

MusICA Seminar:
Parsing Jazz:
Harmonic Analysis of Music Using
Combinatory Categorical Grammar

Mark Granroth-Wilding & Mark Steedman

University of Edinburgh

Tues 4th June 2013

Introduction

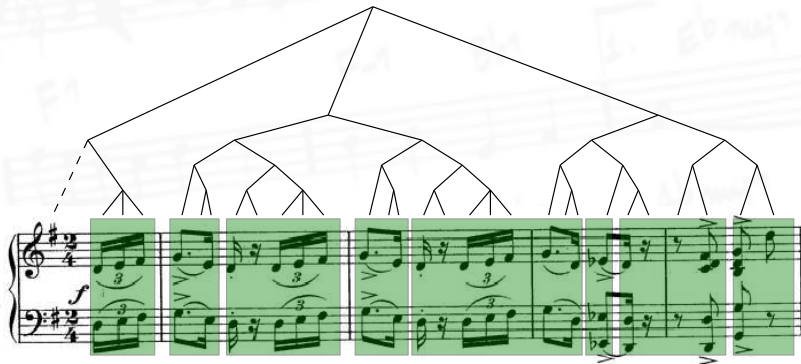
- Structures underlying music
 - Hierarchical structures
 - Metrical structure
 - Harmonic structure

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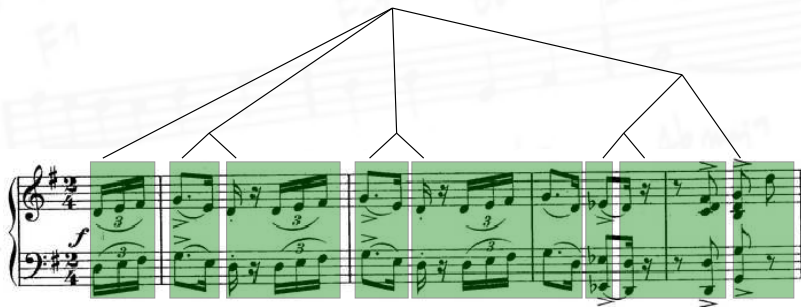
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Approaches to Musical Analysis

- Varying goals:

- Often not clearly defined

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- Varying goals:
 1. model/aid compositional process
 2. model listener's cognition
 3. suggest interpretations
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Main Claim

- Tonal harmony has a syntax like that of language
- Statistical parsing can be used to infer harmonic structure

Contributions:

- Formal grammar for syntax of harmony
- Harmonic analysis by parsing
- Practical statistical parsing of chord sequences
- Extension to analysis of performance data

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A Few Applications

- Automatic generation: ...
- MIR: song identification, ...
- 'Language modelling' for transcription
- Pitch spelling

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Consonance and Harmony

- Simultaneous notes create *dissonance / consonance*
- *Harmony*:
 - Relationships between chords
 - Expectation / fulfilment
- Used by composers:
 - tension / relaxation



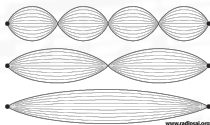
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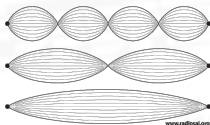
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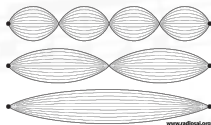
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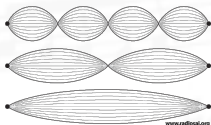
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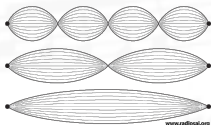
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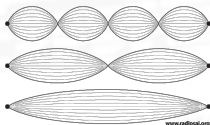


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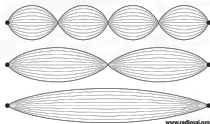


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Approaches to Harmonic Analysis

Approaches to Harmonic Analysis

Rameau (1722): *Traité de l'harmonie*

Roman numeral analysis

D: I IV I IV V⁷ I IV⁶ V I



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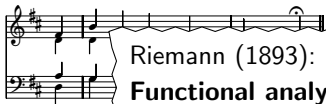


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Functional analysis

T S T S D T S D T



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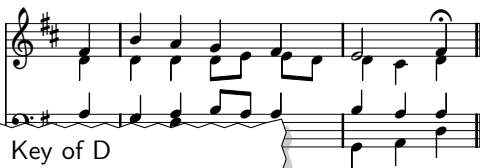
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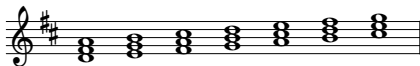


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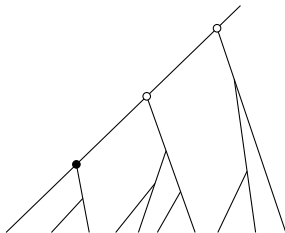
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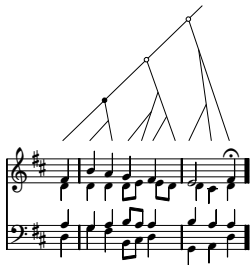


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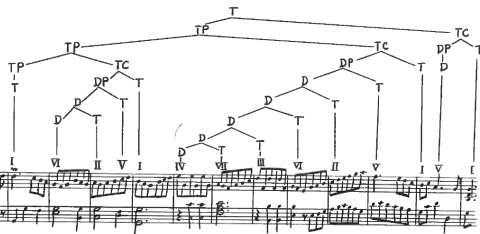
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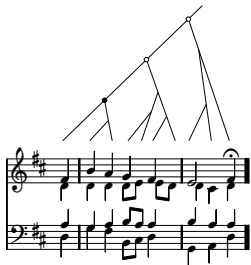


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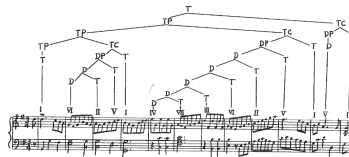
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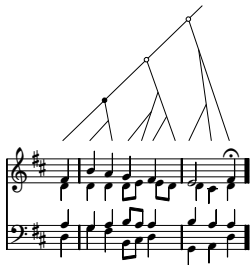


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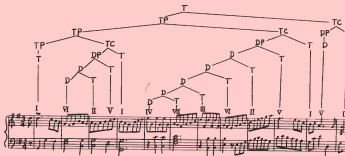
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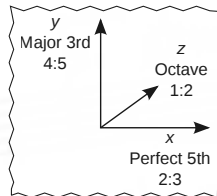


Tonal Space



- Longuet-Higgins' formalization of harmonic tonal theory

- Tonal relations between notes



- Harmonic analysis disambiguates tonal relations

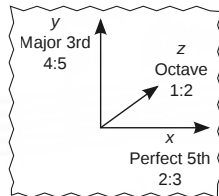


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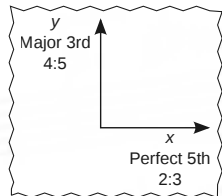


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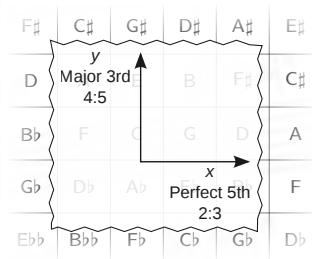
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D	A	E	B	F#	C#
Bb	F	C	G	D	A
Gb	Db	Ab	Eb	Bb	F
Ebb	Bbb	Fb	Cb	Gb	Db

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Harmony in the Tonal Space

C♯	G♯	D♯	A♯	E♯	B♯	F♯♯	C♯♯	G♯♯	D♯♯	A♯♯
A	E	B	F♯	C♯	G♯	D♯	A♯	E♯	B♯	F♯♯
F	C	G	D	A	E	B	F♯	C♯	G♯	D♯
D♭	A♭	E♭	B♭	F	C	G	D	A	E	B
B♭♭	F♭	C♭	G♭	D♭	A♭	E♭	B♭	F	C	G
G♭♭	D♭♭	A♭♭	E♭♭	B♭♭	F♭	C♭	G♭	D♭	A♭	E♭
E♭♭♭	B♭♭♭	F♭♭	C♭♭	G♭♭	D♭♭	A♭♭	E♭♭	B♭♭	F♭	C♭

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A	E	B	F♯	C♯	G♯	D♯	A♯	E♯	B♯	F♯♯
F	C	G	D	A	E	B	F♯	C♯	G♯	D♯
D♭	A♭	E♭	B♭	F	C	G	D	A	E	B
B♭♭	F♭	C♭	G♭	D♭	A♭	E♭	B♭	F	C	G
G♭♭	D♭♭	A♭♭	E♭♭	B♭♭	F♭	C♭	G♭	D♭	A♭	E♭
E♭♭♭	B♭♭♭	F♭♭	C♭♭	G♭♭	D♭♭	A♭♭	E♭♭	B♭♭	F♭	C♭

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C $\sharp$	G $\sharp$	D $\sharp$	A $\sharp$	E $\sharp$	B $\sharp$	F $\sharp\sharp$	C $\sharp\sharp$	G $\sharp\sharp$	D $\sharp\sharp$	A $\sharp\sharp$
A	E	B	F $\sharp$	C $\sharp$	G $\sharp$	D $\sharp$	A $\sharp$	E $\sharp$	B $\sharp$	F $\sharp\sharp$
F	C	G	D	A	E	B	F $\sharp$	C $\sharp$	G $\sharp$	D $\sharp$
D $\flat$	A $\flat$	E $\flat$	B $\flat$	F	C	G	D	A	E	B
B $\flat\flat$	F $\flat$	C $\flat$	G $\flat$	D $\flat$	A $\flat$	E $\flat$	B $\flat$	F	C	G
G $\flat\flat$	D $\flat\flat$	A $\flat\flat$	E $\flat\flat$	B $\flat\flat$	F $\flat$	C $\flat$	G $\flat$	D $\flat$	A $\flat$	E $\flat$
E $\flat\flat\flat$	B $\flat\flat\flat$	F $\flat\flat$	C $\flat\flat$	G $\flat\flat$	D $\flat\flat$	A $\flat\flat$	E $\flat\flat$	B $\flat\flat$	F $\flat$	C $\flat$

