Annotation automatisée des métadonnées structurelles dans les partitions musicales

Cas des modulations et des cadences pour la forme sonate

Automated annotation of structural metadata in musical scores

Laurent Feisthauer

Soutenance pour l'obtention du doctorat de l'université de Lille, spécialité Informatique

Université de Lille

Encadrement : Louis Bigo – Mathieu Giraud – Florence Levé

Many thanks to the jury !

Marc Rigaudière	Professeur, Univ. Reims Champagne-Ardennes	*rapporteur*
Philippe Rigaux	Professeur, CNAM	*rapporteur*
David R. W. Sears	Assistant Professor, Texas Tech University	*examinateur*
Marc Tommasi	Professeur, Univ. Lille	*examinateur*
Anja Volk	Associate Professor, Utrecht University	*examinatrice*
Louis Bigo	Maître de conférences, Univ. Lille	*co-encadrant*
Mathieu Giraud	Directeur de recherche, CNRS	*co-directeur*
Florence Levé	Maître de conférences, UPJV, Amiens	*co-directrice*

Computational Music Analysis

Bridges ?

Music analysis*

- Study of musical objects
- Low-level music objects : pitch, rhythm...
- **High-level music concepts**
- Linked to music history
- Explain how music creates feelings

Computer science

- Study of algorithmic process
- Handle numbers and data
- Process exact instructions
- **Can the computer understand the music abstraction ?**

* mainly for Western classical music

Pythagore

Consonant and dissonant intervals

Blacksmith sounds

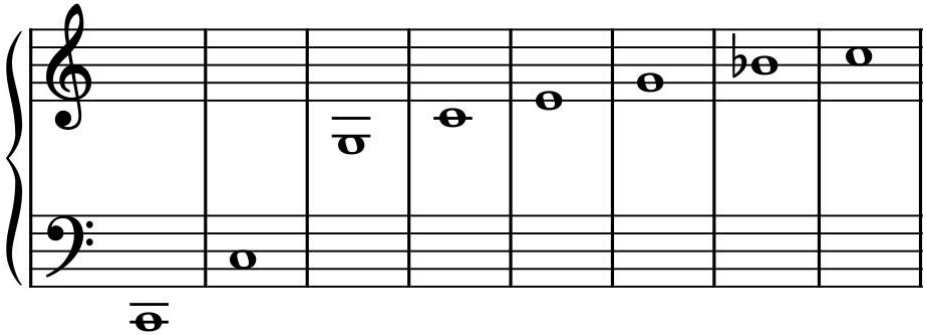
- Octave 2:1
- Fifth 3:2
- Fourth 4:3
- Major second 9:8

Musica universalis, ~ 500 BC

Rameau

Traité de l'harmonie réduite à ses principes naturels, 1722

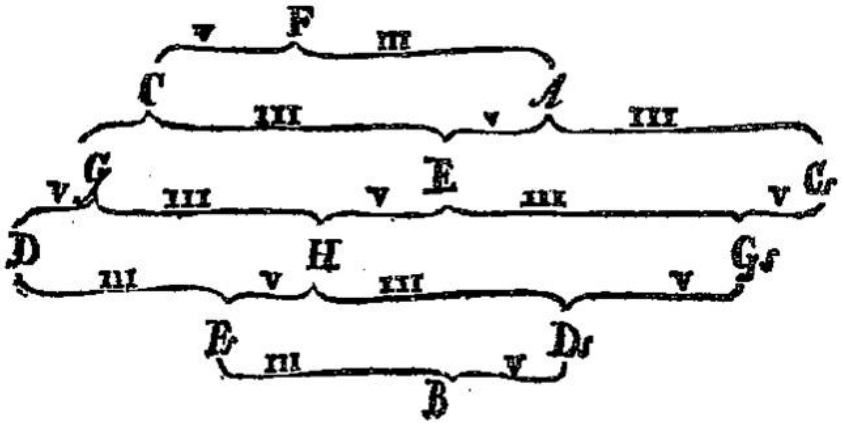
Harmonics of the C pitch

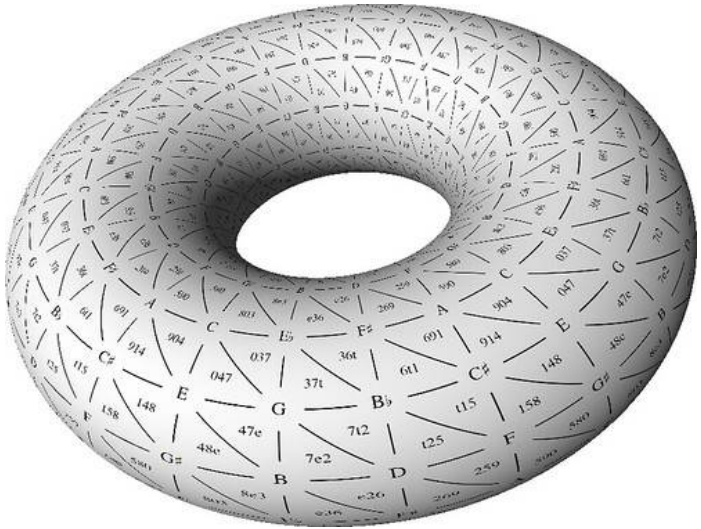


The six first natural harmonics of a pitch are the pitches of its major triad

Euler

Tentamen novae theoriae musicae ex certissismis harmoniae principiis dilucide expositae, 1739





Tonnetz, a spatial representation
of acoustic proximity between pitches.

It has a toroidal form (like a donut).

Ada Lovelace

« la machine pourrait composer de manière scientifique et élaborée des morceaux de musique de n'importe quelle longueur ou degré de complexité… »

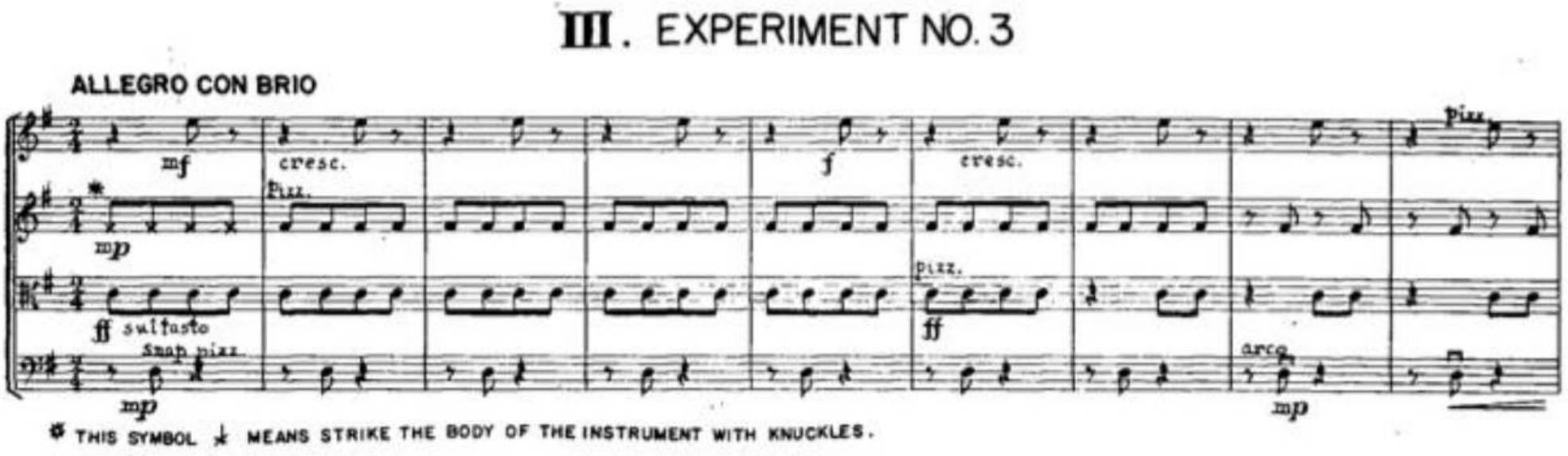
« the Engine might compose elaborate and scientific pieces of music of any degree of complexity or extent. »

A sketch of the analytical engine from Scientific Memoirs, 1843

L. Hiller and L. Isaacson

Illiac suite, 1955-1956

Computer Music
Hidden Markov Model

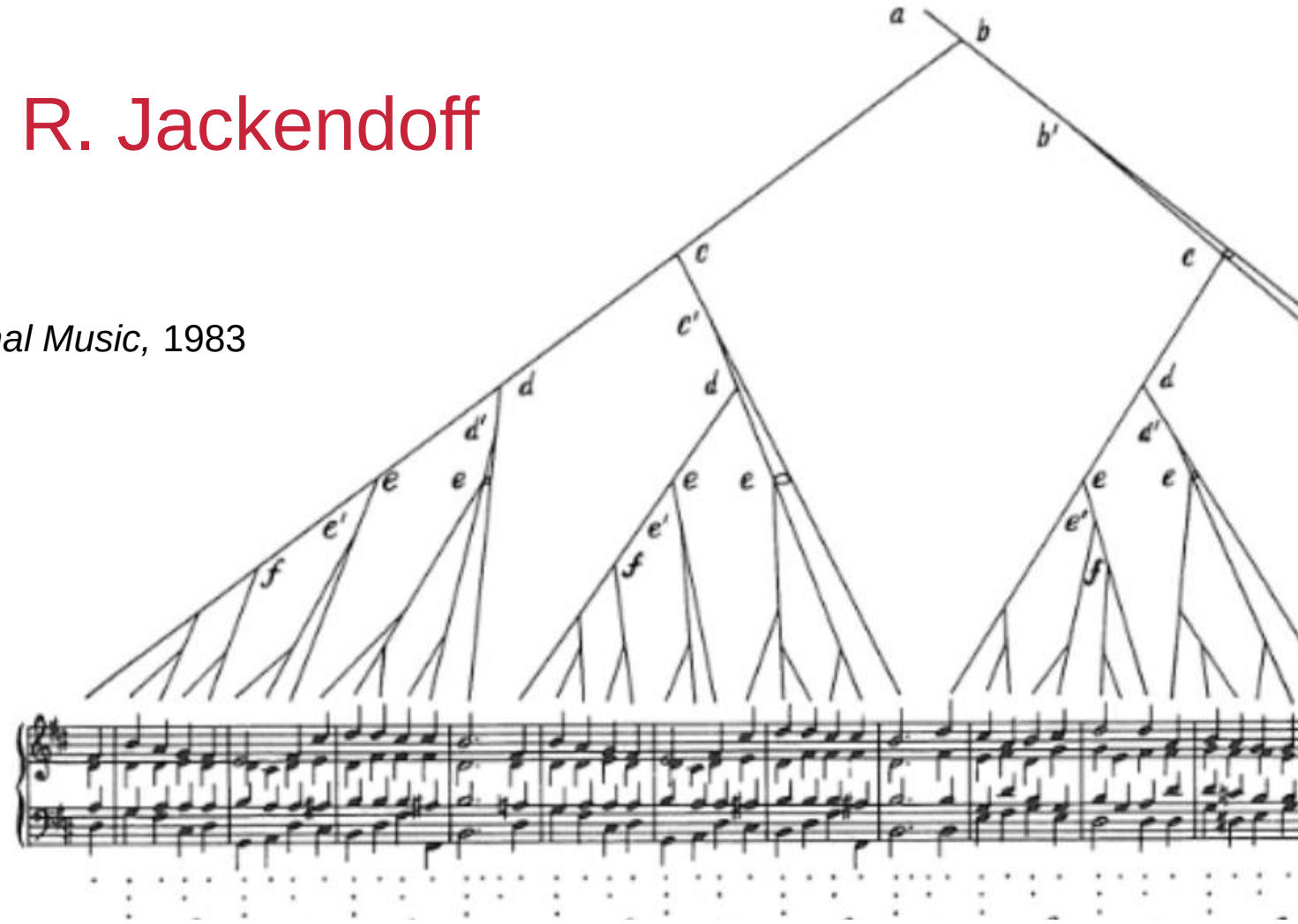


F. Lerdahl and R. Jackendoff

A Generative Theory of Tonal Music, 1983

Musical structure as a tree

Computational structure



Computational Music Analysis

Attention si ce slide est modifié
Modifier aussi les copies

Bridges

.

Music analysis

- XXX Music score / niveau neutre ? / écoute XXX ?

