

# Application of Classification Algorithms to Renaissance Music Attribution

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13 December 2013

## 1 Introduction

The goal of this project is to use classification techniques to assist in attempts to attribute pieces of contentious authorship to a single composer. I am particularly interested in the attribution of high Renaissance music and the work of the composer of the periods most enduring pieces, Josquin de Prez. In this paper, I explain the source of my data and its processing. Then, I outline the process of conducting classification experiments on the pieces, giving insight into what seem to be the most important factors in high Renaissance music attribution along the way. Finally, I briefly report the results of my experiments.

## 2 Background, Preliminary, and Related Work

Josquin des Prez (c. 1450-1521) enjoyed unrivaled popularity during his lifetime and for decades thereafter as a composer of polyphonic choral pieces. He came to be considered the central figure of Franco-Flemish school, and as a result of that identification with the larger school and his prestige in general, many printers began spuriously attributing pieces written by other composers to Josquin. As one German editor put it, "Now that Josquin is dead, he is putting out more works than when he was alive." The extent to which what were once canonical Josquin pieces could be questioned as misattributions was only realized in the last fifty or so years. Hence, much work has been done recently to try and sort out the misattributions from the veritable Josquin pieces.

Over the course of this project, I worked with Jesse Rodin, a professor at the Stanford Department of Music specializing in Renaissance music. Rodin and others have worked extensively over the last decade trying to work towards more conclusive attribution of a number of pieces that have endured since the high Renaissance, particularly a set of works that were once considered to be a part of the Josquin canon but have since been questioned. The work has consisted of historical (e.g. such and such piece could not have been written by this composer at this time because he was under the commission of this patron rather than that one) and musicological investigations. Rodin was interested in finding out if machine learning could provide any additional insight to how the problem may be solved or if machine learning techniques could provide an answer.

## 3 Data

The data used initially consisted of a collection of digitized compositions (in the `**kern` format) provided to me by the Josquin project ([josquin.stanford.edu](http://josquin.stanford.edu)). Table 1 shows the number of pieces in the dataset by composer.

### 3.1 Processing

Initially, on the recommendation of Rodin, I experimented with programmatically measuring how "conspicuous repetition" was used within a piece. I would consider a single measure (or measure and a half) for a single voice, represent that measure as a series of melodic intervals (without regard for the note durations), and compare that series of intervals to the series of intervals around it (4 to 6 measures) in other voices and assign that measure a score based on the average edit distance between its series and the series of those around it. In doing so, I hoped to quantify to what extent and in what way a short series of intervals formed the backbone of a piece, being repeatedly stretched out and transposed across voices, but nevertheless the same theme once controlled for note duration and absolute pitch.

I normalized these scores to between 0 and 1 and created a 100 element feature vector for each song where the  $i^{th}$  element is how many measures had a score of  $\frac{i}{100}$ . My intention was to use these vectors in a multinomial event model. Unfortunately, the resulting model had terrible results (about 34% training accuracy in a multi-class setting).

I moved away from the attempt at capturing how a theme is used and instead turned to traditional featurization. I used the jSymbolic library within the music21 package released by MIT. jSymbolic allows the extraction of features from a MIDI file (which I had converted the `**kern` files to). Using jSymbolic, I converted each piece into a vector of 185 features including pitch class histograms, melodic interval histograms, importance of different registers, and equality of certain features across voices, among other things. Finally, I normalized each feature.

## 3.2 Data Used in Modeling

The training data for my models consisted of the feature vectors for all composers other than the anonymous pieces and the questionable Josquin pieces. The vectors were labelled by composer, and pieces in the definitely Josquin and the nearly definitely Josquin category were classified together. There were a total of 465 compositions in the training set.

## 4 Modeling

I used the training data to train support vector classifiers, logistic regression classifiers, and a neural network. For the support vector classifiers and logistic regression classifiers, each model consisted of nine binary classifiers (trained to decide whether a composition should be attributed to a particular artist or the eight other composers), each of which used the same cost parameter. All support vector classifiers used a linear kernel. I used ten-fold cross validation to decide the cost parameter of the support vector classifiers and logistic regression classifiers. The neural network was trained using the Levenberg-Marquadt backpropagation update rule. I used a single hidden layer with ten neurons and a sigmoid transfer function, and an output layer also using a sigmoid transfer function. I repeatedly trained (using 70%/15%/15% train/test/validation proportions) the neural network with different initial conditions until one converged to a model with reasonably good performance.