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A	E	B	F $\sharp$	C $\sharp$	G $\sharp$	D $\sharp$	A $\sharp$	E $\sharp$	B $\sharp$	F $\sharp\sharp$
F	C	G	D	A	E	B	F $\sharp$	C $\sharp$	G $\sharp$	D $\sharp$
D $\flat$	A $\flat$	E $\flat$	B $\flat$	F	C	G	D	A	E	B
B $\flat\flat$	F $\flat$	C $\flat$	G $\flat$	D $\flat$	A $\flat$	E $\flat$	B $\flat$	F	C	G
G $\flat\flat$	D $\flat\flat$	A $\flat\flat$	E $\flat\flat$	B $\flat\flat$	F $\flat$	C $\flat$	G $\flat$	D $\flat$	A $\flat$	E $\flat$
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A	E	B	F $\sharp$	C $\sharp$	G $\sharp$	D $\sharp$	A $\sharp$	E $\sharp$	B $\sharp$	F $\sharp\sharp$
F	C	G	D	A	E	B	F $\sharp$	C $\sharp$	G $\sharp$	D $\sharp$
D $\flat$	A $\flat$	E $\flat$	B $\flat$	F	C	G	D	A	E	B
B $\flat\flat$	F $\flat$	C $\flat$	G $\flat$	D $\flat$	A $\flat$	E $\flat$	B $\flat$	F	C	G
G $\flat\flat$	D $\flat\flat$	A $\flat\flat$	E $\flat\flat$	B $\flat\flat$	F $\flat$	C $\flat$	G $\flat$	D $\flat$	A $\flat$	E $\flat$
E $\flat\flat\flat$	B $\flat\flat\flat$	F $\flat\flat$	C $\flat\flat$	G $\flat\flat$	D $\flat\flat$	A $\flat\flat$	E $\flat\flat$	B $\flat\flat$	F $\flat$	C $\flat$

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A	E	B	F $\sharp$	C $\sharp$	G $\sharp$	D $\sharp$	A $\sharp$	E $\sharp$	B $\sharp$	F $\sharp\sharp$
F	C	G	D	A	E	B	Dominant		G $\sharp$	D $\sharp$
D $\flat$	A $\flat$	E $\flat$	B $\flat$	F	C	G	D	A	E	B
B $\flat\flat$	F $\flat$	C $\flat$	G $\flat$	D $\flat$	A $\flat$	E $\flat$	B $\flat$	F	C	G
G $\flat\flat$	D $\flat\flat$	A $\flat\flat$	E $\flat\flat$	B $\flat\flat$	F $\flat$	C $\flat$	G $\flat$	D $\flat$	A $\flat$	E $\flat$
E $\flat\flat\flat$	B $\flat\flat\flat$	F $\flat\flat$	C $\flat\flat$	G $\flat\flat$	D $\flat\flat$	A $\flat\flat$	E $\flat\flat$	B $\flat\flat$	F $\flat$	C $\flat$

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A	E	B	F $\sharp$	Tonic		D $\sharp$	A $\sharp$	E $\sharp$	B $\sharp$	F $\sharp\sharp$
F	C	G	D	A	E	B	Dominant		G $\sharp$	D $\sharp$
D $\flat$	A $\flat$	E $\flat$	B $\flat$	F	C	G	D	A	E	B
B $\flat\flat$	F $\flat$	C $\flat$	G $\flat$	D $\flat$	A $\flat$	E $\flat$	B $\flat$	F	C	G
G $\flat\flat$	D $\flat\flat$	A $\flat\flat$	E $\flat\flat$	B $\flat\flat$	F $\flat$	C $\flat$	G $\flat$	D $\flat$	A $\flat$	E $\flat$
E $\flat\flat\flat$	B $\flat\flat\flat$	F $\flat\flat$	C $\flat\flat$	G $\flat\flat$	D $\flat\flat$	A $\flat\flat$	E $\flat\flat$	B $\flat\flat$	F $\flat$	C $\flat$

Harmony in the Tonal Space

C $\sharp$	G $\sharp$	D $\sharp$	A $\sharp$	E $\sharp$	B $\sharp$	F $\sharp\sharp$	C $\sharp\sharp$	G $\sharp\sharp$	D $\sharp\sharp$	A $\sharp\sharp$
A	E	B	F $\sharp$	Tonic		D $\sharp$	A $\sharp$	E $\sharp$	B $\sharp$	F $\sharp\sharp$
F	C	G	D	A	E	B	Dominant		G $\sharp$	D $\sharp$
D $\flat$	A $\flat$	E $\flat$	B $\flat$	F	C	G	D	A	E	B
B $\flat\flat$	F $\flat$	C $\flat$	G $\flat$	D $\flat$	A $\flat$	E $\flat$	B $\flat$	F	C	G
G $\flat\flat$	D $\flat\flat$	A $\flat\flat$	E $\flat\flat$	B $\flat\flat$	F $\flat$	C $\flat$	G $\flat$	D $\flat$	A $\flat$	E $\flat$
E $\flat\flat\flat$	B $\flat\flat\flat$	F $\flat\flat$	C $\flat\flat$	G $\flat\flat$	D $\flat\flat$	A $\flat\flat$	E $\flat\flat$	B $\flat\flat$	F $\flat$	C $\flat$

Functional Harmony

C♯	G♯	D♯	A♯	E♯	B♯	F♯♯	C♯♯	G♯♯	D♯♯	A♯♯
A	E	B	F♯	C♯	G♯	D♯	A♯	E♯	B♯	F♯♯
F	C	G	D	A	E	B	F♯	C♯	G♯	D♯
D♭	A♭	E♭	B♭	F	C	G	D	A	E	B
B♭♭	F♭	C♭	G♭	D♭	A♭	E♭	B♭	F	C	G
G♭♭	D♭♭	A♭♭	E♭♭	B♭♭	F♭	C♭	G♭	D♭	A♭	E♭
E♭♭♭	B♭♭♭	F♭♭	C♭♭	G♭♭	D♭♭	A♭♭	E♭♭	B♭♭	F♭	C♭

Functional Harmony

C $\sharp$	G $\sharp$	D $\sharp$	A $\sharp$	E $\sharp$	B $\sharp$	F $\sharp\sharp$	C $\sharp\sharp$	G $\sharp\sharp$	D $\sharp\sharp$	A $\sharp\sharp$
A	E	B	F $\sharp$	C $\sharp$	G $\sharp$	D $\sharp$	A $\sharp$	E $\sharp$	B $\sharp$	F $\sharp\sharp$
F	C	G	D	A	E	B	F $\sharp$	C $\sharp$	G $\sharp$	D $\sharp$
D $\flat$	A $\flat$	E $\flat$	B $\flat$	F	C	G	D	A	E	B
B $\flat\flat$	F $\flat$	C $\flat$	G $\flat$	D $\flat$	F	C	G	D	A	B
G $\flat\flat$	D $\flat\flat$	A $\flat\flat$	E $\flat\flat$	B $\flat\flat$	F $\flat$	C $\flat$	G $\flat$	D $\flat$	A $\flat$	E $\flat$
E $\flat\flat\flat$	B $\flat\flat\flat$	F $\flat\flat$	C $\flat\flat$	G $\flat\flat$	D $\flat\flat$	A $\flat\flat$	E $\flat\flat$	B $\flat\flat$	F $\flat$	C $\flat$

Diagram illustrating Functional Harmony. The table shows chords (A, E, B, F $\sharp$, C $\sharp$, G $\sharp$, D $\sharp$) and their functional relationships. The central 3x3 grid (rows 3-5, columns 4-6) is highlighted in green. The central cell (row 4, column 5) contains the chord C, which is circled and labeled "Tonic". The cell to its right (row 4, column 6) contains the chord G, which is circled and labeled "Dominant". An arrow points from G to C, indicating a functional relationship.

Functional Harmony

C#	G#	D#	A#	E#	B#	F##	C##	G##	D##	A##
A	E	B	F#	C#	G#	D#	A#	E#	B#	F##
F	C	G	D	A	E	B	F#	C#	G#	D#
Db	Ab	Eb	Bb	F	C	G	D	A	E	B
Bbb	Fb	Cb	Gb	F	C	G	D	A	E	B
Gbb	Dbb	Abb	Ebb	Bbb	Fb	Cb	Gb	Db	Ab	Eb
Ebbb	Bbbb	Fbb	Cbb	Gbb	Dbb	Abb	Ebb	Bbb	Fb	Cb

Functional Harmony diagram highlighting the Subdominant (F), Tonic (C), and Dominant (G) chords in the key of C major.

The diagram shows the following chords highlighted in green:

- Subdominant (F): F, C, G
- Tonic (C): C, E, G
- Dominant (G): G, B, D

The diagram also shows the relationship between the Subdominant (F) and the Tonic (C) chords, indicated by an arrow pointing from F to C.