- Low-level music objects : pitch, rhythm...
- **High-level music concepts**

- Linked to music history
- Explain how music creates feelings

Computer science

- Study of algorithmic process

- Handle numbers and data

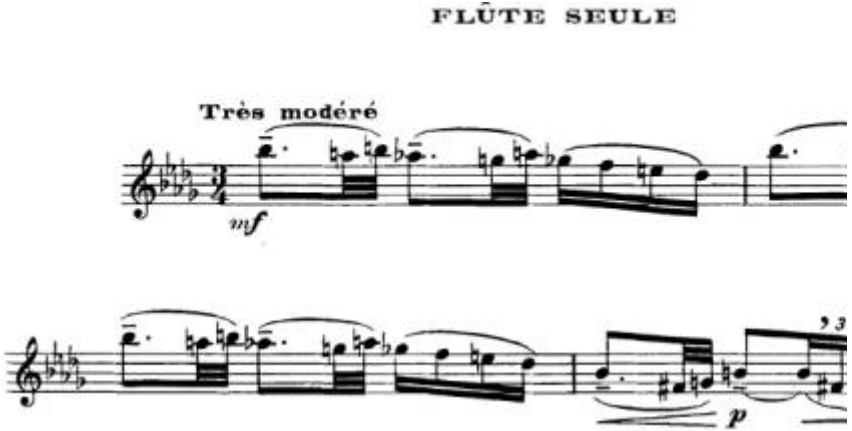
- Process instructions **that can't be**

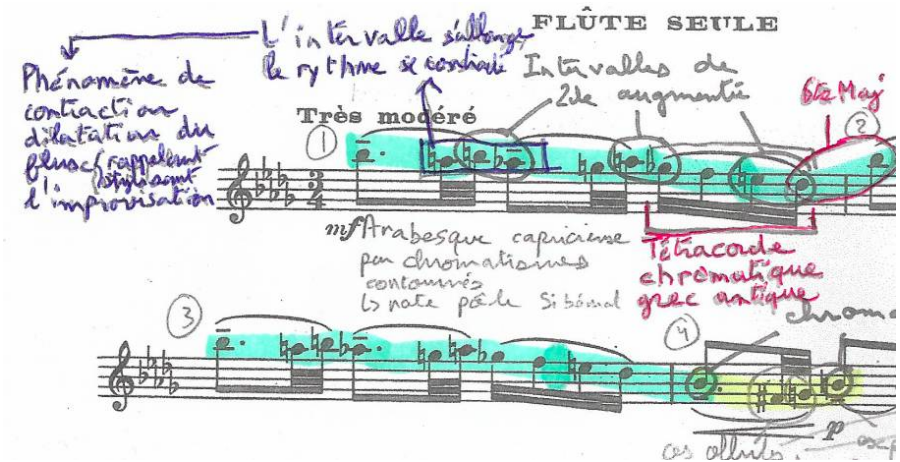
  wrong *XXX je ne comprends pas XXX*

A SUPPRIMER

Computational Music Analysis* (CMA)

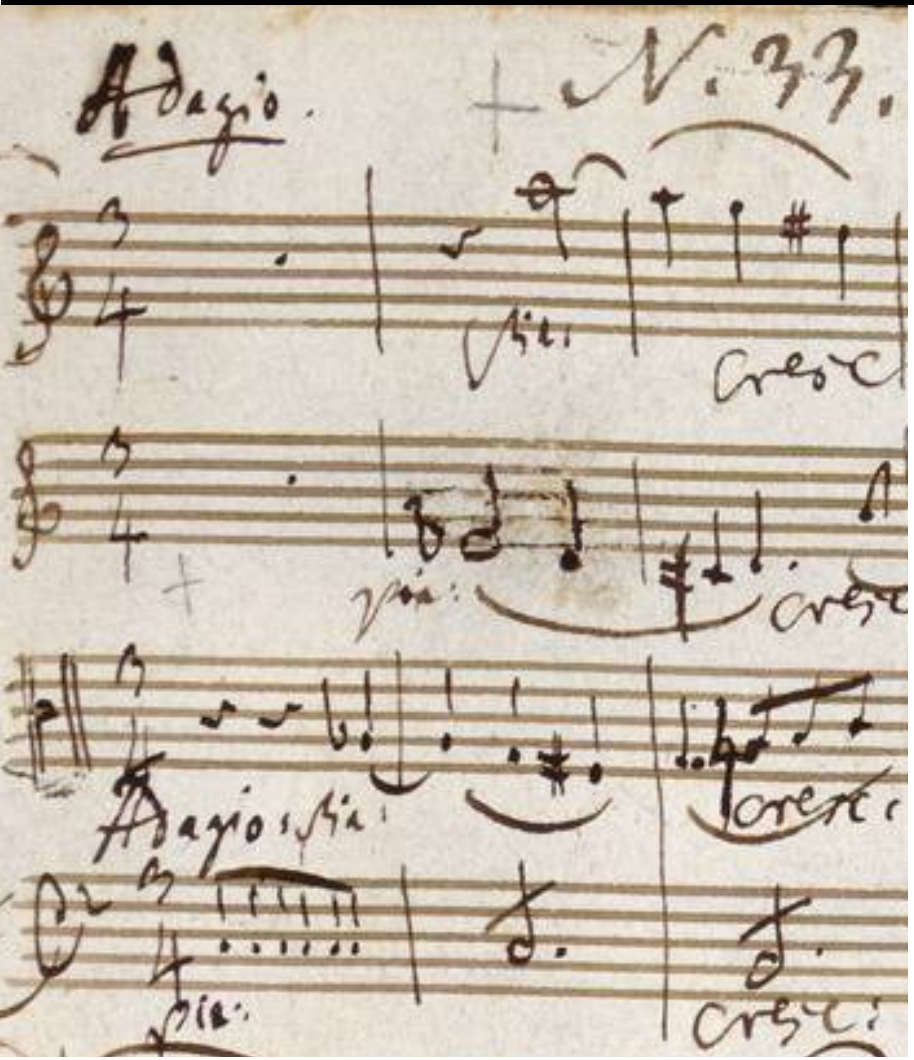
From low-level music objects to **high-level music concepts**





- CMA **models** these objects and concepts
- CMA propose **methods and algorithms** to compute music annotations

* for Western classical music



Defense Roadmap

What is tonality ? (Music, CMA previous studies)

What are cadences ? (music, CMA previous studies)

Thesis contributions, towards *high-level music concepts*

- Corpus
- **Modulation estimation**
- **Cadence detection**
- MC detection

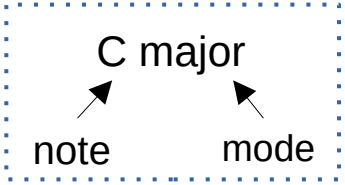
Conclusion, Applications, Perspectives

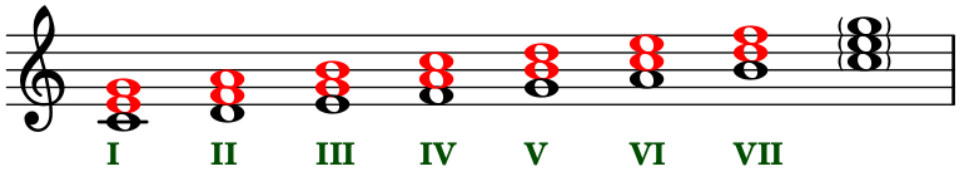
Mozart, String Quartet « Dissonnances » K 465, British Library

What is tonality ?

The word « *tonalité* » is ambiguous in French :

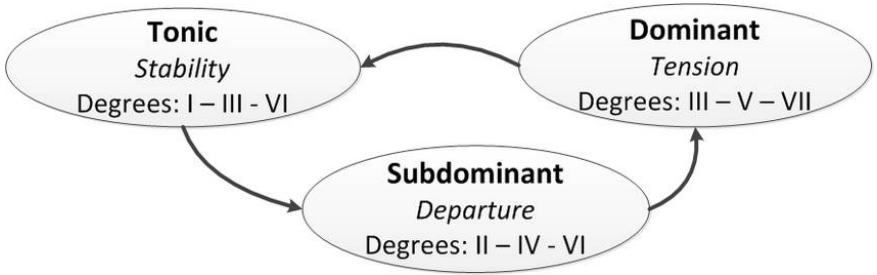
- « *Tonalité* » as the tonal system (related to the common practice period)
- « *Tonalité* » as a key



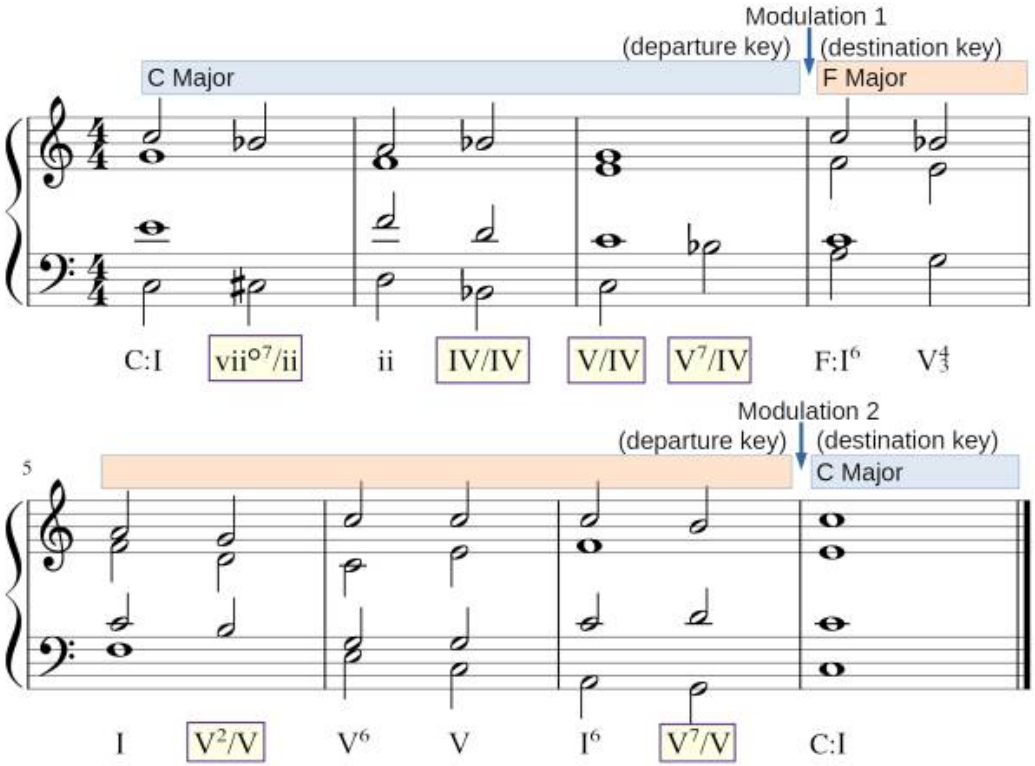


Scale

Functions and relationship

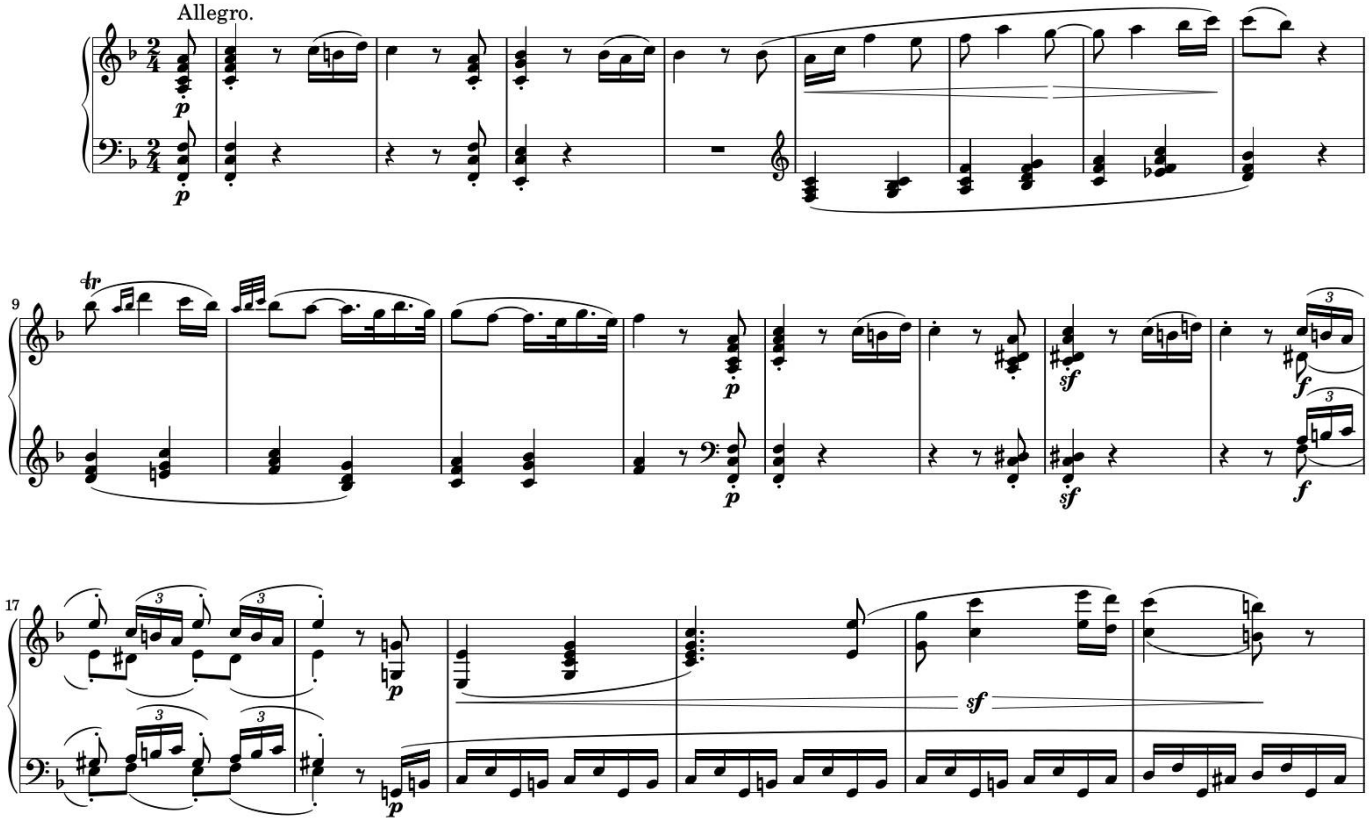


Keys



Two kind of keys :

