

音楽的期待に基づく漸進的構造解析による ジャズ和声の意外性に関する考察

小椋裕太¹ 大村英史¹ 東条敏² 桂田浩一¹

目次

1. はじめに

1.1 背景

1.2 目的

2. 確率文脈自由文法に基づく漸進的構造解析

2.1 確率文脈自由文法

2.2 漸進的チャート解析

2.3 意外性の指標 U

3. 楽曲 *CUTE* の解析例と意外性評価

3.1 ECSA の概要

3.2 楽曲 *CUTE* の漸進的構造解析

3.3 意外性の考察

4. まとめ・今後の展望

1.1 背景

認知的音楽理論 (cognitive musicology)

伝統的音楽理論： 音楽を「**作る側**」の理論

認知的音楽理論： 「**聴く側**」の認知過程を踏まえた分析理論
GTMM, IRモデル 等



伝統的音楽理論



認知的音楽理論

音楽認知の計算モデルを作りたい！

1.1 背景

従来の認知的音楽理論

Generative Syntax Model [1]

和声構造を分析

G7の時に次の和音を（何か来るだろうと）期待する
CM7で期待が実現したような感じ

[1] M. Rohrmeier, *Towards a generative syntax of tonal harmony*, Journal of Mathematics and Music, 2011

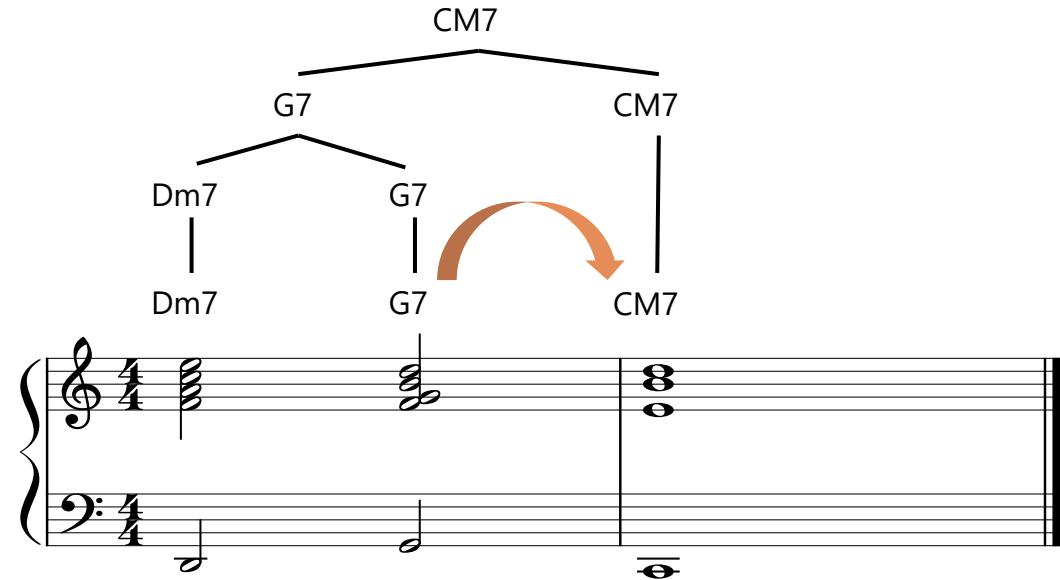
1.1 背景

従来の認知的音楽理論

Generative Syntax Model [1]

音楽認知に基づく文脈自由規則
(CFG)を定義

$CM7 \rightarrow G7 \ CM7$
 $G7 \rightarrow Dm7 \ G7$
 $Dm7 \rightarrow Dm7$
 $G7 \rightarrow G7$
 $CM7 \rightarrow CM7 \text{ etc.}$



和声進行の期待-実現の関係を階層的に表現可能であると提案

[1] M. Rohrmeier, *Towards a generative syntax of tonal harmony*, Journal of Mathematics and Music, 2011

1.2 目的

5

Generative Syntax Model の問題点

楽曲途中の認知構造が表現できない

楽曲全体に対する解析のみである

A musical score consisting of two staves. The top staff is for the piano, showing a treble clef, a 4/4 time signature, and a melody line with eighth and sixteenth notes. Below it, the piano's harmonic progression is indicated by Roman numerals: Dm7 and G7. The bottom staff is for the bass, showing a bass clef, a 4/4 time signature, and a bass line with quarter notes. The score ends at a bar line.