Harmonic Analysis

- Functional harmonic structure
 - Segmentation into chords
 - Identification of keys
 - Functional relationships between chords

C E⁷ A⁷ Dm⁷ G⁷ Dm⁷ D^b7 C

Harmonic Analysis

- Functional harmonic structure
- Segmentation into chords
- Identification of keys
- Functional relationships between chords

C E⁷ A⁷ Dm⁷ G⁷ Dm⁷ D^b7 C

Harmonic Analysis

- Functional harmonic structure
- Segmentation into chords
- Identification of keys
- Functional relationships between chords

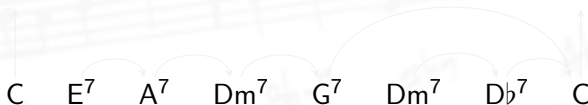
C E⁷ A⁷ Dm⁷ G⁷ Dm⁷ D^b7 C

Harmonic Analysis

- Functional harmonic structure
- Segmentation into chords
- Identification of keys
- Functional relationships between chords

Harmonic Analysis

- Functional harmonic structure
- Segmentation into chords
- Identification of keys
- Functional relationships between chords



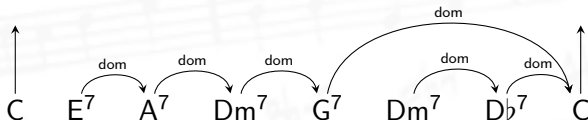
Harmonic Analysis

- Functional harmonic structure
- Segmentation into chords
- Identification of keys
- Functional relationships between chords



Harmonic Analysis

- Functional harmonic structure
- Segmentation into chords
- Identification of keys
- Functional relationships between chords

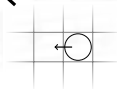


Harmonic Analysis

- Chords function as: **dominant**, **subdominant** or **tonic**
- Dominant-tonic resolution
- Subdominant-tonic resolution
- Recursion
- Substitution
- Delayed resolution

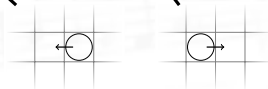
Harmonic Analysis

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- Subdominant-tonic resolution
- Recursion
- Substitution
- Delayed resolution



Harmonic Analysis

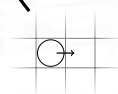
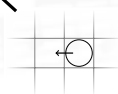
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- Substitution
- Delayed resolution



Harmonic Analysis

- Chords function as: **dominant**, **subdominant** or **tonic**

- Dominant-tonic resolution
- Subdominant-tonic resolution
- Recursion
- Substitution
- Delayed resolution



A	E	B
F	C	G
D $\flat$	A $\flat$	E $\flat$

Harmonic Analysis

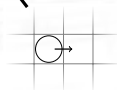
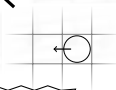
- Chords function as: **dominant**, **subdominant** or **tonic**
- Dominant-tonic resolution

• Subdominant-tonic resolution

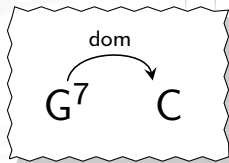
• Recursion

• Substitution

• Delayed resolution

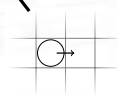
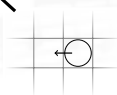


A	E	B
F	C	G
D $\flat$	A $\flat$	E $\flat$

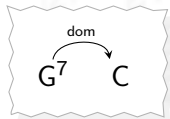


Harmonic Analysis

- Chords function as: **dominant**, **subdominant** or **tonic**
- Dominant-tonic resolution
- Subdominant-tonic resolution
- Recursion
- Substitution
- Delayed resolution

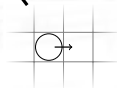
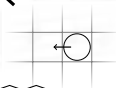


A	E	B
F	C	G
D $\flat$	A $\flat$	E $\flat$

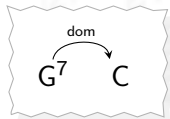
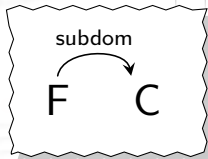


Harmonic Analysis

- Chords function as: **dominant**, **subdominant** or **tonic**
- Dominant-tonic resolution
- Subdominant-tonic resolution

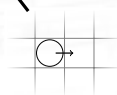
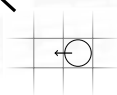


A	E	B
F	C	G
D $\flat$	A $\flat$	E $\flat$

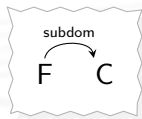
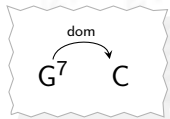


Harmonic Analysis

- Chords function as: **dominant**, **subdominant** or **tonic**
- Dominant-tonic resolution
- Subdominant-tonic resolution
- Recursion
- Substitution
- Delayed resolution



A	E	B
F	C	G
D $\flat$	A $\flat$	E $\flat$

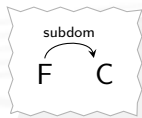
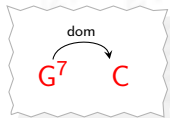
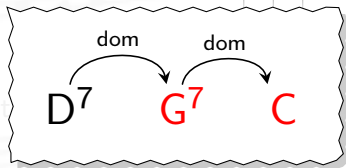


Harmonic Analysis

- Chords function as: **dominant**, **subdominant** or **tonic**
- Dominant-tonic resolution
- Subdominant-tonic resolution
- Recursion



A	E	B
F	C	G
D♭	A♭	E♭



Harmonic Analysis

- Chords function as: **dominant**, **subdominant** or **tonic**
- Dominant-tonic resolution
- Subdominant-tonic resolution

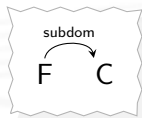
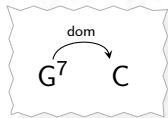
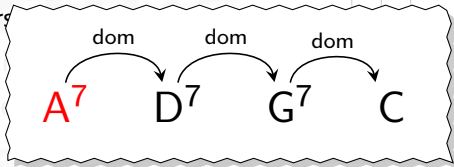


A	E	B
F	C	G
D♭	A♭	E♭

- Recursive

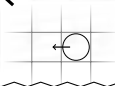
- Substitution

- Delay

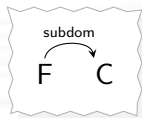
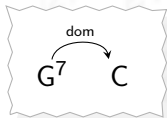
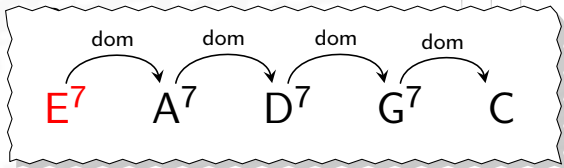


Harmonic Analysis

- Chords function as: **dominant**, **subdominant** or **tonic**
- Dominant-tonic resolution
- Subdominant-tonic resolution



A	E	B
F	C	G
D♭	A♭	E♭



Harmonic Analysis

- Chords function as: **dominant**, **subdominant** or **tonic**

- Dominant-tonic resolution
- Subdominant-tonic resolution

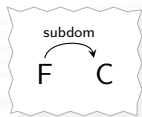
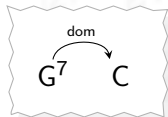
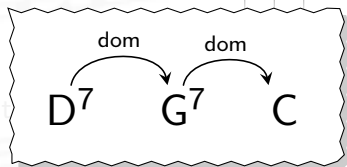
- Recursion

- Substitution

- Delayed resolution

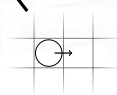
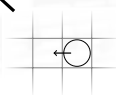


A	E	B
F	C	G
D $\flat$	A $\flat$	E $\flat$

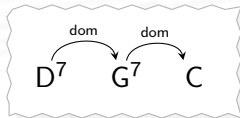
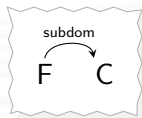
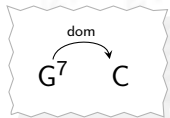


Harmonic Analysis

- Chords function as: **dominant**, **subdominant** or **tonic**
- Dominant-tonic resolution
- Subdominant-tonic resolution
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- Substitution
- Delayed resolution

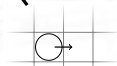


A	E	B
F	C	G
D $\flat$	A $\flat$	E $\flat$

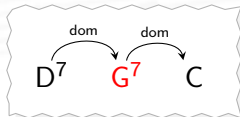
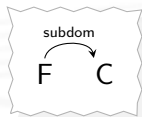
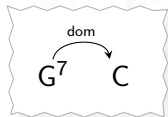
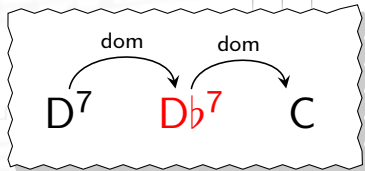


Harmonic Analysis

- Chords function as: **dominant**, **subdominant** or **tonic**
- Dominant-tonic resolution
- Subdominant-tonic resolution
- Recursion
- Substitution

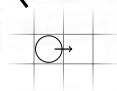
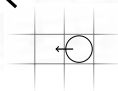


A	E	B
F	C	G
D $\flat$	A $\flat$	E $\flat$

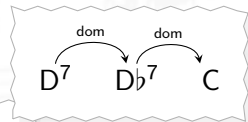
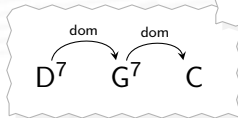
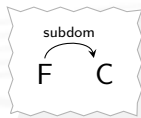
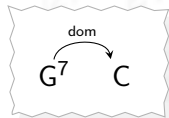


Harmonic Analysis

- Chords function as: **dominant**, **subdominant** or **tonic**
- Dominant-tonic resolution
- Subdominant-tonic resolution
- Recursion
- Substitution
- Delayed resolution

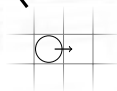
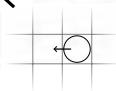


A	E	B
F	C	G
D $\flat$	A $\flat$	E $\flat$

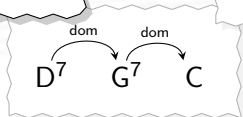
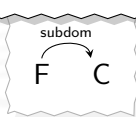
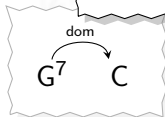
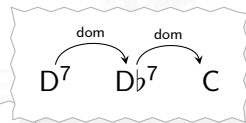
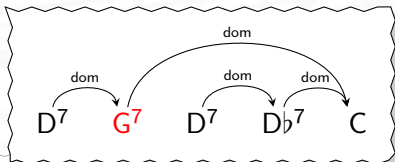


Harmonic Analysis

- Chords function as: **dominant**, **subdominant** or **tonic**
- Dominant-tonic resolution
- Subdominant-tonic resolution
- Recursion
- Substitution
- Delayed resolution **coordination**