- Global key or main key, for the whole piece
  C Major in the exemple
- Local key, for a given instant
  C Major - F Major - C Major

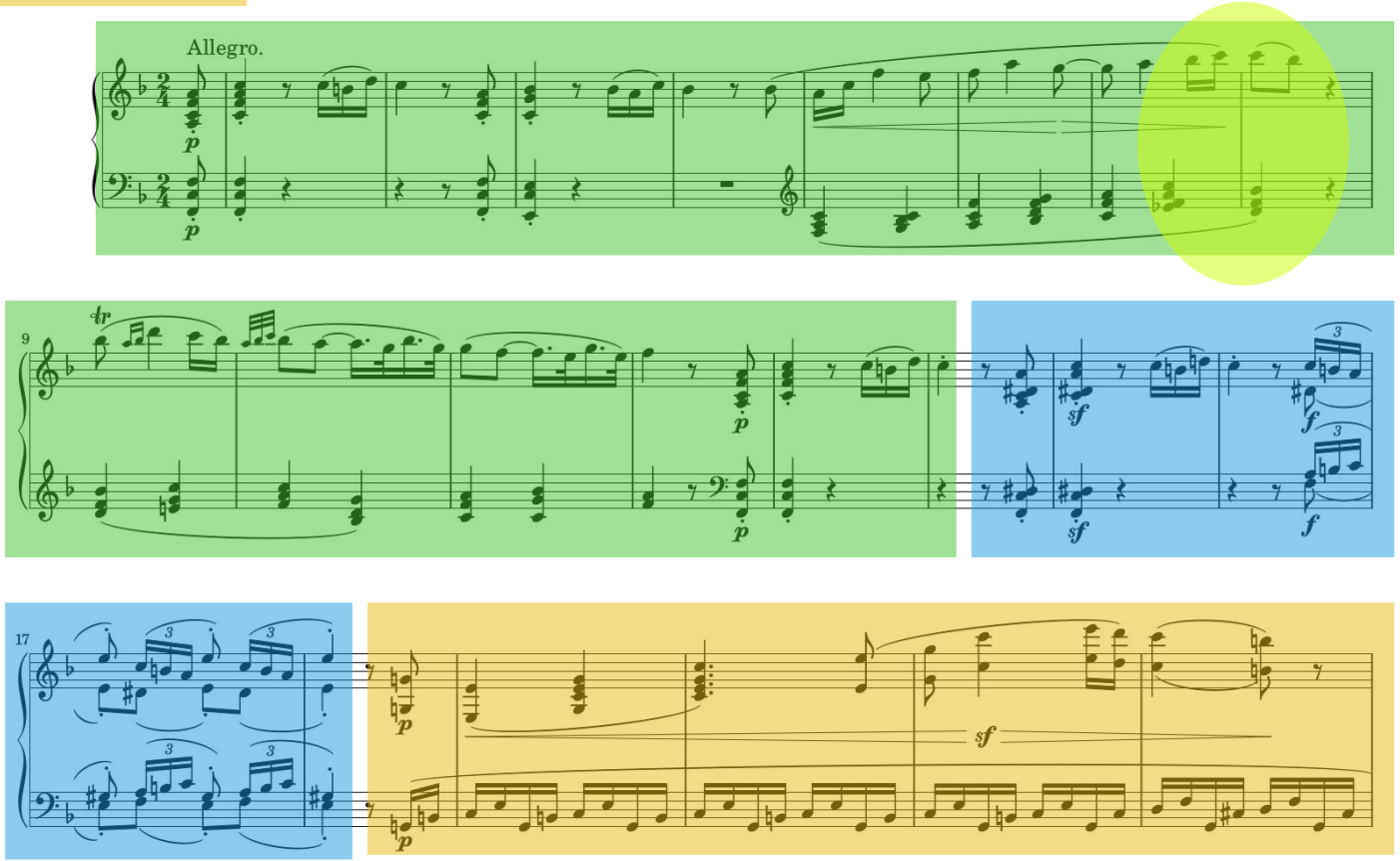


L. V. Beethoven , piano sonata #6 op10 n°2, 1st movement

Two modulations :

Where are they ?

To hear them, try to identify where your harmonic expectations are evolving.

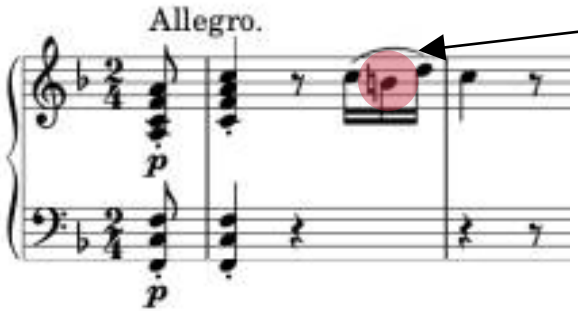


L. V. Beethoven , piano sonata #6 op10 n°2, 1st movement

Methods for key estimation

- First approaches : looking at pitches and matching them against the scale of a key
  [Longuet-Higgins and Steedman.,1971], [Vos and Van Geenen, 1996]

→ ***rules*** *linked to music theory*



Not a pitch of the F Major scale
NON-CHORD TONE

Methods for key estimation

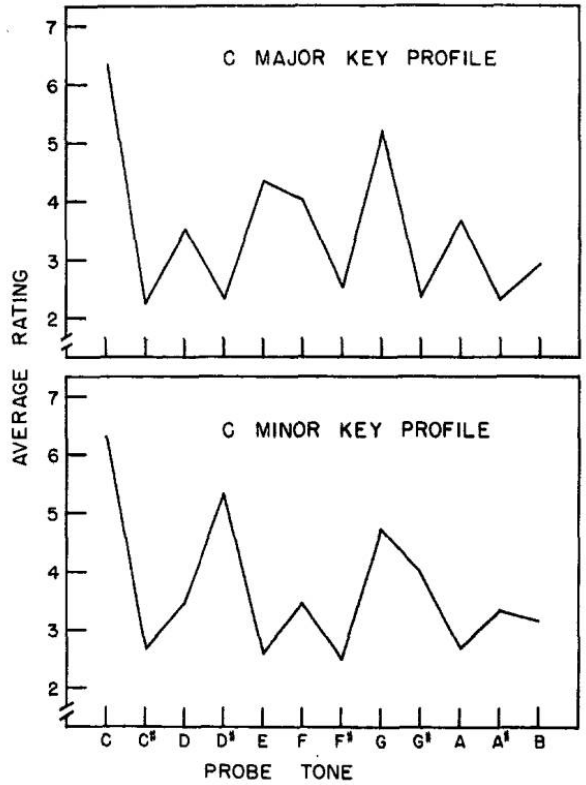
- First approaches : looking at pitches and matching them against the scale of a key
  [Longuet-Higgins and Steedman.,1971], [Vos and Van Geenen, 1996]

→ ***rules*** *linked to music theory*

- More flexible *Key Profiles* : weights for each pitch given the key
  [Krumhansl and Kessler,1982], [Temperley,1999], [Aarden,2003]…

→ ***rules****, but also* ***human/machine learning*** *of weights on music data*

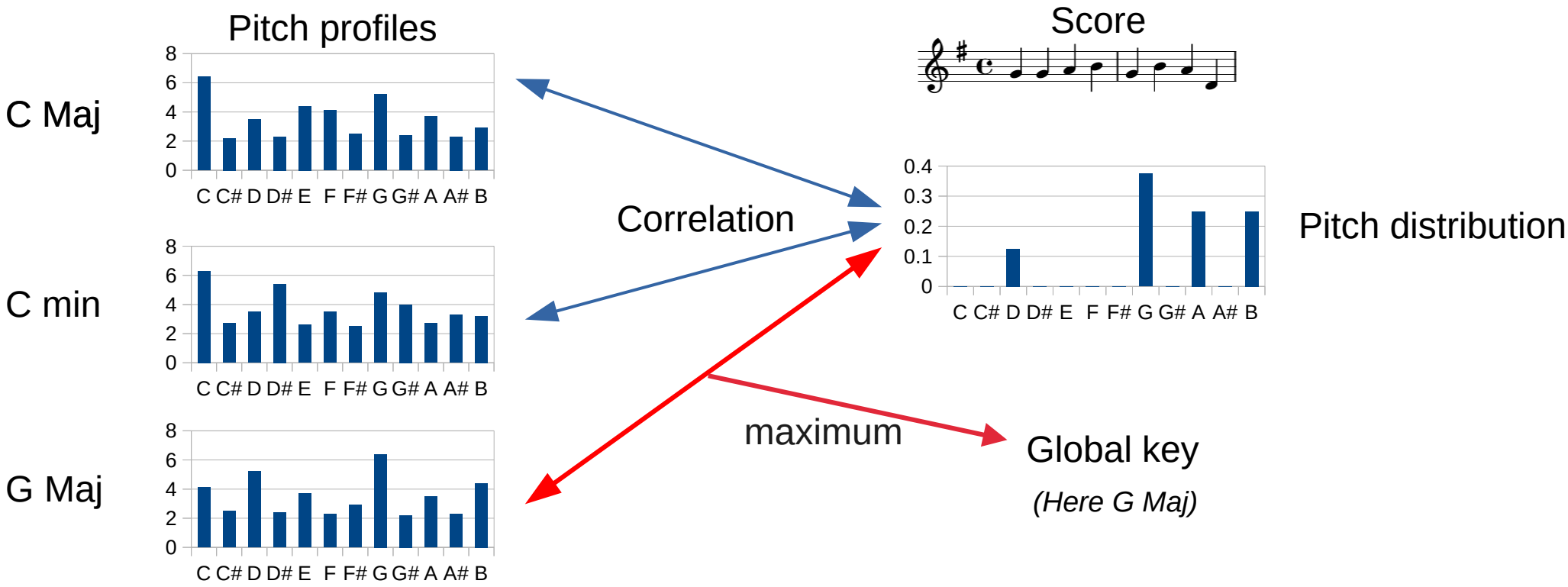
Key profiles



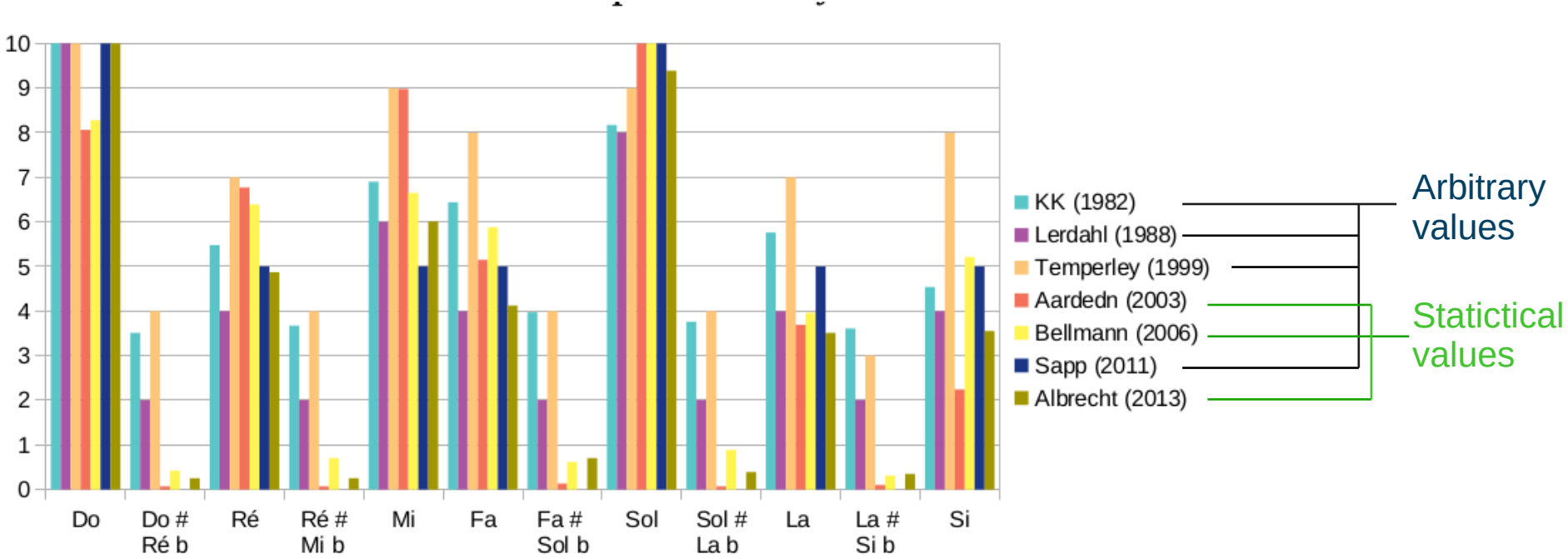
Krumhansl and Kessler. Tracing the dynamic changes in perceived tonal organization in a spatial representation of musical keys, 1982.