?



1.2 目的

Generative Syntax Model の問題点

和声進行の**意外性**が音楽の面白さになりうる

A musical score consisting of three staves. The top staff is treble clef, 4/4 time, with notes Dm7, G7, D♭7 (circled in orange), and CM7. The middle staff is also treble clef, 4/4 time, with chords Dm7, G7, D♭7, and CM7. The bottom staff is bass clef, 4/4 time, with notes corresponding to the chords above. The D♭7 chord is highlighted with an orange circle.

楽曲**途中**の構造を表示して
コード進行の**意外性**を評価する

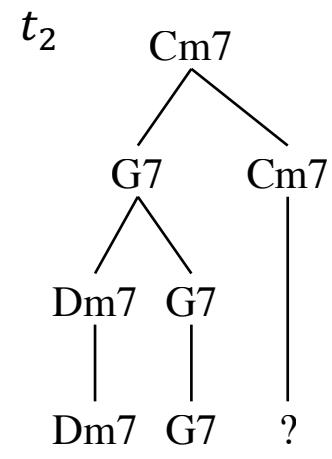
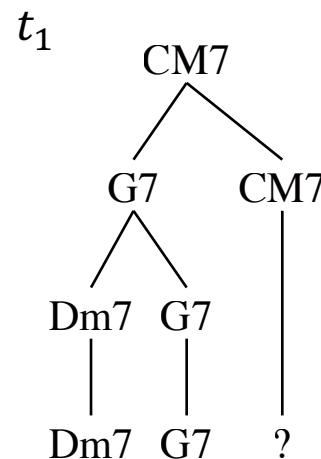
2. 確率文脈自由文法に基づく漸進的構造解析

2.1 確率文脈自由文法

確率文脈自由文法 (Probabilistic Context-Free Grammar)

各構文規則に適用確率を付与
→構文木の生成確率を計算可能

Rule	Prob.
$CM7 \rightarrow G7 CM7$	0.7
$CM7 \rightarrow CM7 CM7$	0.3
$Cm7 \rightarrow G7 Cm7$	0.4
$Cm7 \rightarrow Cm7 Cm7$	0.6
$G7 \rightarrow Dm7 G7$	0.4
$G7 \rightarrow G7 G7$	0.3
$G7 \rightarrow D7 G7$	0.3



$$\text{ex.) } P(t_1) = 0.7 \times 0.4 = 0.28 \quad P(t_2) = 0.4 \times 0.4 = 0.16$$