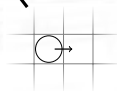
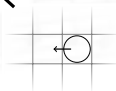


A	E	B
F	C	G
D $\flat$	A $\flat$	E $\flat$

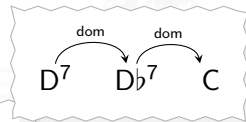
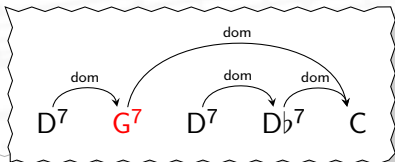


Harmonic Analysis

- Chords function as: **dominant**, **subdominant** or **tonic**
- Dominant-tonic resolution
- Subdominant-tonic resolution
- Recursion
- Substitution
- Delayed resolution: **coordination**

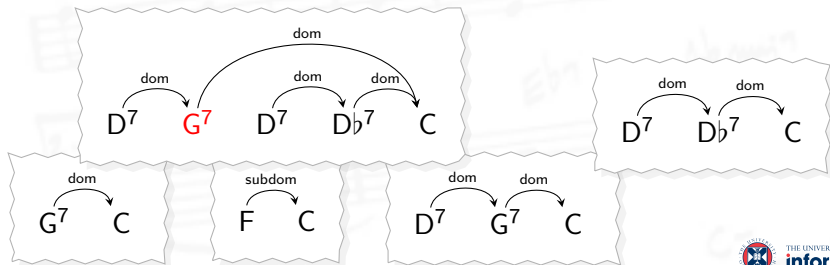
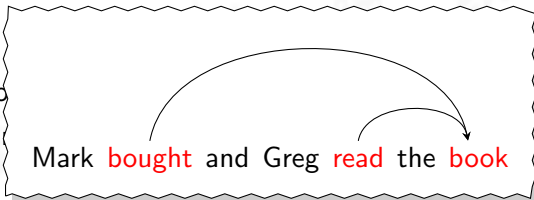


A	E	B
F	C	G
D $\flat$	A $\flat$	E $\flat$



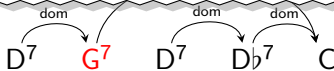
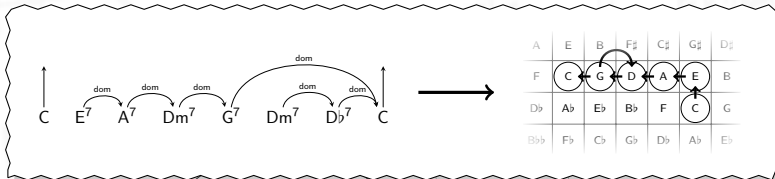
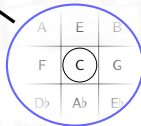
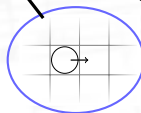
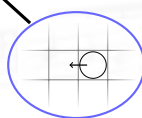
Harmonic Analysis

- Chords function as:
- Dominant-tonic reso
- Subdominant-tonic
- Recursion
- Substitution
- Delayed resolution: **coordination**



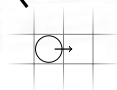
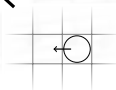
Harmonic Analysis

- Chords function as: **dominant**, **subdominant** or **tonic**
- Dominant-tonic resolution
- Subdominant-tonic resolution
- Recursion

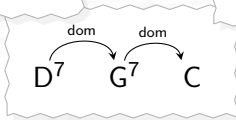
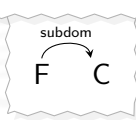
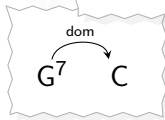
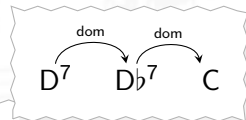
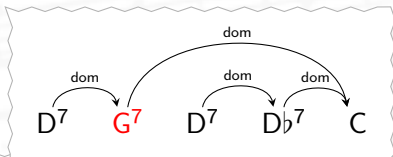


Harmonic Analysis

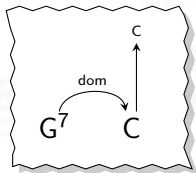
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A	E	B
F	C	G
D $\flat$	A $\flat$	E $\flat$



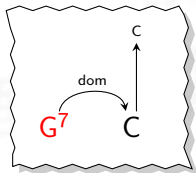
Harmonic Combinatory Categorical Grammar



A	E	B	F#
F	C	G	D
D♭	A♭	E♭	B♭

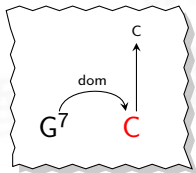
Harmonic Combinatory Categorical Grammar

$$G^7 \Rightarrow G/C$$



A	E	B	F#
F	C	G	D
D♭	A♭	E♭	B♭

Harmonic Combinatory Categorical Grammar

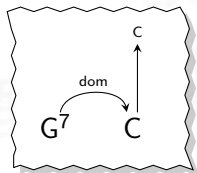


$$G^7 \Rightarrow G/C$$

$$C \Rightarrow C$$

A	E	B	F#
F	C	G	D
D♭	A♭	E♭	B♭

Harmonic Combinatory Categorical Grammar



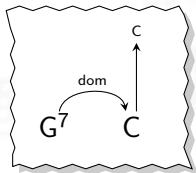
$$G^7 \Rightarrow G/C$$

$$C \Rightarrow C$$

A	E	B	F#
F	C	G	D
D♭	A♭	E♭	B♭

$$\frac{\frac{G^7}{G/C} \quad \frac{C}{C}}{G-C} >$$

Harmonic Combinatory Categorical Grammar



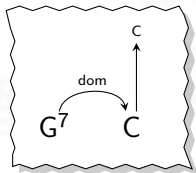
$$G^7 \Rightarrow G/C : \overset{\text{dom}}{\bullet}$$

$$C \Rightarrow C$$

A	E	B	F#
F	C	G	D
Db	Ab	Eb	Bb

$$\frac{\frac{G^7}{G/C} \quad \frac{C}{C}}{G-C} >$$

Harmonic Combinatory Categorical Grammar



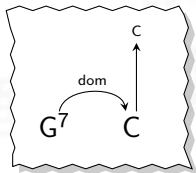
$$G^7 \Rightarrow G/C : \overset{\text{dom}}{\bullet}$$

$$C \Rightarrow C : \overset{C}{\uparrow} \bullet$$

A	E	B	F#
F	C	G	D
D♭	A♭	E♭	B♭

$$\frac{\frac{G^7}{G/C} \quad \frac{C}{C}}{G-C} >$$

Harmonic Combinatory Categorical Grammar



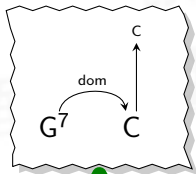
$$G^7 \Rightarrow G/C : \overset{\text{dom}}{\bullet}$$

$$C \Rightarrow C : \overset{C}{\uparrow} \bullet$$

A	E	B	F#
F	C	G	D
Db	Ab	Eb	Bb

$$\frac{\frac{G^7}{G/C : \overset{\text{dom}}{\bullet}} \quad \frac{C}{C : \overset{C}{\uparrow} \bullet}}{G-C : \overset{\text{dom}}{\bullet} \overset{C}{\uparrow} \bullet} \rightarrow$$

Harmonic Combinatory Categorical Grammar



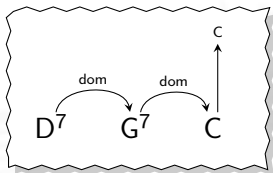
$$G^7 \Rightarrow G/C : \overset{\text{dom}}{\bullet}$$

$$C \Rightarrow C : \overset{c}{\uparrow} \bullet$$

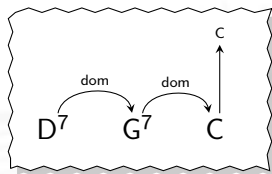
A	E	F#
F	C	G
D♭	A♭	E♭

$$\frac{\frac{G^7}{G/C : \overset{\text{dom}}{\bullet}} \quad \frac{C}{C : \overset{c}{\uparrow} \bullet}}{G-C : \overset{\text{dom}}{\bullet} \overset{c}{\uparrow} \bullet} \rightarrow$$

Harmonic CCG: Recursion



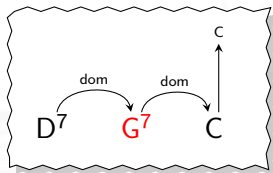
Harmonic CCG: Recursion

 D^7 G^7 C $D/G :$ $G/C :$ $C :$ $G-C :$ $D-C :$

Dom: $G^7 \Rightarrow G/C :$

Ton: $C \Rightarrow C :$

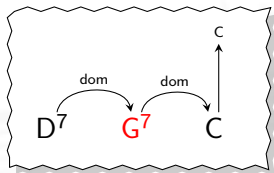
Harmonic CCG: Recursion

 D^7 G^7 C $D/G :$ $G/C :$ $C :$ $G-C :$ $D-C :$

Dom: $G^7 \Rightarrow G/C :$

Ton: $C \Rightarrow C :$

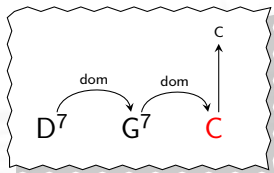
Harmonic CCG: Recursion

 D^7 G^7 C $D/G :$ $G/C :$ $C :$ $\overset{\text{dom}}{\bullet}$ $G-C :$ $D-C :$

Dom: $G^7 \Rightarrow G/C : \overset{\text{dom}}{\bullet}$

Ton: $C \Rightarrow C : \overset{c}{\bullet}$

Harmonic CCG: Recursion

 D^7 G^7 C $D/G :$ $G/C :$

dom

 $C :$

c

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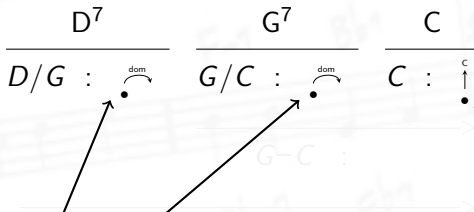
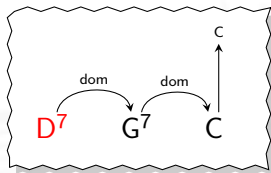
Dom: $G^7 \Rightarrow G/C :$

dom

Ton: $C \Rightarrow C :$

c

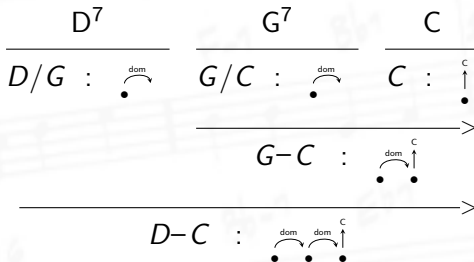
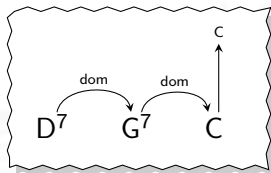
Harmonic CCG: Recursion