Give a weight to each pitch related to its importance regarding the key.

Global key estimation



A variety of pitch profiles



Methods for key estimation

- First approaches : looking at pitches and matching them against the scale of a key
  [Longuet-Higgins and Steedman.,1971], [Vos and Van Geenen, 1996]
  → ***rules*** *linked to music theory*

- More flexible *Pitch Profiles : weights for each pitch given the key*
  [Krumhansl and Kessler,1982], [Temperley,1999], [Aarden,2003]…
  → ***rules****, but also* ***human/machine learning*** *of weights on music data*

- Recent approaches, more flexible learning models
  Hidden Markov Model [Chai,2004], [Mearns,2011], [Napoles Lopez,2019]
  Neural networks [Chen and Su,2018-2019], [Micchi et al.,2020]
  → *mainly* ***machine learning***

Methods for key estimation

- Already solid approaches… mostly for global key estimation
- Model the hierarchy between pitches but do not consider temporal progressions.
- Machine learning approaches are not helpful to model the tonal system.

What is a cadence ?

What is a cadence ?

Harmonic formulae closing or suspending the musical flow. It ends a musical sentence.

Authentic cadences (AC)

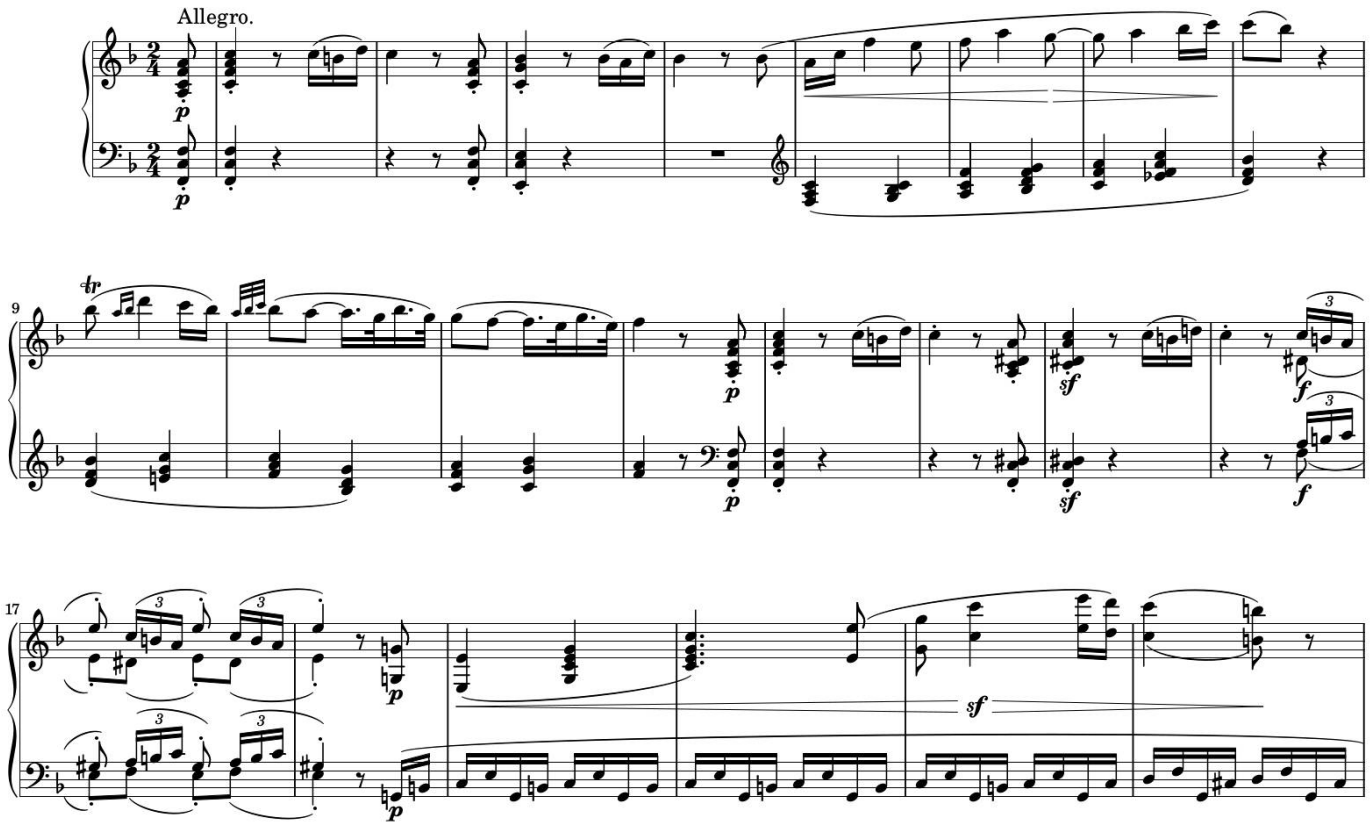
- **Conclusive**
- Arrival on a tonic harmony
- Imperfect (IAC) / Perfect (PAC)

Half cadences (HC)

- **Suspensive**
- Arrival on a dominant harmony
- HC

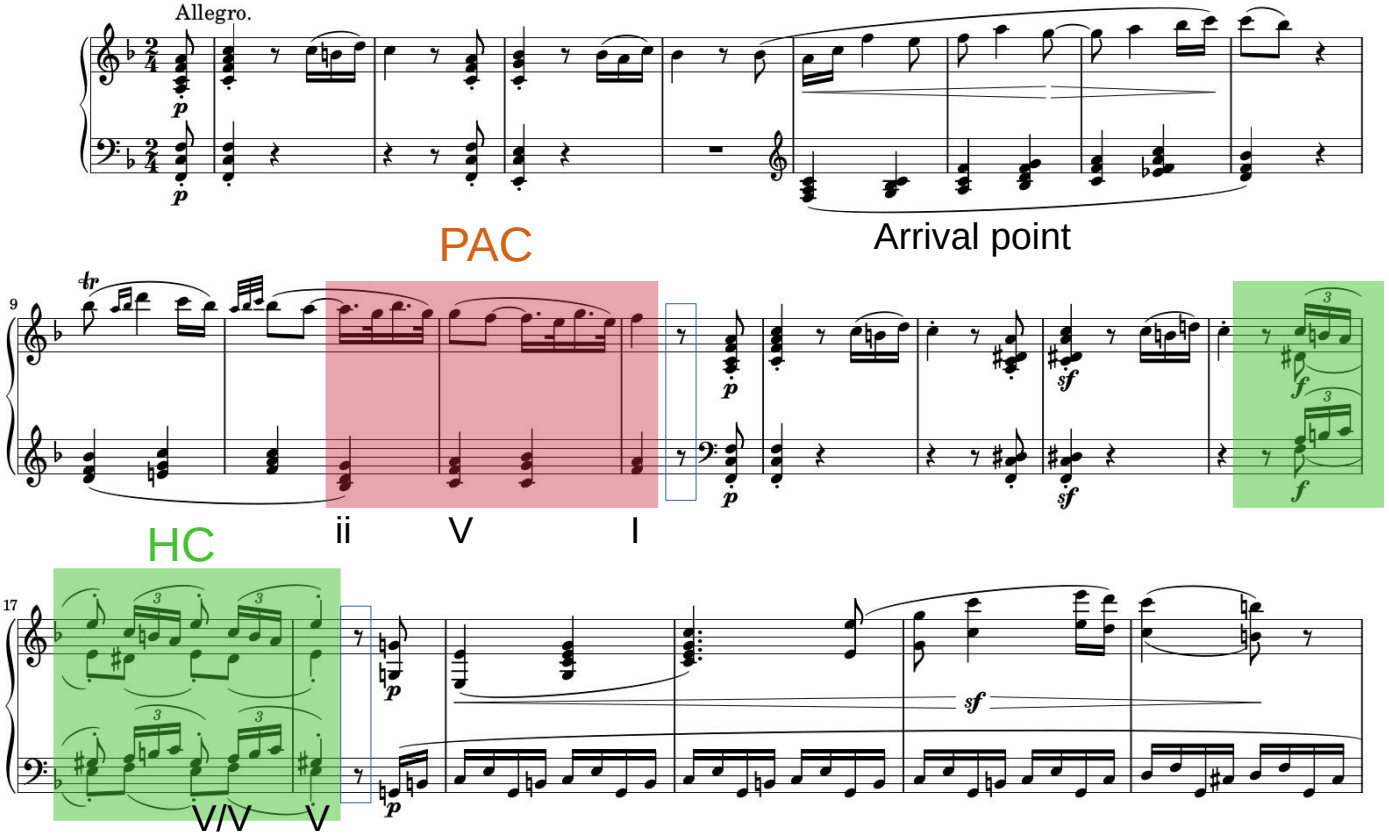
Deceptive (DC) and Evaded cadences (EV)

- **Denied arrival** instead of expected tonic harmony



There are 2 cadences in this extract.

L. V. Beethoven , piano sonata #6 op10 n°2, 1st movement



L. V. Beethoven , piano sonata #6 op10 n°2, 1st movement

Models and detection of cadences

- Perception studies
  [Sears and al.,2017;2017;2018], [Smit and al.,2020]

Perception studies *[Sears and al.,2017;2017;2018], [Smit and al.,2020]*

- The *most conclusive and expected cadence is the PAC*, the less conclusive is the EV. The less expected is the HC.
- Musicians tend to *listen to the bass* to identify a musical end.
- Some *features* like a cadential trill help people to identify the cadence.
- Events near *before* the arrival point of the cadence are the *most predictable*
- Events directly *after* the arrival point of the cadence are the *less predictable*

Models and detection of cadences

- Perception studies
  [Sears and al.,2017;2017;2018], [Smit and al.,2020]

- Cadence detection in monophonic pieces
  [Kranenburg et al.,2014]

Kranenburg et al.