The resulting models are shown in Table 3 and Table 4. Interestingly, there was little variance between the maximal cross-validation accuracy between rotationally invariant algorithms (the support vector classifiers, the L2-regularized logistic regression classifier) and the only rotationally sensitive algorithm (L1-regularized logistic regression). This seems to suggest that there were few irrelevant features among the 185 relative to the sample size. I could not eliminate more than a few features via either forward-search or backward-search, which is consistent with the thought that almost all features provided information relevant to classification.

That being said, I did use the RELIEFF algorithm with 10 nearest neighbors per class to see which features best distinguished an example. The strongest predictors according to RELIEFF are listed in table 4. Note that I did not use the weights produced by RELIEFF in training any models.

Over the course of model training, it became clear that the most frequently confused classes were Josquin and Pierre de la Rue (as seen in Table 2). This makes sense intuitively since of the composers considered, Josquin and de la Rue had arguably the most overlap in influences (they were members of the same generation of Netherlandish composers of high Renaissance polyphonic music). I have provided in Table 5 the most important elements in distinguishing between de la Rue and Josquin as determined by the RELIEFF algorithm.

## 5 Results

Once I finished training the models, I used them to predict the composer of each of the 191 pieces that had been attributed to Josquin, but were still of questionable authorship.

The models tended to classify in a manner that suggests they could generalize from the training examples reliably. For instance, several compositions were split into four movements, and each movement was classified separately by the models. If a particular model attributed a single movement in the composition to a particular composer, it attributed the remaining movements to the same composer a heavy majority of the time. Additionally, for any particular piece, the majority of models (and in most cases, all models) attributed the piece to the same composer.

Finally, the proportion of pieces attributed to each composer were consistent with what one would expect for a set of pieces from the period and area. Mouton, de la Rue, and Josquin were active and prolific over roughly the same period and in the same area (especially de la Rue and Josquin), so intuitively it seems like it should be the case that a random composition from the period (or of the general style of the Franco-Flemish school and hence associated with Josquin) that had been attributed to Josquin would either actually be composed by one of those three composers or be stylistically similar enough to one of the three that a model would classify it as one of them.

Composer	Pieces
Josquin (positively attributed)	96
Josquin (nearly positively attributed)	26
Agricola	5
Anonymous	8
Busnoys	3
Mouton	15
Obrecht	9
Ockeghem	91
de Orto	38
Pipelare	5
Pierre de la Rue	177
Josquin (questionable)	191
	664

Table 1: Number of compositions in dataset by composer

Composer	Josquin	Agricola	Busnoys	Mouton	Obrect	Ockeghem	de Orto	Pipelare	Rue
Josquin	33	0	0	0	0	2	2	0	11
Agricola	0	2	0	0	0	0	0	0	0
Busnoys	2	2	0	0	0	1	0	0	0
Mouton	1	0	0	1	0	0	1	0	2
Obrecht	0	0	0	0	2	1	0	0	0
Ockeghem	2	2	0	0	1	22	1	0	0
de Orto	0	0	0	0	0	1	8	0	3
Pipelare	0	0	0	0	0	0	0	2	0
Rue	1	2	0	0	0	1	2	0	45

Table 2: Testing confusion matrix for L2-Regularized L2-loss SVC. Note the dramatic drop in recall for Josquin caused by misclassifying Josquin pieces as PdIR pieces

Model	Cost Paramater	Training Accuracy	CV Accuracy
L2-Regularized L2-loss SVC	216	98.50%	76.97%
L2-Regularized L1-loss SVC	113	91.61%	76.98%
L1-Regularized L2-loss SVC	17	96.77%	76.99%
L1-Regularized LR	70	94.41%	76.75%
L2-Regularized LR	296	92.26%	75.27%

Table 3: Accuracy and cost parameters of various models in the multi-class setting