木構造どうしの比較が可能に

2.1 確率文脈自由文法

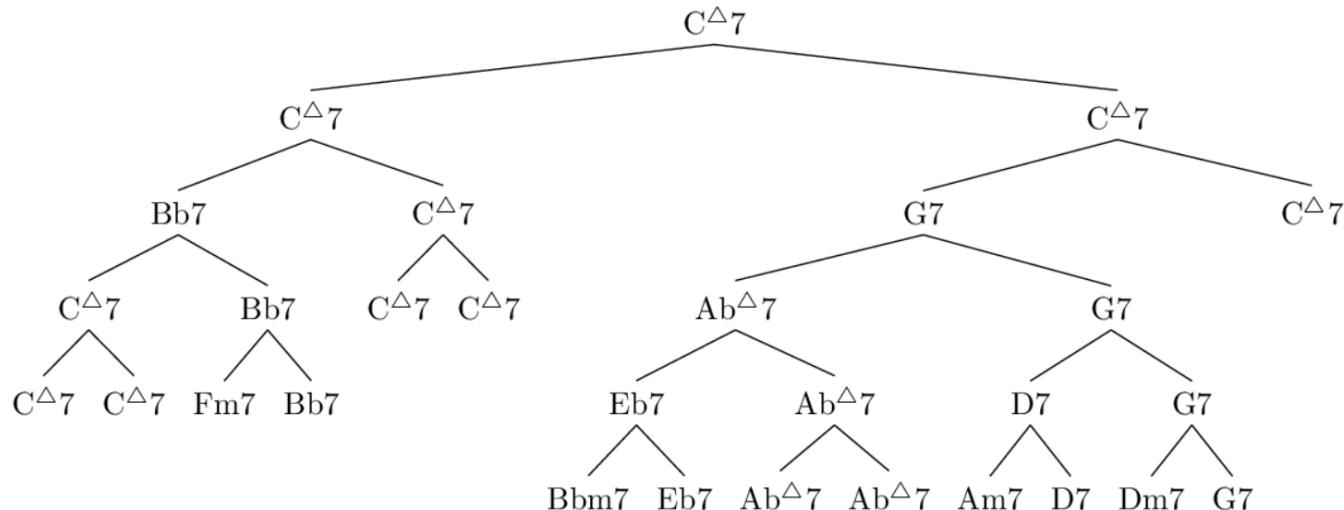
PCFG 適用確率の推定

[4]

Jazz Harmony Treebank

- ・確率文脈自由文法のパラメータ決定に使用
- ・150のジャズコード進行に対して人手で構文木をアノテーション
- ・平均27.75コードシンボル長（合計11697コード, 92種類）

Lady Bird



2.2 漸進的チャート解析

楽曲途中の木構造の表示

漸進的チャート解析^[3]

1. 辞書引き

語彙規則を参照し, Local Chartに追加

2. 規則適用

文法規則を参照し, Local Chartを構成

3. 項の置き換え

Local Chart中の項を用いて

Global Chartの未決定項を書き換え

input chord	global chart			
	ID	edge	term	rules
Cmaj7	(1)	0-0	[(u)]s	
	(6)	0-1	[(Cmaj7]lc)s	(1)(3)
	(7)	0-1	[[Cmaj7]lc[(u)]lc]lc)s	(1)(5)
D7	(14)	0-2	[[Cmaj7]lc[[D7]vc[(u)]vc]vc[(u)]lc]lc)s	(7)(10)
	(15)	0-2	[[Cmaj7]lc[[D7]vc[(u)]vc]vc[(u)]lc]lc[(u)]lc]lc)s	(7)(12)
Dmin7	(22)	0-3	[[Cmaj7]lc[[D7]vc[(Dmin7]lc[(u)]vc]vc[(u)]lc]lc]lc)s	(14)(17)
	(23)	0-3	[[Cmaj7]lc[[D7]vc[(Dmin7]lc[(u)]vc)vc]vc[(u)]lc]lc[(u)]lc]lc)s	(15)(17)
G7	(29)	0-4	[[Cmaj7]lc[[D7]vc[(Dmin7]lc[G7]vc)vc]vc[(u)]lc]lc]lc)s	(22)(24)
	(30)	0-4	[[Cmaj7]lc[[D7]vc[(Dmin7]lc[G7]vc)vc]vc[(u)]lc]lc[(u)]lc]lc)s	(23)(24)

Algorithm 1 Algorithm of incremental parsing

```
function CHART_PARSING( $G\_chart, w$ )
   $L\_chart \leftarrow \{\}$  /*Local charts*/
   $temp \leftarrow \{\}$ 
```

```
/*step1 Lexicon Consultation*/
for  $X \in \text{Lexicon}$  do
  if  $w = X$  then
     $L\_chart \leftarrow L\_chart \cup \{[w]_X\}$ 
```

```
/*step2 Rule Application*/
for  $\sigma \in L\_chart$  and  $A \rightarrow XY\dots Z \in \text{Rules}$  do
  if  $\sigma = X$  then
     $L\_chart \leftarrow$ 
     $L\_chart \cup \{[\sigma[(u)]_Y\dots[(u)]_Z]_A\}$ 
```

```
/*step3 Term Replacement*/
for  $\phi \in G\_chart$  and  $\psi \in L\_chart$  do
  if  $\exists \gamma \gamma = lut(\phi) \wedge \gamma = \psi$  then
    replace  $lut(\phi)$  with  $\psi$ 
     $temp \leftarrow temp \cup \{\phi\}$ 
 $G\_chart \leftarrow temp$  /*Global charts*/
return  $G\_chart$ 
```