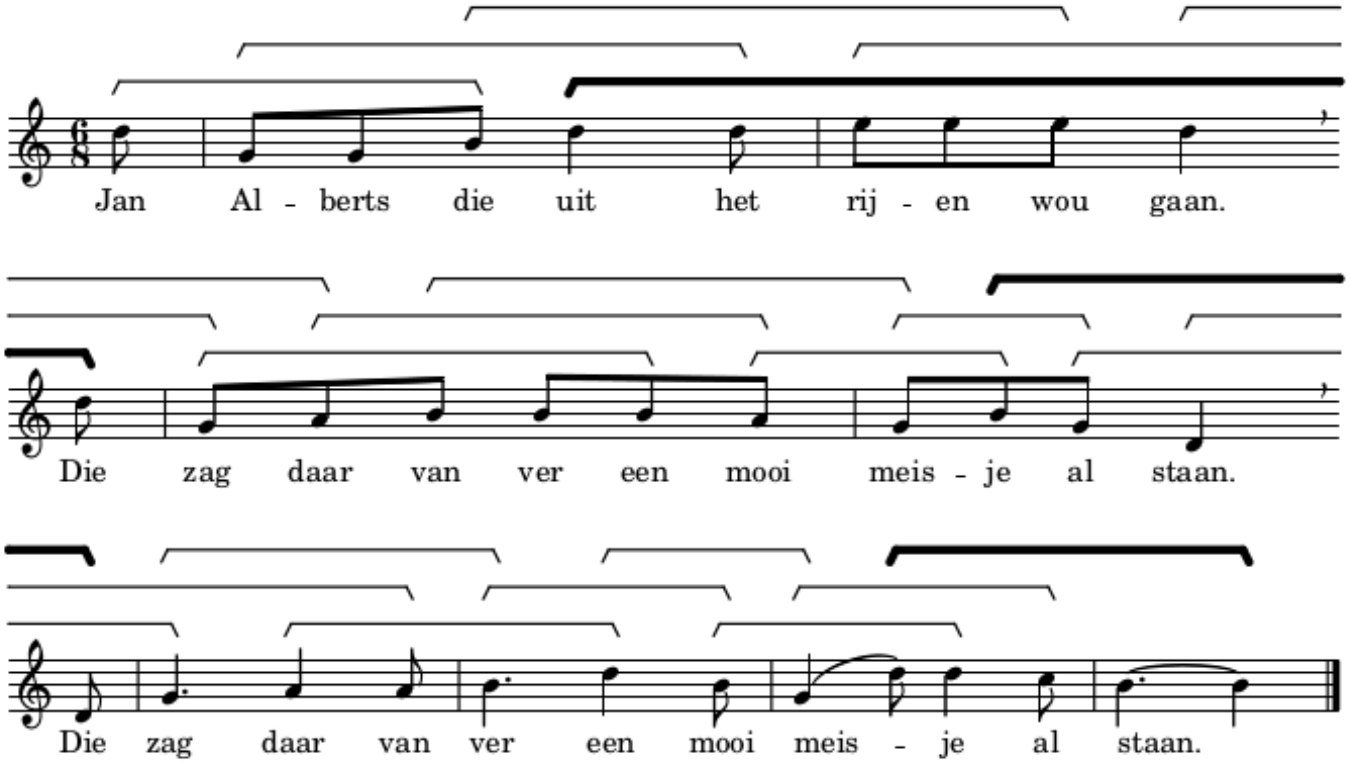
Kranenburg et al.,2014

Features (pitch, note trigrams)

- Pitch
- Rhythm
- Contour
- Textual
- Contextual
- Narmour closure

Cadence detection on the *Meertens Tune Collection*

F1 measure = 0.8



Models and detection of cadences

- Perception studies
  [Sears and al.,2017;2017;2018],[Smit and al.,2020]

- Cadence detection in monophonic pieces
  [Kranenburg et al.,2014]

- Harmonic clustering for cadence detection
  [Duane et al., 2018-2019]

Duane et al.

Duane et al., 2018 ;2019

5 harmonic clusters according to the scale degree distribution of pieces from the corpus (classical string quartets) with K-means clustering.

Perfect and Half Cadence detection.

Authentic cadence : almost 80 % accuracy, but with a lot of false positives.

Many points are identified as cadential one but are not cadential in the reference.

Cadence detection

- Good results for Kranenburg et al. but mostly thanks to the textual features. And not really your classical cadence...

- A cadence is more than an harmonic progression… but also the end of a musical sentence.

Contributions of this thesis

Three original corpora *(*)*
- Mendelssohn's string quartets
- Mozart's string quartet
- Modulation excerpts

TISMIR 2019
(with the Algomus team)

ISMIR 2020, DLfM 2020
(with Fujinaga's lab, McGill)

A new model to detect and identify PAC and HC cadences
from 44 features

ISMIR 2018

A new approach to estimate modulations in the score
- Pitch compatibility
- Key anchoring
- Key proximity

SMC 2020

Finding the Medial Caesura (MC) *(*)*
a particular cadence in sonata form

ISMIR 2019

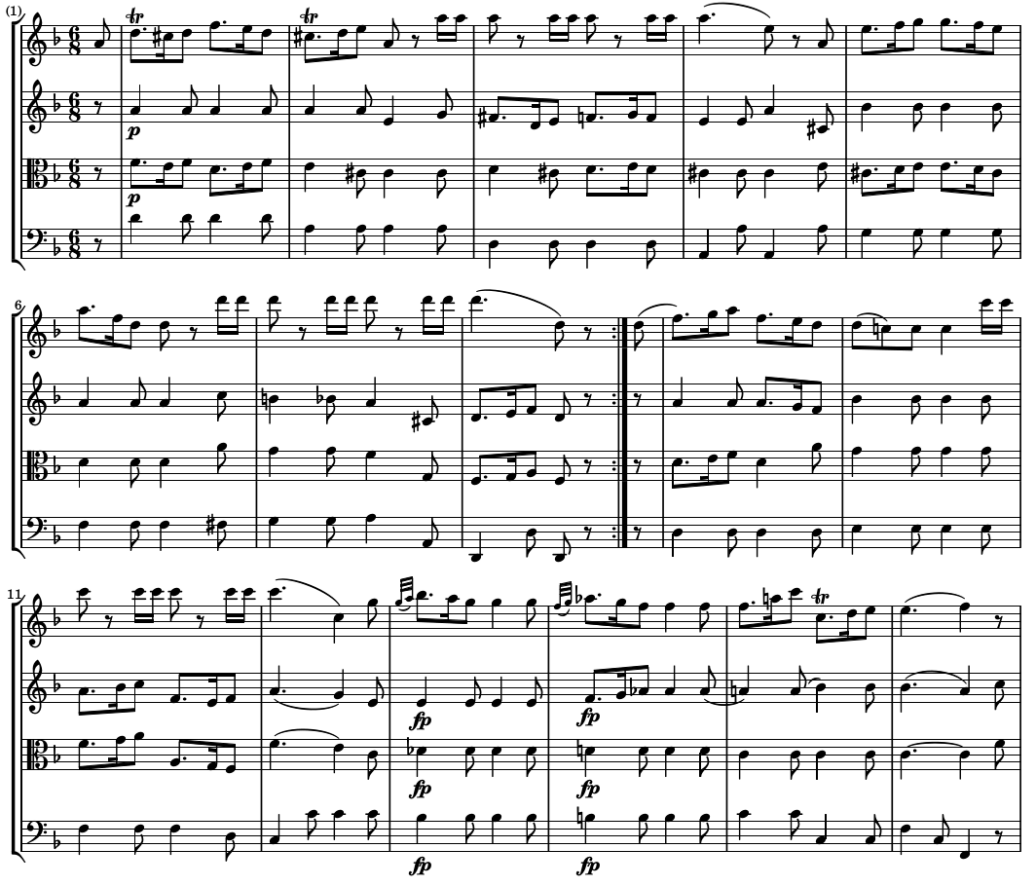
** not detailed in this defense...*

Estimating the modulations: The main idea

We try to model the tonal system.

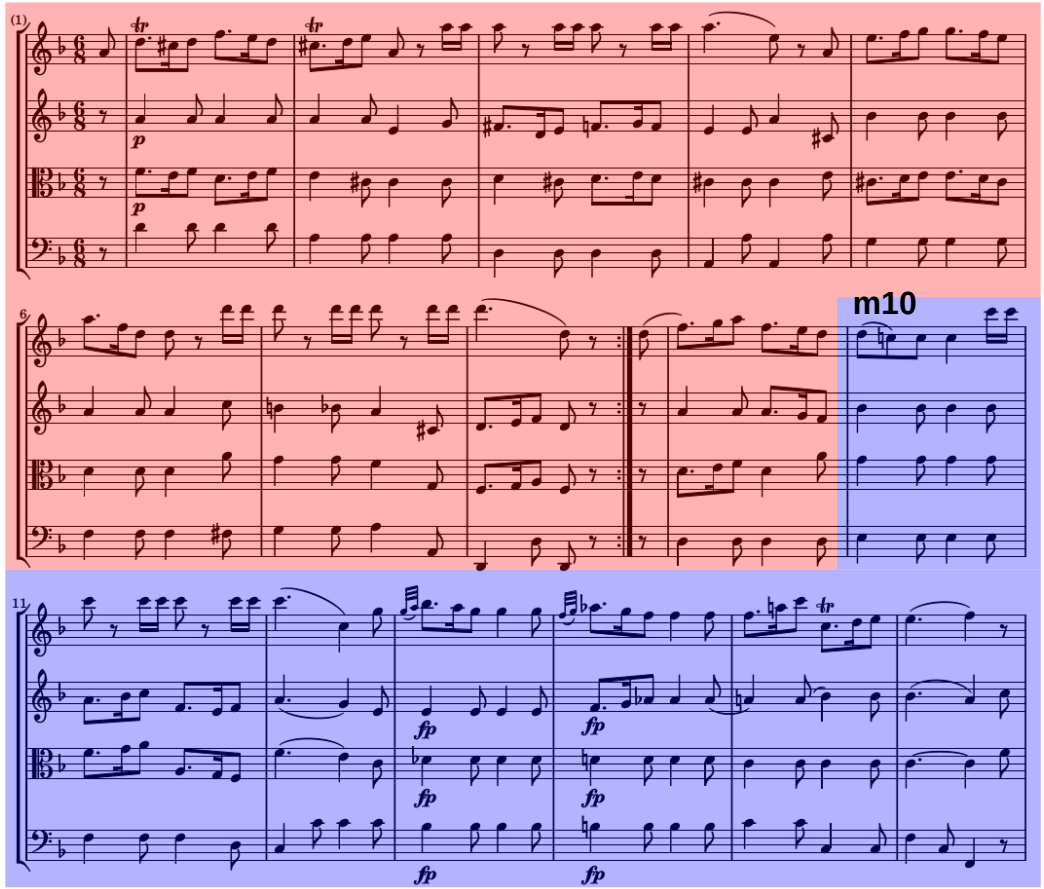
Being in a key is setting an « equilibrium state ».
Modulating consists in breaking this stability to establish a new one.
This change requires « energy » provided by some « signals ».

Our model provides a cost for being in a key in regard to these « signals ».



W. A. Mozart, *String quartet n°16 in d minor* K. 421, 4th mvmt, mm1-16

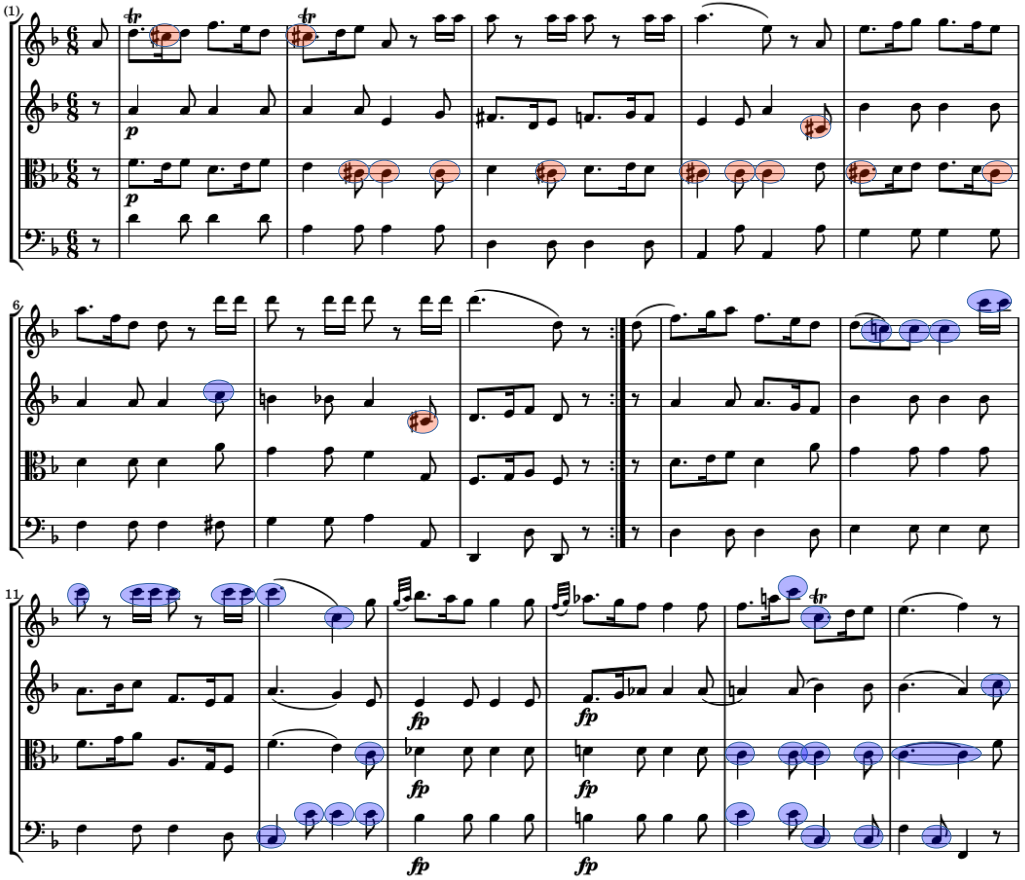
D minor



F Major

W. A. Mozart, *String quartet n°16 in d minor* K. 421, 4th mvmt, mm1-16

What do we expect for a modulation ?