Model	Training Accuracy	Test Accuracy
Unilayer, ten neuron neural network (logsig transfer function)	99.65%	85.68%

Table 4: Accuracy of neural network

Feature	Weight
Most Common Pitch Prevalence	0.0437
Maximum Number of Independent Voices	0.0420
Number of Moderate Pulses	0.0376
Pitch Variety	0.0265
Pitch Class Variety	0.0257

Table 5: RELIEFF weights for binary classification problem between Josquin and Pierre de la Rue

Feature	Weight
Number of Moderate Pulses	0.0336
Maximum Number of Independent Voices	0.0306
Pitch Class Variety	0.0237
Importance of High Register	0.0228
Number of Common Melodic Intervals	0.0228
Voice Equality - Melodic Leaps	0.0227
Direction of Motion	0.0226
Pitch Variety	0.0218

Table 6: RELIEFF weights for multi-class classification problem



Piece	L2L2SVC	L2L1SVC	L1L2SVC	L1LR	L2-R	Nnet
'Jos1409-Planxit_audem_David.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos1410-Quam_pulchra_es.krn.mid.vec'	Mouton	Mouton	Mouton	Mouton	Mouton	Mouton
'Jos1411-Qui_edunt_me.krn.mid.vec'	Josquin	de la Rue	Josquin	de la Rue	de la Rue	Josquin
'Jos1412-Responde_mihi.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos1413-Si_dormiero.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos1414-Stetit_audem_Salomon.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos1501-Alleluia_Laudate_Dominum.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos1502-Beati_omnes_qui_timent_Dominum.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos1503-Beati_omnes_qui_timent_Dominum.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos1505-Bonitatem_fecisti_cum_servo_tuo.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos1506-Cantate_Domino_canticum_novum.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos1509-Confitemini_Domino.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos1510-Conserva_me_domine.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos1511-De_profundis_clamavi.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos1512-De_profundis_clamavi.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos1514-De_profundis_clamavi.krn.mid.vec'	Mouton	Mouton	Mouton	Mouton	Mouton	Mouton
'Jos1601-Deus_in_adiutorium_meum.krn.mid.vec'	Josquin	Josquin	Josquin	Josquin	Josquin	Josquin
'Jos1604-Domine_dominus_noster.krn.mid.vec'	Josquin	Josquin	Josquin	Josquin	Josquin	Josquin
'Jos1605-Domine_exaudi_orationem_meam.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos1606-Domine_ne_in_furore.krn.mid.vec'	de Orto	de Orto	de Orto	de Orto	de Orto	de Orto
'Jos1607-Domine_ne_in_furore.krn.mid.vec'	de la Rue	Josquin	de la Rue	Josquin	Josquin	Josquin
'Jos1608-Domine_ne_in_furore.krn.mid.vec'	Mouton	de la Rue	de la Rue	de la Rue	de la Rue	Mouton
'Jos1609-Domine_ne_projicias_me.krn.mid.vec'	Mouton	de la Rue	de la Rue	Mouton	Ockeghem	de la Rue
'Jos1702-Illumina_oculos.krn.mid.vec'	de Orto	Josquin	de Orto	Josquin	Josquin	de Orto
'Jos1703-In_dominio_confido.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos1704-In_exitu_Israel_de_Egypto.krn.mid.vec'	Josquin	Josquin	Josquin	Josquin	Josquin	Josquin
'Jos1705-In_pace_in_idipsum.krn.mid.vec'	Josquin	de la Rue	de la Rue	de la Rue	de la Rue	de Orto
'Jos1706-Iniquos_odio_habui.krn.mid.vec'	Josquin	Josquin	Josquin	Josquin	Josquin	Josquin
'Jos1707-Jubilate_Deo_omnis_terra.krn.mid.vec'	de Orto	de Orto	de Orto	de Orto	de Orto	de Orto
'Jos1708-Judica_me_Deus.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos1711-Laudate_pueri_Dominum.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos1712-Letare_nova_Syon.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos1713-Levavi_oculos_meos.krn.mid.vec'	Mouton	Josquin	de la Rue	Josquin	Josquin	de la Rue
'Jos1801-Mirabilia_testimonia_tua_Domine.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos1802-Mirabilia_testimonia_tua.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos1808-Qui_habitat_in_adiutorio_altissimi.krn.mid.vec'	de Orto	de Orto	Agricola	Josquin	Josquin	de Orto
'Jos1901-Christus_mortuus_est.krn.mid.vec'	Mouton	Mouton	Mouton	Mouton	Mouton	Mouton
'Jos1902-Ecce_video_celos_apertos.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos1905-In_illo_tempore_assumpsit_Jesus.krn.mid.vec'	Josquin	de la Rue	Josquin	de la Rue	de la Rue	de la Rue
'Jos1906-In_illo_tempore_stetit_Jesus.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos1908-In_principio_erat_verbum.krn.mid.vec'	Josquin	de la Rue	Josquin	Josquin	Josquin	Josquin
'Jos1910-Inter_natos_mulierum.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	Obrecht
'Jos1912-Lectio_actuum_apostolorum.krn.mid.vec'	de la Rue	de la Rue	Agricola	de la Rue	de la Rue	de la Rue

