Blathmac son of Cú Brettan: reassessments*. Ed. by Pádraig Ó Riain. Subsidiary Series 27. London: Irish Texts Society.
— (2017). “Phonology of Celtic”. In: *Handbook of Comparative and Historical Indo-European Linguistics. An International Handbook*. Ed. by Jared S. Klein, Brian Joseph, and Matthias Fritz. Handbücher zur Sprach- und Kommunikations-wissenschaft 41.1. Berlin/New York: Walter de Gruyter.
Stifter, David et al. (2021). *Corpus Palaeohibernicum (CorPH)*. Version 1.0. URL: http://chronhib.maynoothuniversity.ie.
Stokes, Whitley and John Strachan, eds. (1901). *Thesaurus Palaeohibernicus: a collection of Old-Irish glosses, scholia, prose, and verse, Vol. 1: Biblical glosses and scholia*. Cambridge: Cambridge University Press.
— eds. (1903). *Thesaurus Palaeohibernicus: a collection of Old-Irish glosses, scholia, prose, and verse, Vol. 2: Non-Biblical glosses and scholia; Old-Irish prose; names of persons and places; inscriptions; verse; indexes*. Cambridge: Cambridge University Press.
Thomas, Charles (1971). *Britain and Ireland in Early Christian times: AD 400-800*. London: Thames and Hudson.
Thurneysen, Rudolf (1946). *Grammar of Old Irish*. The Dublin Institute for Advanced Studies.

Tigges, Wim and Feargal Ó Béarra (2006). *An Old Irish Primer*. Nijmegen/Münster: Stichting Uitgeverij de Keltische Draak/Nodus Publikationen.

Torres-Tamarit, Francesc (2016). "Compensatory and opaque vowel lengthening in Harmonic Serialism". In: *Harmonic Grammar and Harmonic Serialism*.

Watkins, T. Arwyn (1966). "Points of similarity between Old Welsh and Old Irish orthography". In: *Billetin of the Board of Celtic Studies* 22, pp. 135–141.

Wheatley, David and Pavel Iosad (2021). "Acoustic Correlates of the Fortis/Lenis Distinction in Early 20th Century Donegal Irish". In: *13th Forum for Research on the Languages of Scotland and Ulster Conference*.

Yang, Xin-She (2021). "Chapter 6 - Genetic Algorithms". In: *Nature-Inspired Optimization Algorithms (Second Edition)*. Ed. by Xin-She Yang. Second Edition. Academic Press, pp. 91–100. ISBN: 978-0-12-821986-7. DOI: https://doi.org/10.1016/B978-0-12-821986-7.00013-5. URL: https://www.sciencedirect.com/science/article/pii/B9780128219867000135.

Zhang, Jie (2016). "Using nonce-probe tests and auditory priming to investigate speakers' phonological knowledge of tone sandhi". In: *Proceedings of the 5th International Symposium on Tonal Aspects of Languages*. Ed. by Christian DiCanio et al. International Speech Communication Association, pp. 12–18.

— (2019). "Speakers treat transparent and opaque alternation patterns differently — evidence from Chinese tone sandhi". In: *Proceedings of the 36th West Coast Conference on Formal Linguistics*. Ed. by Richard Stockwell et al. Cascadilla Proceedings Project, pp. 22–40.

Zhang, Jie, Yuwen Lai, and Craig Sailor (2009). "Opacity, phonetics, and frequency in Taiwanese tone sandhi". In: *Current issues in unity and diversity of languages: Collection of papers selected from the 18th International Congress of Linguists*. Ed. by Manghyu Pak. Linguistic Society of Korea, pp. 3019–3038.