C# are circled in red
C are circled in blue.

After the modulation point, C# have become C.

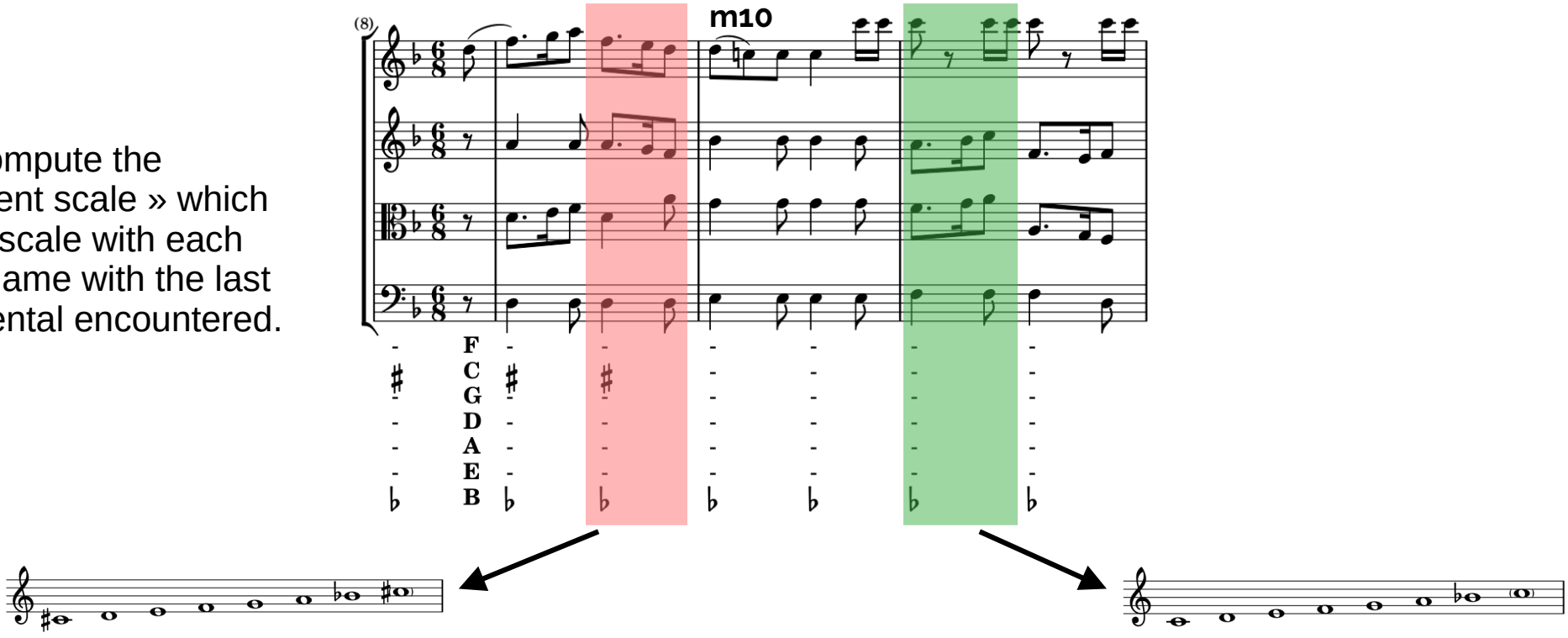
W. A. Mozart, *String quartet n°16 in d minor* K. 421, 4th mvmt, mm1-16

What do we expect for a modulation ?

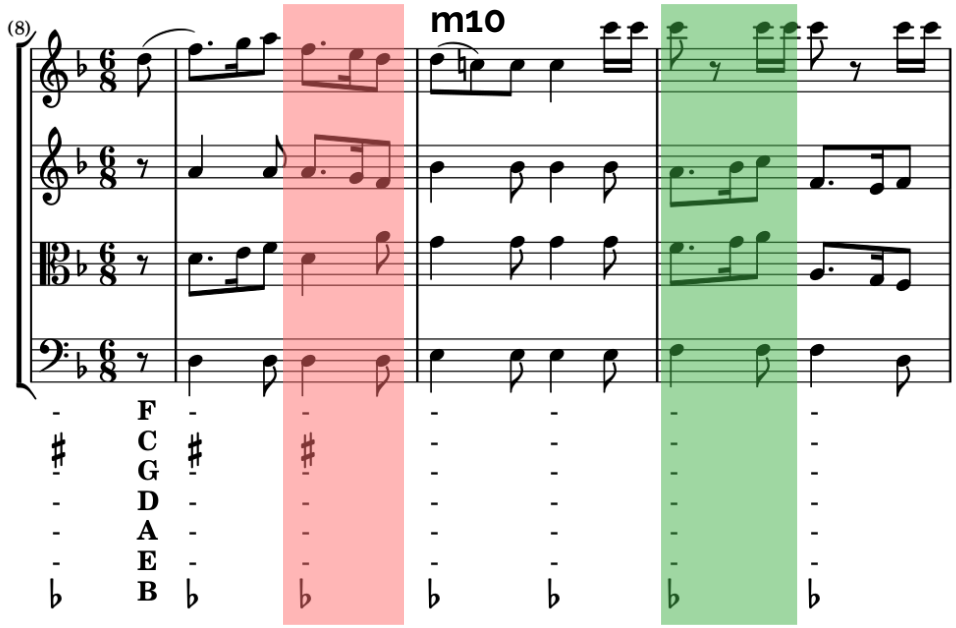
- A change of scale → Pitch compatibility

Estimating the pitch compatibility

We compute the « current scale » which is the scale with each note name with the last accidental encountered.



Estimating the pitch compatibility

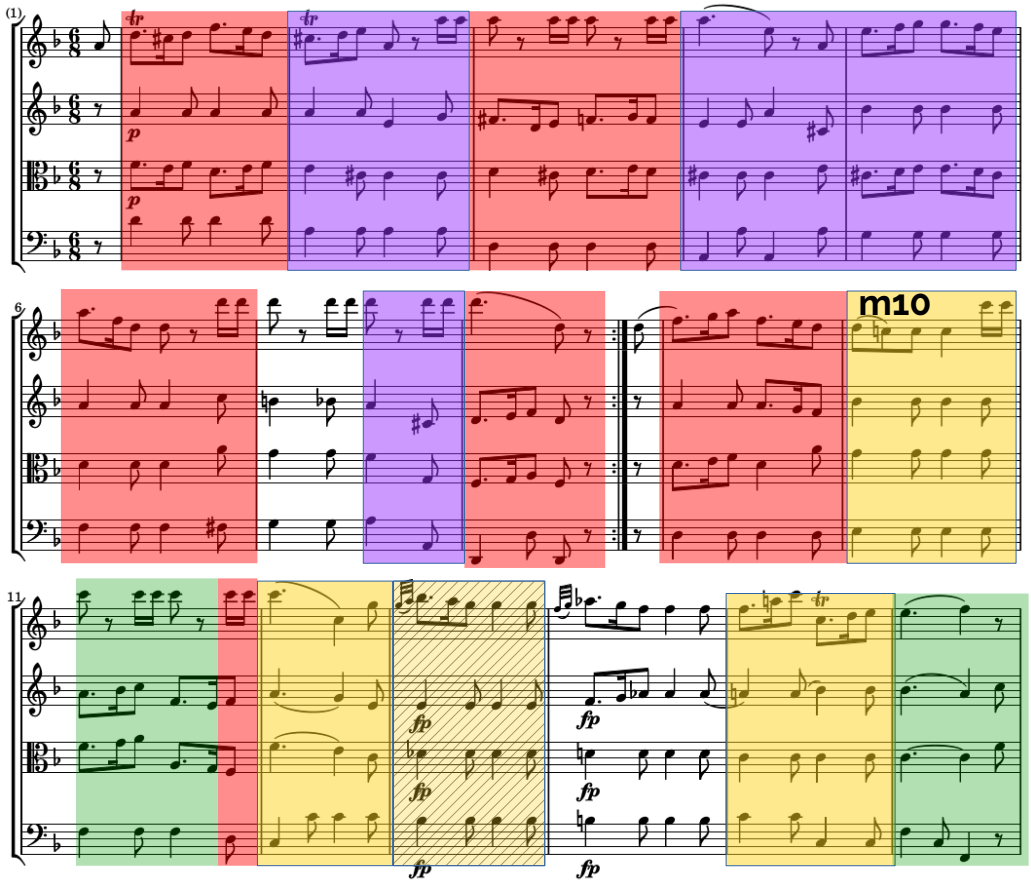


$d_{diat}(\mathcal{CS}(b), \mathcal{S}(C\ Major))$	2	2	1	1	1	1
$d_{diat}(\mathcal{CS}(b), \mathcal{S}(D\ minor))$	0	0	1	1	1	1
$d_{diat}(\mathcal{CS}(b), \mathcal{S}(F\ Major))$	1	1	0	0	0	0

We count the number of differences between the current scale and the scale of each key.

What do we expect for a modulation ?

- A change of scale → Pitch compatibility $d_{diat}(\mathcal{CS}(b), \mathcal{S}(k))$



Root A
Root D
Root F
Root C

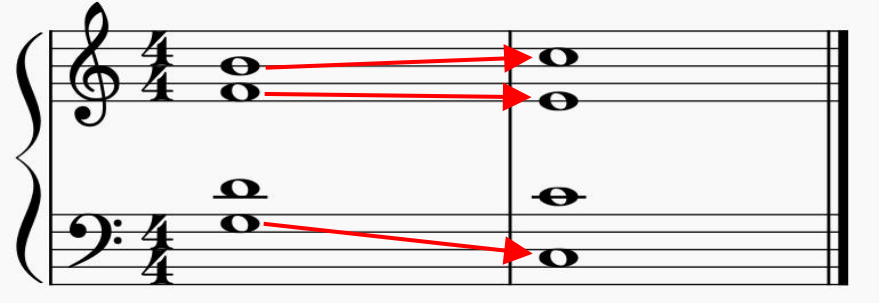
V and I of d minor
have become
V and I of F Major.

W. A. Mozart, *String quartet n°16 in d minor* K. 421, 4th mvmt, mm1-16

What do we expect for a modulation ?

- A change of scale → Pitch compatibility $d_{diat}(\mathcal{CS}(b), \mathcal{S}(k))$
- A change of harmonies → Key anchoring

Estimating the key anchoring

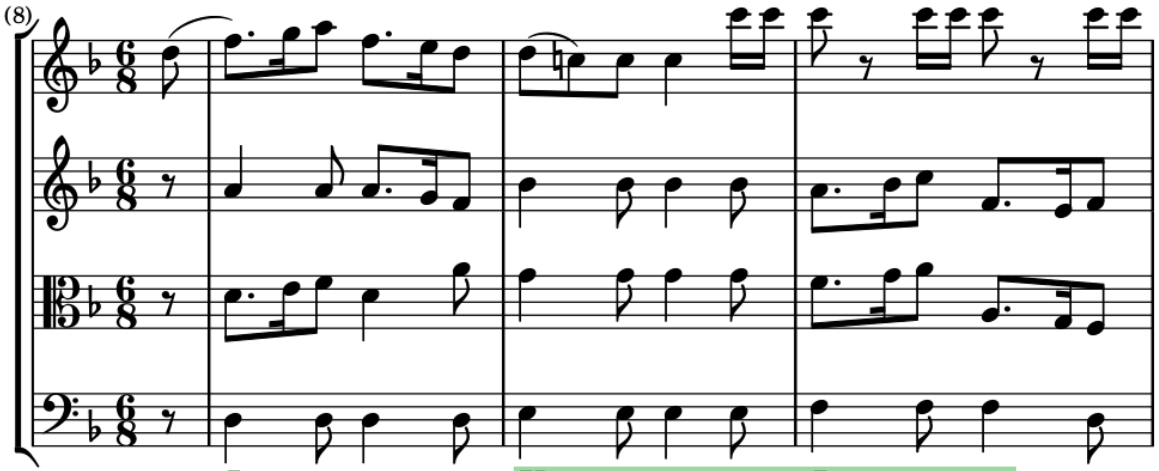


V → I progression anchors a key

Characteristic voice leadings

Heuristic threshold : two such voice leadings

Estimating the key anchoring



16	$c_{V \to I}(b, C\ Major)$	17	16	19	20	21	22
0	$c_{V \to I}(b, d\ minor)$	0	0	1	2	3	4
16	$c_{V \to I}(b, F\ Major)$	17	18	0	0	0	0

What do we expect for a modulation ?