Piece	L2L2SVC	L2L1SVC	L1L2SVC	L1LR	L2-R	Nnet
'Jos2002-Magnificat_Tertii_toni.krn.mid.vec'	de Orto	Ockeghem	de Orto	de la Rue	de la Rue	de Orto
'Jos2003-Magnificat_Quarti_toni.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos2004-Magnificat_Quinti_Verse_6_Fecit_potentiam.krn.mid.vec'	Josquin	Josquin	Josquin	de la Rue	de la Rue	de la Rue
'Jos2006-Missus_est_Gabriel.krn.mid.vec'	Mouton	de la Rue	de la Rue	de la Rue	de la Rue	Mouton
'Jos2008-Nunc_dimittis_krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	Josquin	de la Rue
'Jos2011-Responsum_acceperat_Simeon.krn.mid.vec'	Mouton	Obrecht	Mouton	Mouton	Ockeghem	Obrecht
'Jos2013-Sic_Deus_dilexit_mundum_Circumdederunt_me.krn.mid.vec'	Mouton	de la Rue	Mouton	de la Rue	de la Rue	Mouton
'Jos2014-Tulerunt_Dominum.krn.mid.vec'	de Orto	de Orto	de Orto	de Orto	de Orto	de Orto
'Jos2016-Verbum_caro_factum_est.krn.mid.vec'	Josquin	Josquin	Josquin	Josquin	Josquin	Josquin
'Jos2103-Ave_verum_corpus.krn.mid.vec'	Obrecht	Obrecht	Obrecht	Obrecht	Obrecht	Obrecht
'Jos2104-Ave_verum.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos2105_2-Huc_me_sydereo_a_6.krn.mid.vec'	Josquin	Josquin	Josquin	Josquin	Josquin	Josquin
'Jos2106-Magnus_es_tu_domine.krn.mid.vec'	Josquin	Josquin	Josquin	Josquin	Josquin	Josquin
'Jos2109-O_bone_et_dulcissime_Jesu.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos2202-Pange_lingua_gloriosi.krn.mid.vec'	Josquin	Josquin	de Orto	Josquin	Josquin	Josquin
'Jos2207-Victime_paschali_laudes.krn.mid.vec'	de Orto	de Orto	de Orto	de Orto	Josquin	de Orto
'Jos2301-Alma_redemptoris_mater.krn.mid.vec'	Josquin	Josquin	Josquin	Josquin	Josquin	Josquin
'Jos2304-Ave_Maria_benedicta_tu.krn.mid.vec'	de Orto	de Orto	de Orto	de la Rue	de la Rue	de Orto
'Jos2305-Ave_Maria.krn.mid.vec'	Mouton	de la Rue	Mouton	de la Rue	de la Rue	Mouton
'Jos2308-Ave_maris_stella.krn.mid.vec'	de la Rue	Josquin	de la Rue	Josquin	Josquin	de la Rue
'Jos2310-Ave_mundi_spes.krn.mid.vec'	Josquin	Josquin	Josquin	Josquin	Josquin	Josquin
'Jos2311-Ave_nobilissima_creatura.krn.mid.vec'	Josquin	Josquin	Josquin	Josquin	Josquin	Josquin
'Jos2312-Ave_virgo_sanctissima.krn.mid.vec'	Josquin	de Orto	Josquin	Josquin	Josquin	de Orto
'Jos2405-Inviolata_integra_et_casta_es.krn.mid.vec'	Mouton	de la Rue	Mouton	Mouton	de la Rue	Mouton
'Jos2406-Mittit_ad_virginem.krn.mid.vec'	Josquin	Josquin	Josquin	Josquin	Josquin	Josquin