Dom: $G^7 \Rightarrow G/C : \overset{\text{dom}}{\bullet}$

Ton: $C \Rightarrow C : \overset{c}{\bullet}$

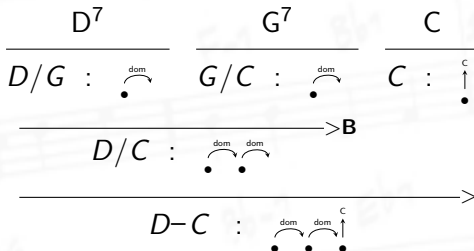
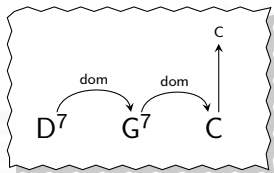
Harmonic CCG: Recursion



Dom: $G^7 \Rightarrow G/C : \dot{\bullet} \xrightarrow{\text{dom}}$

Ton: $C \Rightarrow C : \dot{\bullet} \xrightarrow{c}$

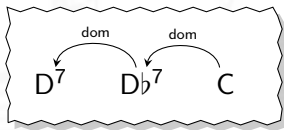
Harmonic CCG: Recursion



Dom: $G^7 \Rightarrow G/C : \overset{\text{dom}}{\curvearrowright}$

Ton: $C \Rightarrow C : \overset{c}{\uparrow}$

Harmonic CCG: Substitution

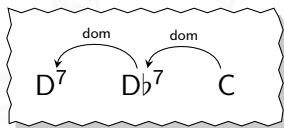


$$\begin{array}{ccc} D^7 & D^b7 & C \\ \hline D/G & G/C & C \\ \hline D/C & & B \\ \hline D-G & & \end{array}$$

Dom: $G^7 \Rightarrow G/C$

Ton: $C \Rightarrow C$

Harmonic CCG: Substitution



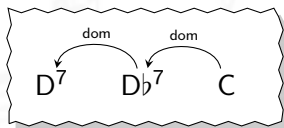
$$\frac{D^7}{D/G} \quad \frac{D_b^7}{G/C} \quad \frac{C}{C}$$

Dom_tritone: $D_b^7 \Rightarrow G/C$

Dom: $G^7 \Rightarrow G/C$

Ton: C $\Rightarrow$ C

Harmonic CCG: Substitution



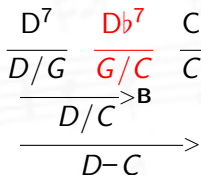
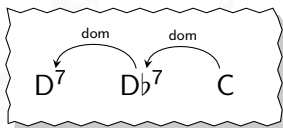
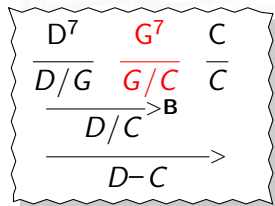
$$\begin{array}{ccc} D^7 & D_b^7 & C \\ \hline D/G & G/C & C \\ \hline D/C & \xrightarrow{B} & \\ \hline D-C & \xrightarrow{\quad} & \end{array}$$

Dom: $G^7 \Rightarrow G/C$

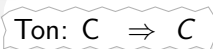
Dom_tritone: $D_b^7 \Rightarrow G/C$

Ton: $C \Rightarrow C$

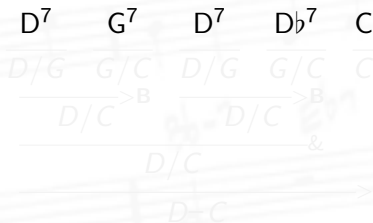
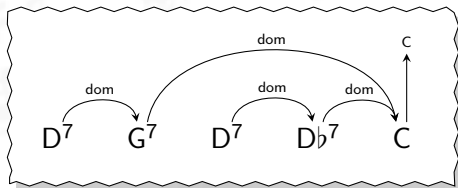
Harmonic CCG: Substitution



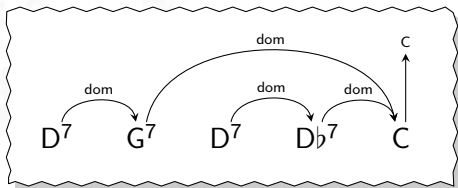
Dom_tritone: $D^b7 \Rightarrow G/C$



Harmonic CCG: Coordination



Harmonic CCG: Coordination

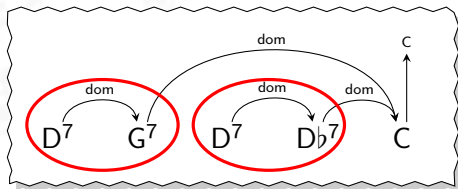


$$\frac{D^7}{D/G} \quad \frac{G^7}{G/C} \quad \frac{D^7}{D/G} \quad \frac{D_b^7}{G/C} \quad \frac{C}{C}$$

$$\frac{D/C >^B}{D/C} \quad \frac{D/C >^B}{D/C} \quad \&$$

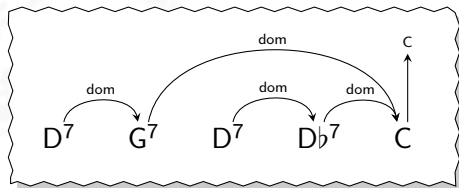
$$\frac{D/C}{D-C} \rightarrow$$

Harmonic CCG: Coordination



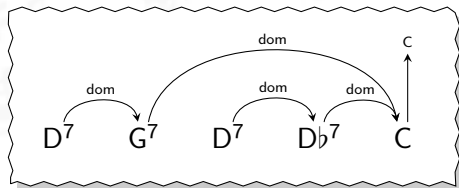
$$\begin{array}{ccccc}
 D^7 & G^7 & D^7 & D_b^7 & C \\
 \hline
 D/G & G/C & D/G & G/C & C \\
 \hline
 \xrightarrow{D/C} & \xrightarrow{B} & \xrightarrow{D/C} & \xrightarrow{B} & \\
 \hline
 & & D/C & & \\
 & & D=C & &
 \end{array}$$

Harmonic CCG: Coordination



$$\begin{array}{ccccc}
 D^7 & G^7 & D^7 & D_b^7 & C \\
 \hline
 D/G & G/C & D/G & G/C & C \\
 \hline
 & >B & >B & & \\
 D/C & & D/C & & \\
 \hline
 & & & & \& \\
 D/C & & & &
 \end{array}$$

Harmonic CCG: Coordination



$$\begin{array}{c}
 \begin{array}{ccccc}
 D^7 & G^7 & D^7 & D_b^7 & C \\
 \hline
 D/G & G/C & D/G & G/C & C \\
 \hline
 & >B & >B & & \\
 D/C & & D/C & & \\
 \hline
 & & & & \& \\
 & & D/C & & \\
 \hline
 & & & & > \\
 & & D-C & &
 \end{array}
 \end{array}$$

Statistical Parsing

- Supervised statistical parsing models
- Guide parser and rank interpretations
- Parsing model: Hockenmaier & Steedman (2002)¹
- Model of CCG derivations, PCCG
- Train on hand-written derivations
- Supervised training

$$\begin{array}{ccccc}
 D^7 & G^7 & D^7 & D_b^7 & C \\
 \hline
 D/G & G/C & D/G & G/C & C \\
 \hline
 & \xrightarrow{D/C} & B & \xrightarrow{D/C} & B \\
 & & & & \& \\
 & & D/C & & \\
 & & \xrightarrow{D-C} & &
 \end{array}$$

¹Generative models for statistical parsing with Combinatory Categorical Grammar. ACL

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$$\begin{array}{ccccccc}
 D^7 & G^7 & D^7 & D^7 & C \\
 \hline
 D/G & G/C & D/G & G/C & C \\
 \hline
 & & & & \\
 D/C & & D/C & & \\
 \hline
 & & & & \\
 & & D/C & & \\
 \hline
 & & & & \\
 & & D-C & &
 \end{array}$$

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$$\begin{array}{ccccc}
 D^7 & G^7 & D^7 & D_b^7 & C \\
 \hline
 D/G & G/C & D/G & G/C & C \\
 \hline
 & \xrightarrow{D/C} B & & \xrightarrow{D/C} B & \\
 \hline
 & & & & \& \\
 & & & D/C & \\
 \hline
 & & & D-C & \rightarrow
 \end{array}$$

¹Generative models for statistical parsing with Combinatory Categorical Grammar. ACL

Statistical Parsing

- Supervised statistical parsing models
- Guide parser and rank interpretations
- Parsing model: Hockenmaier & Steedman (2002)¹
- Model of CCG derivations, PCCG
 - Train on hand-written derivations
 - Supervised training

$$\begin{array}{ccccc}
 D^7 & G^7 & D^7 & D_b^7 & C \\
 \hline
 D/G & G/C & D/G & G/C & C \\
 \hline
 & \xrightarrow{D/C} & \xrightarrow{D/C} & & \\
 & \text{B} & \text{B} & & \\
 & \text{D/C} & \text{D/C} & \text{\&} & \\
 & \text{D/C} & & & \\
 \hline
 & \xrightarrow{D-C} & & &
 \end{array}$$