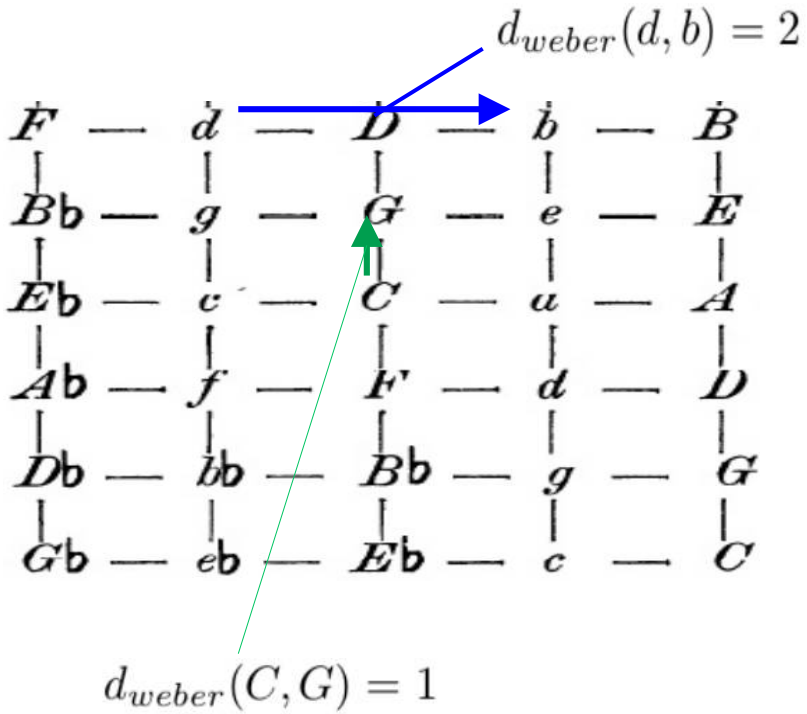
- A change of scale → Pitch compatibility $d_{diat}(\mathcal{CS}(b), \mathcal{S}(k))$
- A change of harmonies → Key anchoring $c_{V \to I}(b, k)$

Ensuring a tonal stability

Modulating is breaking an equilibrium state
→ it should have a cost.
Easier to modulate to some tonalities than others.

J. G. Weber, *Versuch einer geordneten Theorie des Tonsetzkunst* (1817-1821).

Key relationship → Cost estimation



What do we expect for a modulation ?

- A change of scale → Pitch compatibility $d_{diat}(\mathcal{CS}(b), \mathcal{S}(k))$
- A change of harmonies → Key anchoring $c_{V \to I}(b, k)$
- Favor the tonal stability → Key proximity $d_W(k, k')$

Combining the three mesures

Dynamic programming (*shortest path problem*)

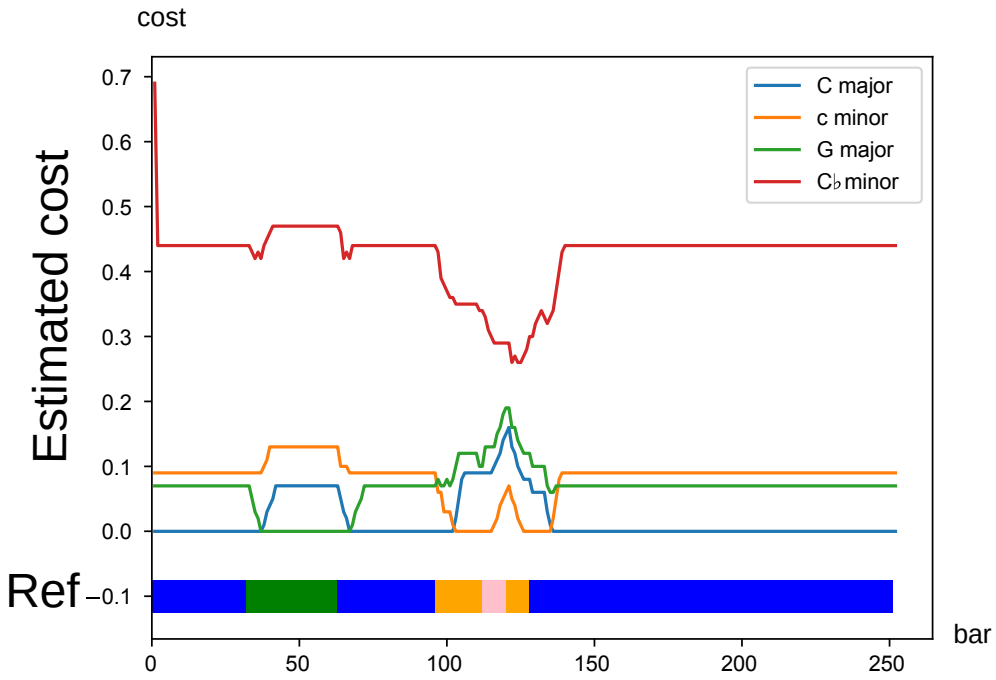
$$\begin{aligned} D(b,k) \quad = \quad & \alpha \cdot c_{V \to I}(b,k)/c \\ & + \beta \cdot d_{diat}(\mathcal{CS}(b), \mathcal{S}(k))/7 \\ & + \min_{k'} \left[\gamma \cdot d_W(k,k')/w \; + \; D(b-1,k')\right] \end{aligned}$$

Coefficients α, β and γ chosen in [0,4]

Key k in $\{C, D, E, F, G, A, B\} \times \{\sharp, \natural, \flat\} \times \{Major, \; minor\}$

Beat b in [0..B] with B total number of beats

Results on Mozart, K157, movement 3



Curves represents the cost estimated for each key.
Thick bar at the bottom represents the local key in the reference.

The key with the minimal cost is the one chosen as the local key on the beat b.

Predictions are very close to the reference. Only 3 beats over the 252 are given a wrong local key.

Results on the corpus

method	α	β	γ	correct
only d_{diat}	0	1	0	67.3
only $c_{V \to I}$	1	0	0	16.3
no modulation	0	0	1	50.0
best coefficients	0.016	0.3	4	84.8

Corpus : 38 movements of *Mozart's* string quartet.

The local key is correctly estimated on almost 85 % of the corpus beats.

Comparison with other studies (different corpora) :

[Izmirli,2007]	77,1 %
[Rocher,2010]	62,4 %
[Pauwels,2014]	74,9 %
[Chen,2019]	78,4 %
[Micchi,2020]	82,9 %

Contributions of this thesis

Three original corpora *(*)*
- Mendelssohn's string quartets
- Mozart's string quartet
- Modulation excerpts

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A new model to detect and identify PAC and HC cadences
from 44 features

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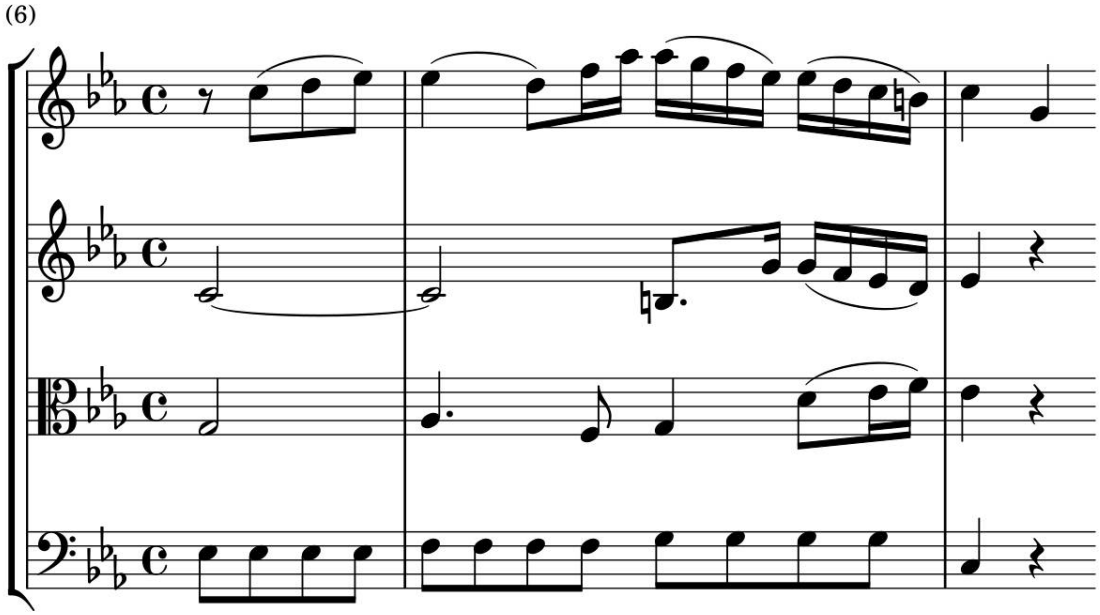
Finding the Medial Caesura (MC) *(*)*
a particular cadence in sonata form

ISMIR 2019

** not detailed in this defense...*

Describing the score as a set of features

For each beat, we extract different features on the point or right before that feel significant to describe a cadence :

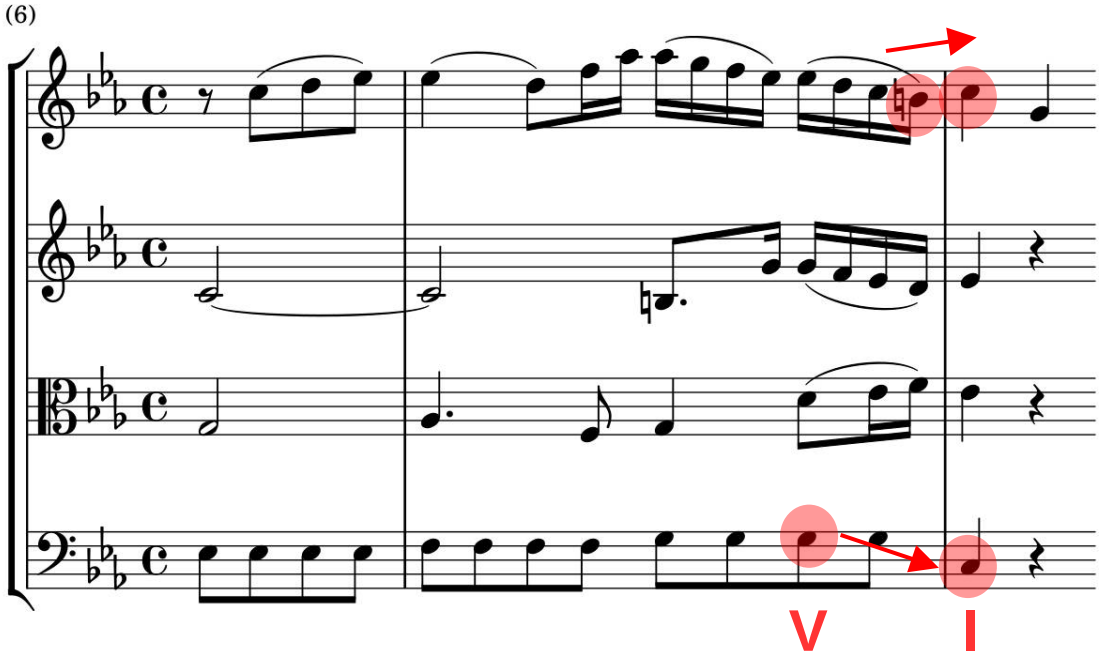


Haydn, *String Quartet op. 17/4*, 1st movement, mm 6-8

Describing the score as a set of features

For each beat, we extract different features on the point or right before that feel significant to describe a cadence :