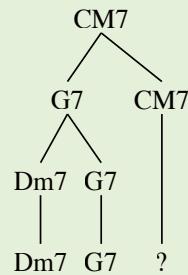
```
/*main*/
 $G\_chart \leftarrow [(u)]_s$ 
for  $i=1\dots \text{last}$  do
   $w_i \leftarrow \text{input\_chord}$ 
   $G\_chart \leftarrow \text{CHART\_PARSING}(G\_chart, w_i)$ 
```

[3] S. Matsubara, S. Arai, K. Toyama, Y. Inagaki,
Chart-based parsing and transfer in incremental spoken language translation,
 in Proc. the 4th Natural Language Processing Pacific Rim Symposium, 1997

2.3 意外性の指標U

確率文脈自由文法 (PCFG)

Rule	Prob.
CM7 → G7 CM7	0.7
G7 → Dm7 G7	0.4



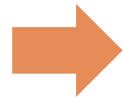
$$\begin{aligned} P(t_1) &= 0.7 \times 0.4 \\ &= 0.28 \end{aligned}$$

木構造どうしの比較

漸進的チャート解析

input chord	globalChart			rules
	ID	edge	term	
(1)	0-0	[(u)]s		
Cmaj7	(6)	0-1	[[Cmaj7]Ic]s	(1)(3)
	(7)	0-1	[[Cmaj7]Ic[(u)]Ic]s	(1)(5)
D7	(14)	0-2	[[Cmaj7]Ic [[[D7]Vc [(u)]Vc]Vc [(u)]Ic]Ic]s	(7)(10)
	(15)	0-2	[[Cmaj7]Ic [[[D7]Vc [(u)]Vc]Vc [(u)]Ic]Ic[(u)]Ic]Ic]s	(7)(12)
Dmin7	(22)	0-3	[[Cmaj7]Ic [[[D7]Vc [[Dmin7]Ic [(u)]Vc]Vc [(u)]Ic]Ic]Ic]s	(14)(17)
	(23)	0-3	[[Cmaj7]Ic [[[D7]Vc [[Dmin7]Ic [(u)]Vc]Vc [(u)]Ic]Ic[(u)]Ic]Ic]Ic]s	(15)(17)
G7	(29)	0-4	[[Cmaj7]Ic [[[D7]Vc [[Dmin7]Ic [G7]Vc]Vc [(u)]Ic]Ic]Ic]s	(22)(24)
	(30)	0-4	[[Cmaj7]Ic [[[D7]Vc [[Dmin7]Ic [G7]Vc]Vc [(u)]Ic]Ic[(u)]Ic]Ic]Ic]s	(23)(24)

楽曲途中の木構造の表示



意外性の指標 U の導入

計算式は解析例の中で説明

3. 楽曲CUTEの解析例と意外性評価

3.1 ECSAの概要

Expectation-based Chord Sequence Analyzer (ECSA)

音楽的期待に基づくジャズ和声の漸進的構造解析システム

The screenshot shows the 'Ex-based Chord Sequence Analyzer' window titled 'Incremental Tree Analysis'. The main input field contains a chord sequence: Dm7 G7 CM7 Dm7 G7 Gm7 C7 FM7 Bb7 Em7 Am7 Dm7 G7 CM7. A red arrow points from the text 'コード進行を入力' (Input chord progression) to this field.

On the left, a vertical toolbar has icons for tree analysis, AB analysis, and settings. A red arrow points from the text '楽曲途中の和声構造' (Chord structure in the middle of a piece) to this toolbar.

The main area displays two rows of incremental tree analysis results. Each row consists of three boxes labeled (0), (1), and (2), each showing a tree diagram and a numerical value U.

Top Row:

- (0) 1.0: Shows a tree where Dm7 branches into Dm7 and Dm7. The value U = 1.0.
- (1) 0.31746031746031744: Shows a tree where Dm7 branches into Dm7 and Dm7, which further branches into Dm7 and a question mark. The value U = 0.31746031746031744.
- (2) 0.09615384615384616: Shows a tree where Gm7 branches into Dm7 and Gm7, which further branches into Dm7 and a question mark. The value U = 0.09615384615384616.

Bottom Row:

- (0) 0.0901386748844376: Shows a tree where CM7 branches into G7 and CM7, which further branches into Dm7 and G7. The value U = 0.0901386748844376.
- (1) 0.08021390374331551: Shows a tree where Cm7 branches into G7 and Cm7, which further branches into Dm7 and G7. The value U = 0.08021390374331551.
- (2) 0.07523510971786833: Shows a tree where CM branches into G7 and CM, which further branches into Dm7 and G7. The value U = 0.07523510971786833.