'Jos2407-Nesciens_mater_virgo.krn.mid.vec'	Josquin	Obrecht	Josquin	Josquin	Josquin	Josquin
'Jos2408-Obsecro_te_domina.krn.mid.vec'	Josquin	Josquin	Josquin	Josquin	Josquin	Josquin
'Jos2501-Recordare_virgo_mater.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos2502-Regina_celi_letare.krn.mid.vec'	de Orto	Josquin	de Orto	de Orto	Josquin	de Orto
'Jos2503-Regina_celi_letare.krn.mid.vec'	Josquin	Josquin	Josquin	Josquin	Josquin	Josquin
'Jos2506-Salve_regina.krn.mid.vec'	Josquin	Josquin	Josquin	Josquin	Josquin	Josquin
'Jos2507-Sancta_Maria_virgo_virginum.krn.mid.vec'	Josquin	de la Rue	Josquin	de la Rue	de la Rue	Josquin
'Jos2508-Sancta_mater_istud_agas.krn.mid.vec'	Josquin	Ockeghem	Josquin	Josquin	Josquin	Ockeghem
'Jos2511-Verbum_bonum_et_suave.krn.mid.vec'	Josquin	Josquin	Josquin	Josquin	Josquin	Josquin
'Jos2512-Virgo_prudentissima.krn.mid.vec'	Josquin	Josquin	Josquin	Josquin	Josquin	Josquin
'Jos2601-Absolve_Quaesumus_Domine.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos2604-Deus_pacis_reduxit.krn.mid.vec'	de la Rue	de la Rue	Josquin	Josquin	Josquin	Josquin
'Jos2608-O_admirabile_commercium_Verbum_caro_factum_est.krn.mid.vec'	Ockeghem	Ockeghem	Ockeghem	de la Rue	de la Rue	Josquin
'Jos2610-Puer_natus_est_nobis.krn.mid.vec'	Mouton	Mouton	Mouton	Mouton	Mouton	Mouton
'Jos2611-Queramus_cum_pastoribus.krn.mid.vec'	Mouton	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos2612-Salva_nos_domine.krn.mid.vec'	Mouton	de la Rue	Mouton	Mouton	de la Rue	Mouton
'Jos2613-Sancta_trinitas.krn.mid.vec'	Mouton	Mouton	Mouton	Mouton	Mouton	Mouton
'Jos2614-Sancti_Dei_omnes.krn.mid.vec'	Mouton	Josquin	Josquin	Josquin	Josquin	de la Rue
'Jos2615-Te_Deum.krn.mid.vec'	de Orto	de la Rue	de Orto	de Orto	de la Rue	de Orto
'Jos2616-Te_Deum_laudamus.krn.mid.vec'	Mouton	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos2617-Tua_est_potentia.krn.mid.vec'	Josquin	Josquin	Josquin	Josquin	Josquin	Josquin
'Jos2618-Veni_sancte_spiritus.krn.mid.vec'	Josquin	Josquin	Josquin	Josquin	Josquin	Josquin
'Jos2702-A_lombre_dung_buissonnet.krn.mid.vec'	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue	de la Rue
'Jos2703-Cela_sans_plus.krn.mid.vec'	Josquin	Josquin	Josquin	Josquin	Josquin	de Orto
'Jos2704-Cela_sans_plus.krn.mid.vec'	Josquin	Josquin	de la Rue	de la Rue	de la Rue	Josquin
'Jos2706-De_tous_biens_plaine.krn.mid.vec'	de Orto	Josquin	de Orto	de Orto	Josquin	de Orto