- Voice leading features



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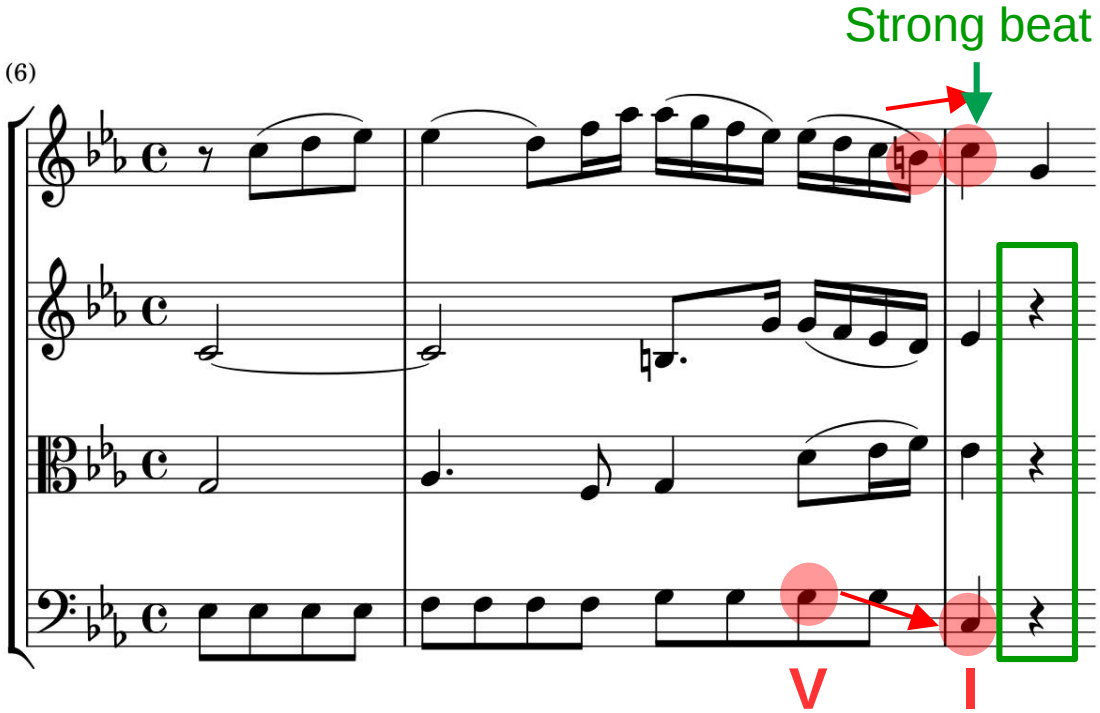
Describing the score as a set of features

For each beat, we extract different features on the point or right before that feel significant to describe a cadence :

- Voice leading features
- Rythmic features



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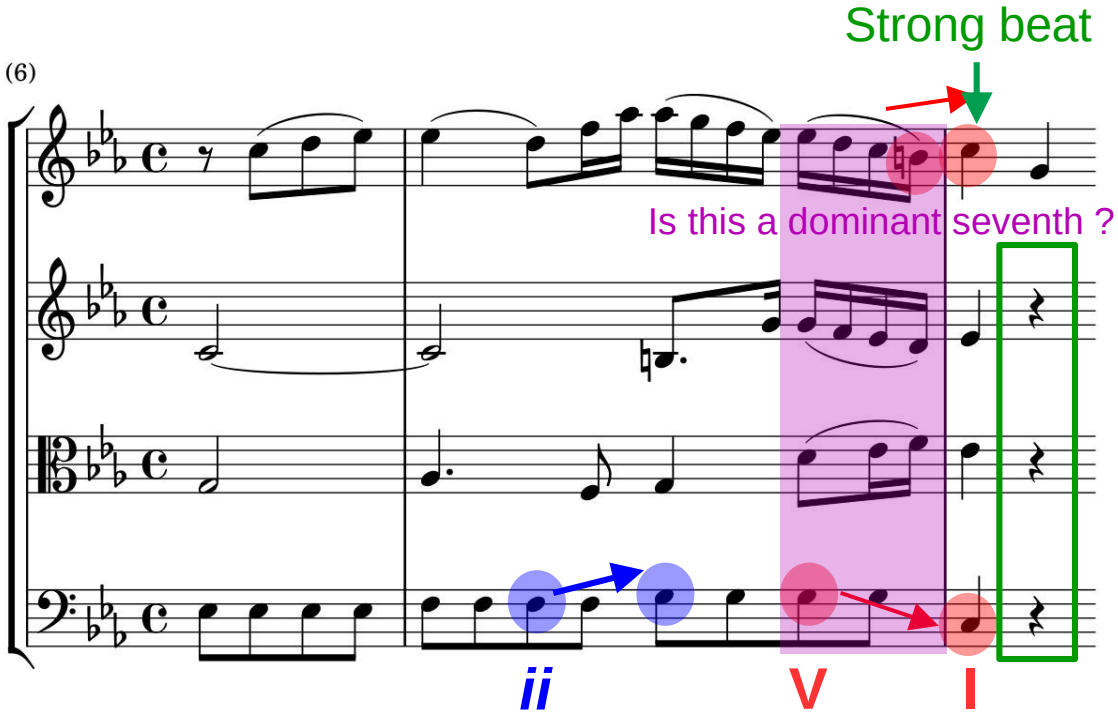
Describing the score as a set of features

For each beat, we extract different features on the point or right before that feel significant to describe a cadence :

- Voice leading features
- Rythmic features
- Preparation chord features
- Harmonic features
- ...



Haydn, *String Quartet op. 17/4*, 1st movement, mm 6-8

Features significance

	Bach-wtc-1			Haydn-quartets		
Feature	beats	PAC	rIAC	beats	PAC	HC
Y-Z-bass-moves-compatible-~~V-I~~	512	62	23	578	95	6
Total	4739	63	24	7173	99	70

Corpus :

42 expositions from Haydn string quartets

99 PAC and 70 HC annotated

24 Bach fugues

63 PAC and 24 rIAC annotated.

Some features are activated for few beats but almost all cadential beats : they are significant for the cadence identification.

Cadence detection

The feature values are used as an input to train a SVM classifier that classifies each beat of the score as a cadential one or not.

Results are good for PAC detection. Less false positives are detected compared to [Duane et al.,2017-2018].

However, results for HC are disappointing due to the lack of a strong feature to identify them.

		beats	ref	TP	FP	FN	F_1
haydn-quartets (21 quatuors)	PAC	3583	51	42	28	9	0.69
	HC	3583	32	18	73	14	0.29
bach-wtc-i (12 fugues)	PAC	2357	36	26	3	10	0.80
	PAC+rIAC	2357	46	30	12	16	0.68

Contributions of this thesis

Three original corpora *(*)*
- Mendelssohn's string quartets
- Mozart's string quartet
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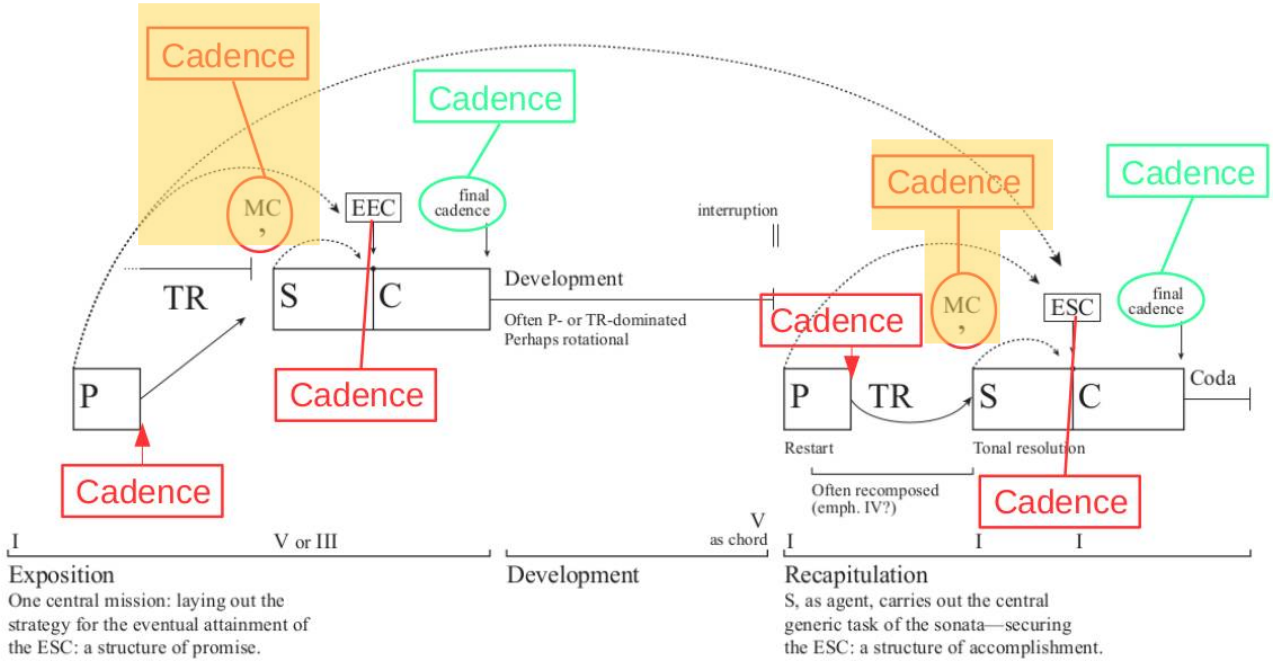
Sonata form

Secondary key

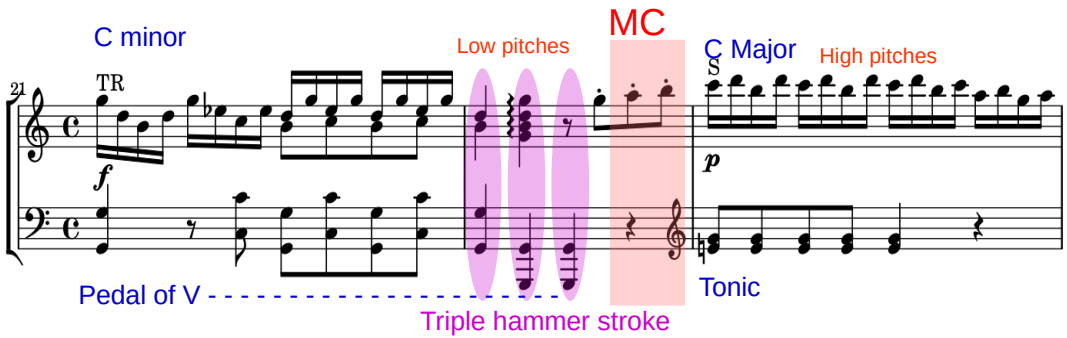
Main key

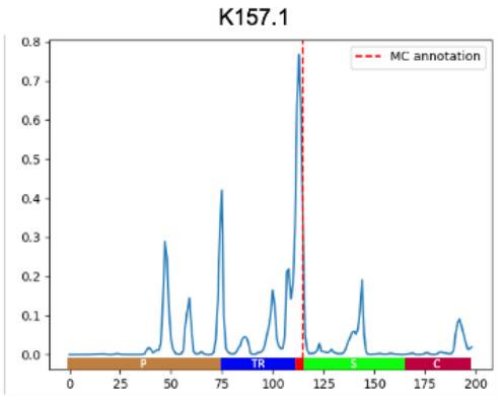


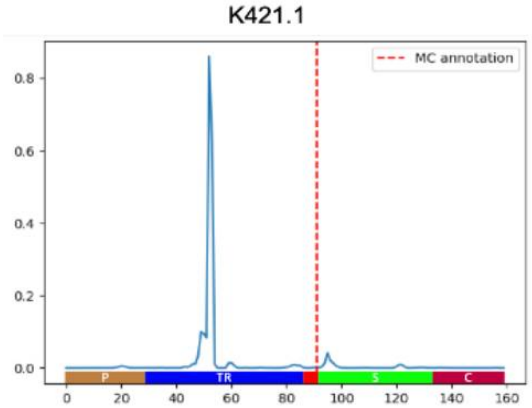
From Hepokoski, J. A., & Darcy, W. (2011). *Elements of sonata theory: norms, types, and deformations in the late-eighteenth century sonata*.

MC detection

The MC can be identified by a set of various features like rests, textural changes, specific harmonies and key change or specific features like the triple (or double) hammer stroke.







These features are used as an input for a LSTM neural network that computes the probability of a beat to be the MC.

Dataset : 27 expositions of Mozart string quartet.

Results : 14 MC found

Summary, Applications, and Perspectives

Summary

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- From low-level music objects to high-level music concepts
- Model of the tonal system with cost estimation. Satisfying results for local key estimation
- Cadence detection by identifying characteristic features for the end of a musical sentence. Good results for the conclusive PAC, need improvment for suspensive HC.
- Test this approach to identify key moment of the sonata form with encouraging results.

Applications

- Offer an automatic tool to support music theorists work. Very interesting to produce annotations on a huge corpus.
- Cadence detection can help the automatic interpretation of musical pieces by putting an emphasis on « breathing » after the end of a phrase.
- Local key estimation is interesting to identify the tonal path and lighten some key choices from composers.
- Help with music generation.

Perspectives

- Find a better way to detect cadences that are not PACs.
- Generalize the local key estimation to other periods / musical langages if possible
- Use these approach to design most succesful algorithm for form detection
- Create bonds with music theorists to propose more musically driven design for CMA tasks.

Thank you for your attention !