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 D^7 & G^7 & D^7 & D_b^7 & C \\
 \hline
 D/G & G/C & D/G & G/C & C \\
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 \hline
 & & & & \& \\
 & & D/C & & \\
 \hline
 & & & & \xrightarrow{D-C}
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 \hline
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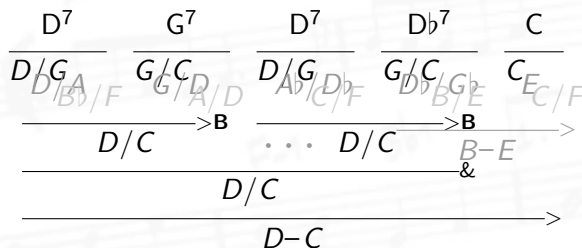
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$$\begin{array}{ccccc}
 D^7 & G^7 & D^7 & D\flat^7 & C \\
 \hline
 D/G & G/C & D/G & G/C & C \\
 \hline
 & \xrightarrow{D/C} B & & \xrightarrow{D/C} B & \\
 \hline
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 & & D/C & & \\
 \hline
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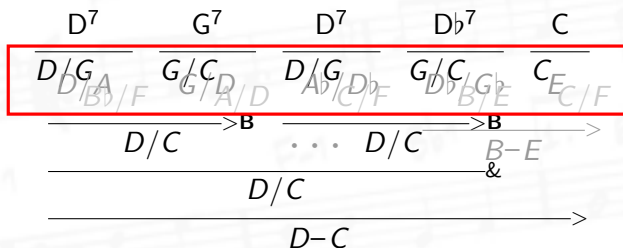
Supertagging



- Experimented with history models
- Adaptive supertagging (Clark & Curran, 2007)²

²Wide-Coverage Efficient Statistical Parsing with CCG and Log-Linear Models

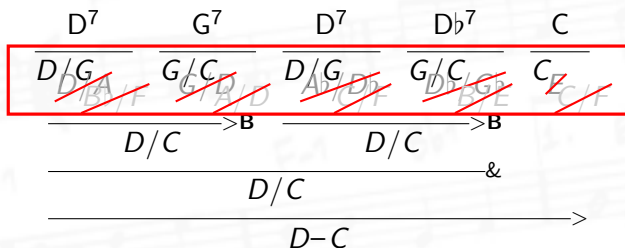
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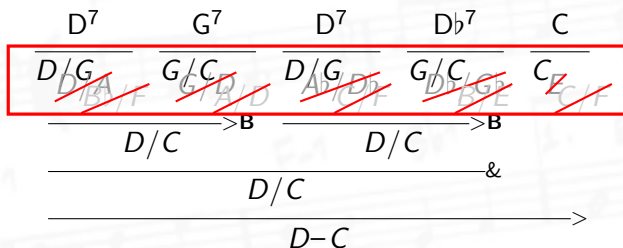
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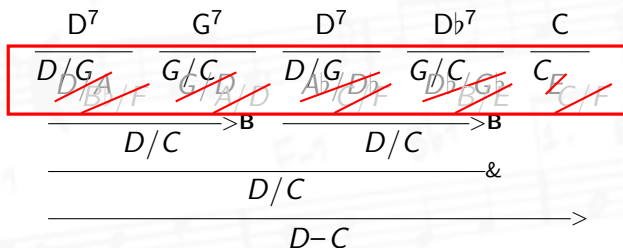
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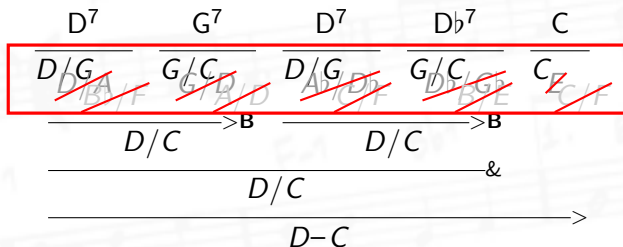
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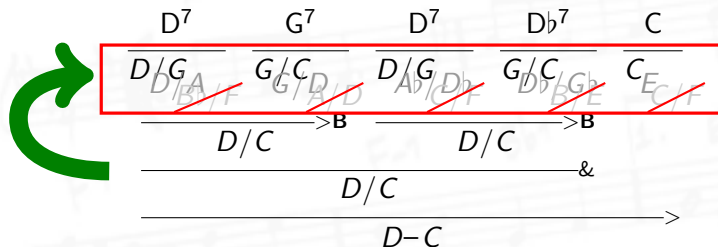
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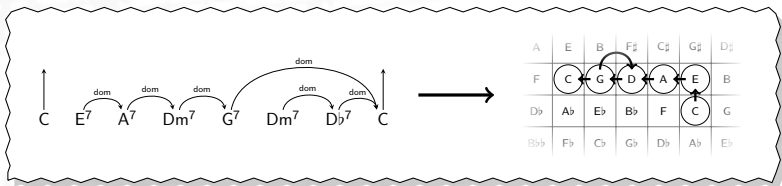


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Baseline: HMMPATH

- Construct path with HMM:



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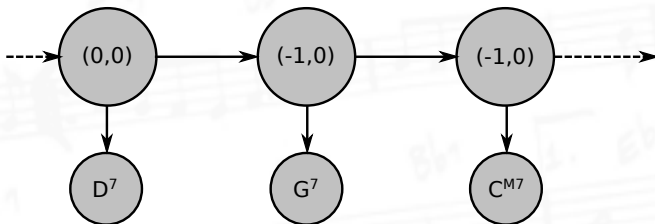
A 5x5 grid of musical notes. The notes are arranged as follows:

A	E	B	F#	C#
F	C	G	D	A
D#	A#	E#	B#	F

The cell containing the note 'D' is circled.

Baseline: HMMPATH

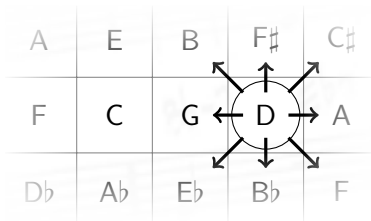
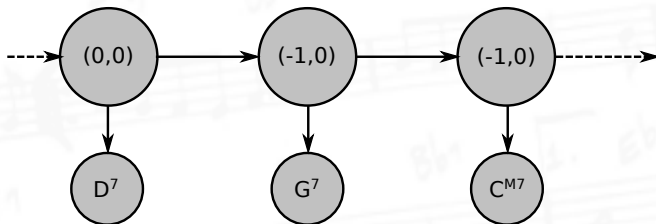
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A	E	B	F#	C
F	C	G	D	A
D#	A#	E#	B#	F

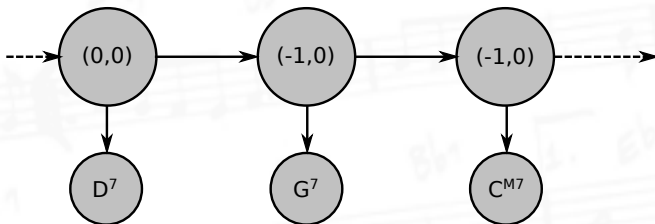
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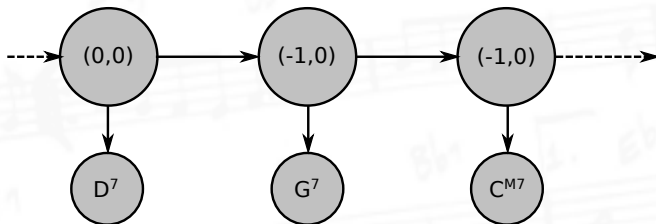
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A	E	B	F $\sharp$	C $\sharp$
F	C	G	D	A
D $\flat$	A $\flat$	E $\flat$	B $\flat$	F

Baseline: HMMPATH

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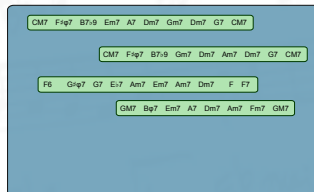
A	E	B	F $\sharp$	C $\sharp$
F	C	G	D	A
D $\flat$	A $\flat$	E $\flat$	B $\flat$	F

Jazz Corpus

- Annotated training corpus
 - Jazz chord sequences
 - Full grammatical derivation annotated
 - → full harmonic analysis
 - 74 sequences: ~3k chords

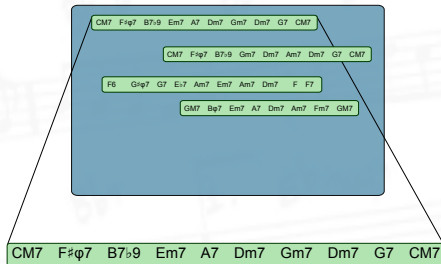
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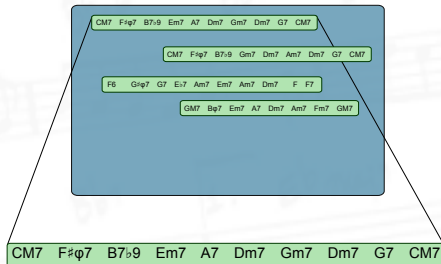
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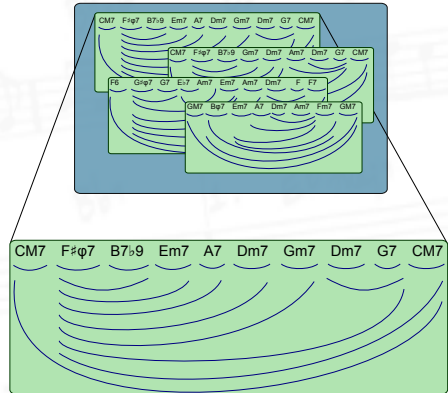
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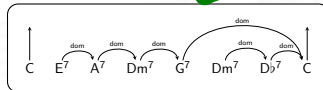
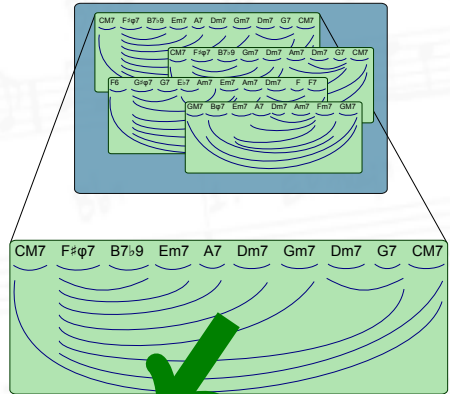
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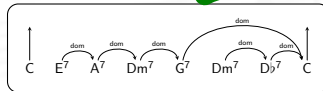
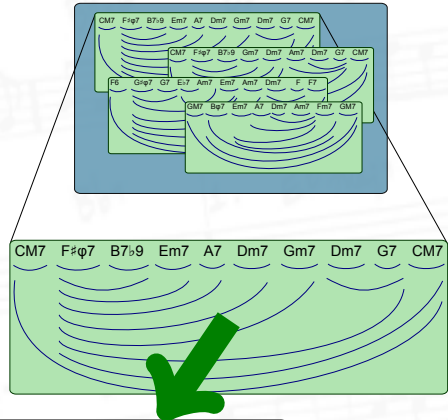
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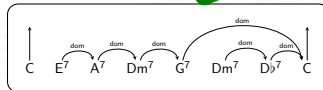
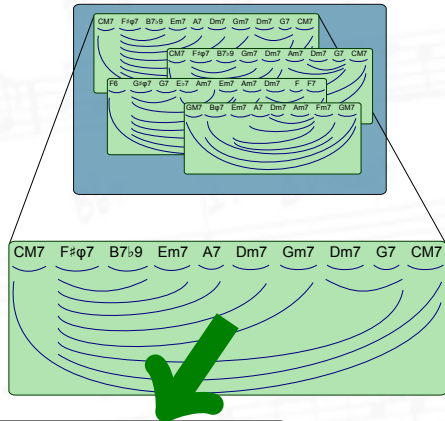
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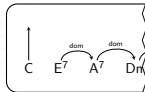
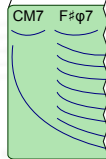
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Afternoon in Paris
Alice in Wonderland
Anthropology
Beauty and the Beast
Black Orpheus
Blackberry Winter
Blue in Green
Boplicity
Bud Powell
Byrd Like
Call Me Irresponsible
Can't Help Lovin' Dat Man
Chelsea Bridge
A Child is Born
Chippie
Chitlins Con Carne
Como En Vietnam
Confirmation
Crescent
Dear Old Stockholm

Evaluation Metric

Tonal space edit distance



Precision, recall, f-score

Evaluation Metric

Tonal space edit distance

A	E	B	F $\sharp$	C $\sharp$
F	C	G	D	A
D $\flat$	A $\flat$	E $\flat$	B $\flat$	F

D	A	E	B
B $\flat$	F	C	G
G $\flat$	D $\flat$	A $\flat$	E $\flat$
E $\flat$	B $\flat\flat$	F $\flat$	C $\flat$

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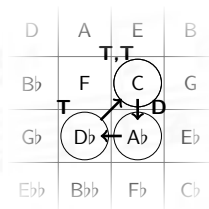
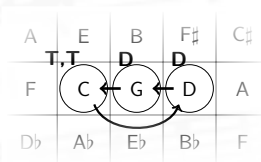
A	E	B	F $\sharp$	C $\sharp$
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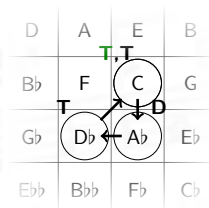
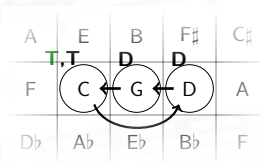
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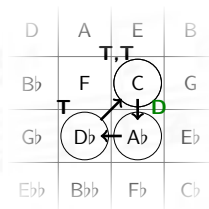
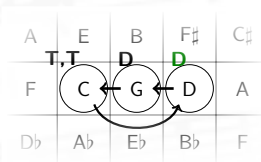
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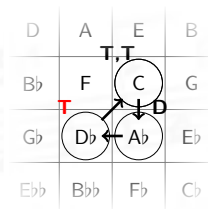
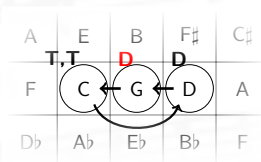
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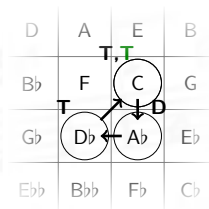
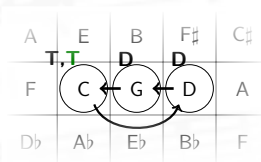
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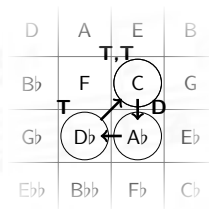
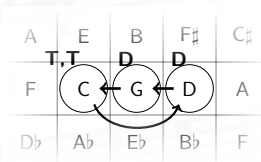
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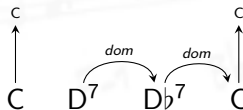


Precision, recall, f-score

Evaluation: Dependency Recovery

- Dependency recovery of harmonic analysis

Annotated:

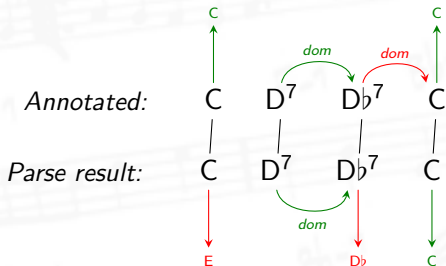


Parse result:



Evaluation: Dependency Recovery

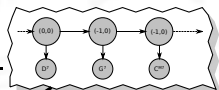
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Results

- Tonal space metric:

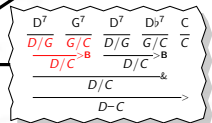
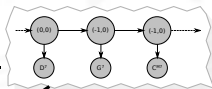
	P (%)	R (%)	F (%)	Cov. (%)
HMMPATH	77.44	84.87	80.98	100
PCCG	92.29	88.78	90.50	97.37
ST+PCCG	90.18	92.79	91.46	100



Results

- Tonal space metric:

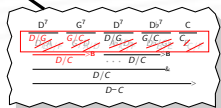
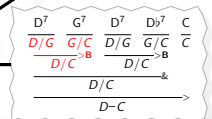
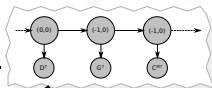
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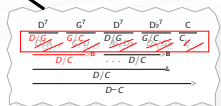
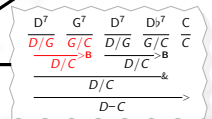
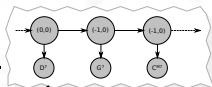
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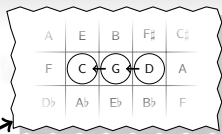
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Conclusion

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- Harmonic adaptation of CCG
- Statistical parsing, adapted from NLP
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- Parser outperforms HMM baseline
- Extension to analysis of performances

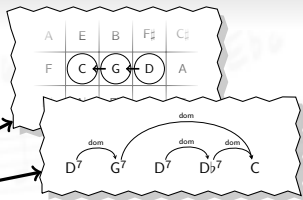
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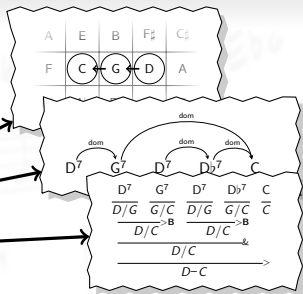
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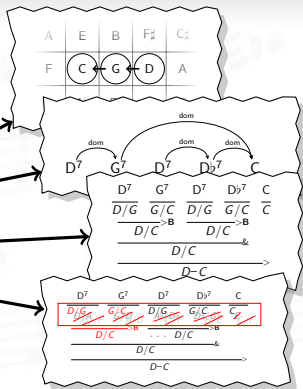
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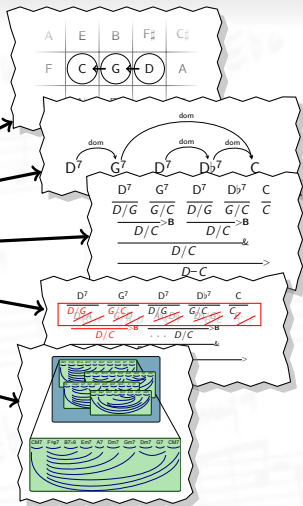
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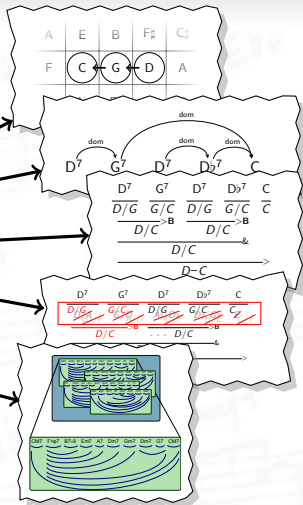


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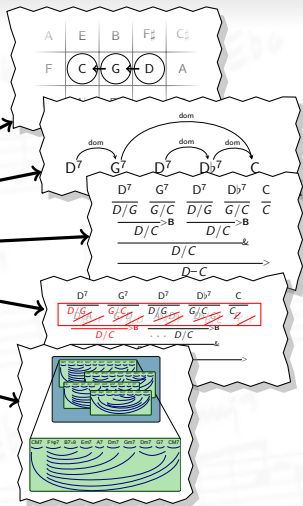
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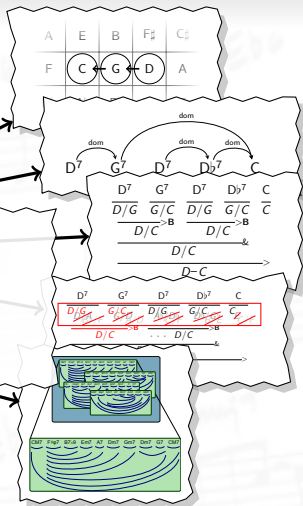
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The End



Bibliography I



Clark, S., & Curran, J. R. (2007).

Wide-coverage efficient statistical parsing with CCG and log-linear models.

Computational Linguistics, 33, 493–552.



Hockenmaier, J., & Steedman, M. (2002).

Generative models for statistical parsing with Combinatory Categorical Grammar.

In *Proceedings of the 40th Meeting of the Association for Computational Linguistics*, (pp. 335–342). Philadelphia, PA: Association for Computational Linguistics.



Keiler, A. (1981).

Two views of musical semiotics.

In W. Steiner (Ed.) *The Sign in Music and Literature*, (pp. 138–168). Austin TX: University of Texas Press.

Bibliography II



Lerdahl, F., & Jackendoff, R. (1983).
A Generative Theory of Tonal Music.
Cambridge, MA: MIT Press.



Rameau, J. P. (1722).
Traité de l'harmonie.
Jean-Baptiste-Christophe Ballard.



Riemann, H. (1893).
Vereinfachte Harmonielehre oder die Lehre von den tonalen Funktionen der Akkorde.
Augener & Co.
Trans. H. Bemerunge, as *Harmony Simplified, or the Theory of the Tonal Functions of Chords*.

Bibliography III



Rohrmeier, M. (2011).

Towards a generative syntax of tonal harmony.

Journal of Mathematics and Music, 5, 35–53.



Steedman, M. (1984).

A generative grammar for jazz chord sequences.

Music Perception, 2, 52–77.



Winograd, T. (1968).

Linguistics and the computer analysis of tonal harmony.

Journal of Music Theory, 12, 2–49.

Atomic Categories

$$\frac{\frac{G^7}{G/C} \quad \frac{C}{C}}{G-C} \rightarrow$$

$$\frac{\frac{C \quad G^7 \quad C}{C \quad G/C \quad C}}{G-C} \xrightarrow{\text{dev}} C-C$$

$$\frac{\frac{B^M7 \quad G^7 \quad C}{B \quad G/C \quad C}}{G-C} \xrightarrow{\text{dev}} B-C$$

Atomic Categories

$$\frac{\frac{G^7}{G/C} \quad \frac{C}{C}}{G-C} \rightarrow$$

$$\frac{\frac{\frac{C}{C} \quad \frac{G^7}{G/C} \quad \frac{C}{C}}{G-C} \rightarrow}{C-C = C} \text{dev}$$

$$\frac{\frac{\frac{B^{M7}}{B} \quad \frac{G^7}{G/C} \quad \frac{C}{C}}{G-C} \rightarrow}{B-C} \text{dev}$$

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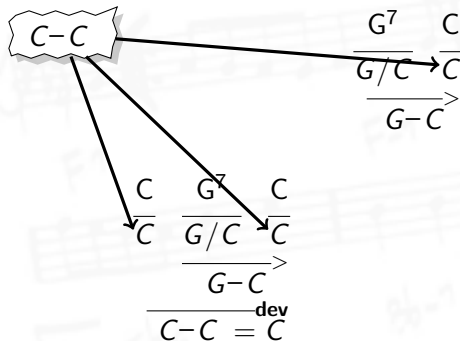
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C

$$\frac{\frac{\frac{B^{\#}M^7}{B} \quad \frac{G^7}{G/C} \quad \frac{C}{C}}{G-C} \rightarrow}{B-C} \text{dev}$$

Atomic Categories



Atomic Categories

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$$\frac{\frac{\frac{\frac{C}{C} \quad \frac{D^7}{D/\textcolor{red}{G}} \quad \frac{G^7}{G/C} \quad \frac{C}{C}}{G-C} >}{D-C} >}{C} \text{dev}$$

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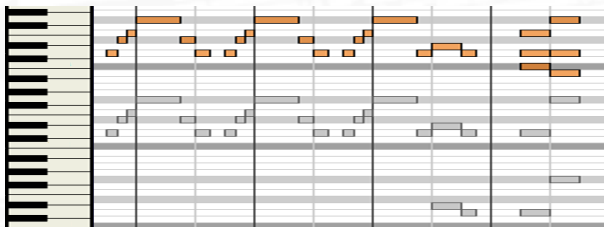
Parsing Performances

- Can we parse a musical performance?

- Proof-of-concept extension
- HMM chord recognizer
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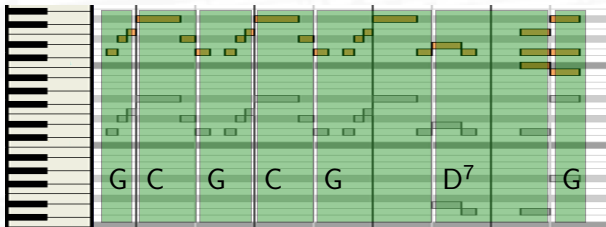
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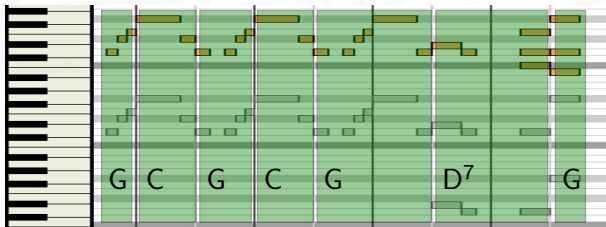
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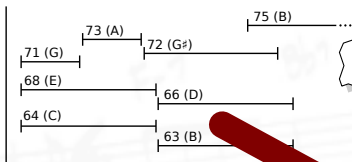
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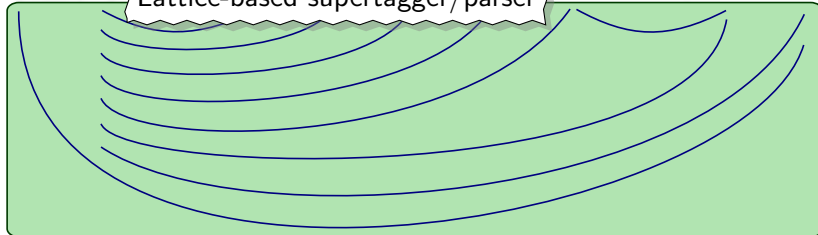


MIDI input

Chord recognizer: lattice

CM7	F# ϕ 7	B ^{7b9}	Em7	F#m7	Dm7	Gm7	Dm7	G7	CM7
Em	Am	Co7	G7	F#m7	Am	Do7	F6	B ϕ 7	Am7
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Lattice-based supertagger/parser



Tonal Space

C $\sharp$	G $\sharp$	D $\sharp$	A $\sharp$	E $\sharp$	B $\sharp$	F $\sharp\sharp$	C $\sharp\sharp$	G $\sharp\sharp$	D $\sharp\sharp$	A $\sharp\sharp$
A	E	B	F $\sharp$	C $\sharp$	G $\sharp$	D $\sharp$	A $\sharp$	E $\sharp$	B $\sharp$	F $\sharp\sharp$
F	C	G	D	A	E	B	F $\sharp$	C $\sharp$	G $\sharp$	D $\sharp$
D $\flat$	A $\flat$	E $\flat$	B $\flat$	F	C	G	D	A	E	B
B $\flat\flat$	F $\flat$	C $\flat$	G $\flat$	D $\flat$	A $\flat$	E $\flat$	B $\flat$	F	C	G
G $\flat\flat$	D $\flat\flat$	A $\flat\flat$	E $\flat\flat$	B $\flat\flat$	F $\flat$	C $\flat$	G $\flat$	D $\flat$	A $\flat$	E $\flat$
E $\flat\flat\flat$	B $\flat\flat\flat$	F $\flat\flat$	C $\flat\flat$	G $\flat\flat$	D $\flat\flat$	A $\flat\flat$	E $\flat\flat$	B $\flat\flat$	F $\flat$	C $\flat$

Roman Numeral Tonal Space

#I ⁻	#V ⁻	#II ⁻	#VI ⁻	#III	#VII	##IV	##I	##V ⁺	##II ⁺	##VI ⁺
VI ⁻	III ⁻	VII ⁻	#IV ⁻	#I	#V	#II	#VI	#III ⁺	#VII ⁺	##IV ⁺
IV ⁻	I ⁻	V ⁻	II ⁻	VI	III	VII	#IV	#I ⁺	#V ⁺	#II ⁺
bII ⁻	bVI ⁻	bIII ⁻	bVII ⁻	IV	I	V	II	VI ⁺	III ⁺	VII ⁺
bbVII ⁻	bIV ⁻	bI ⁻	bV ⁻	bII	bVI	bIII	bVII	IV ⁺	I ⁺	V ⁺
bbV ⁻	bbII ⁻	bbVI ⁻	bbIII ⁻	bbVII	bIV	bI	bV	bII ⁺	bVI ⁺	bIII ⁺
bbbIII ⁻	bbbVII ⁻	bbIV ⁻	bbI ⁻	bbV	bbII	bbVI	bbIII	bbVII ⁺	bIV ⁺	bI ⁺

Parsing Time

Average parse time per chord sequence:

Model	Mean	(std. dev.)
HMMPATH	0:03	(0:01)
PCCG	34:17	(75:23)
ST+PCCG	9:22	(33:32)

Extra Slides

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