Red arrows also point from the text 'その時点での意外性U' (Surprise factor U at that point) to the U values in the first two boxes of both rows.

3.2 楽曲 CUTE の漸進的構造解析

14

CUTE

ジャズスタンダード（一部を抜粋）

Dm7 G7 CM7

Dm7 G7 Gm7 C7

FM7 B♭7 Em7 Am7

Dm7 G7 CM7

Piano trio ver.



Quartet ver.



3.2 楽曲 CUTE の漸進的構造解析

15

CUTE

ECSAによる解析の前に・・・

The image shows a musical score for the song "CUTE". At the top, there is a staff with three chords: Dm7, G7, and CM7. Below this, a large box highlights the harmonic progression: Dm7, G7, Gm7, and C7. Inside this box, the chords are labeled as the 'dia tonic chords' in the key of C major. Below the box, the full harmonic progression is shown: CM7, Dm7, Em7, FM7, G7, Am7, Bm7(♭5). The chords V7 and IIIm7 are circled in orange. The score consists of two staves: a treble clef staff at the top and a bass clef staff at the bottom.

Dm7 G7 CM7

Dm7 G7 Gm7 C7

キーCメジャーのダイアトニックコード

CM7 Dm7 Em7 FM7 G7 Am7 Bm7(♭5)

IM7 IIIm7 IIIIm7 IVM7 V7 VIIm7 VIIIm7(♭5)

Dm7 G7 CM7

3.2 楽曲 CUTE の漸進的構造解析

15

CUTE

ECSAによる解析の前に・・・

The musical score consists of four staves of music, each starting with a treble clef and a 4/4 time signature. The chords are labeled above each staff:

- Staff 1: Dm7, G7, CM7
- Staff 2: Dm7, G7, Gm7, C7
- Staff 3: FM7, B♭7, Em7, Am7
- Staff 4: Dm7, G7, CM7

The chords are color-coded: Dm7, G7, and CM7 in the first staff are orange; Gm7 and C7 in the second staff are green; FM7, B♭7, Em7, and Am7 in the third staff are light green; and the final Dm7, G7, and CM7 are orange.

3.2 楽曲 CUTE の漸進的構造解析

15

CUTE

ECSAによる解析の前に・・・

A musical score in 4/4 time. The first measure shows a Dm7 chord (D, F, A, C) with a bass note D. The second measure shows a G7 chord (G, B, D, E) with a bass note G. The third measure shows a CM7 chord (C, E, G, B) with a bass note C.

A musical score in 4/4 time. The first measure shows a Dm7 chord (D, F, A, C) with a bass note D. The second measure shows a G7 chord (G, B, D, E) with a bass note G. The third measure shows a Gm7 chord (G, B, D, E) with a bass note G. The fourth measure shows a C7 chord (C, E, G, B) with a bass note C.

A musical score in 4/4 time. The first measure shows a FM7 chord (F, A, C, E) with a bass note F. The second measure shows a Dm7 chord (D, F, A, C) with a bass note D. A callout box highlights the F major diatonic chords: FM7, Gm7, Am7, B♭M7, C7, Dm7, and Em7(♭5). The chords are shown with their respective bass notes: F, G, A, B♭, C, D, and E. The Em7(♭5) chord is shown with a bass note E. Below the score, the Roman numerals I through VII are listed, with the V7 chord circled in orange.

キーFメジャーのダイアトニックコード

FM7 Gm7 Am7 B♭M7 C7 Dm7 Em7(♭5)

IIM7 IIIm7 IIIIm7 IVM7 V7 VIIm7 VIIIm7(♭5)

3.2 楽曲 CUTE の漸進的構造解析

16

CUTE

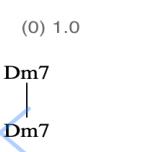
ECSA での 解析結果

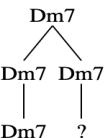
Ex-based Chord Sequence Analyzer
Incremental Tree Analysis

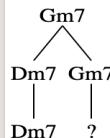
chord sequence: Dm7 G7 CM7 Dm7 G7 Gm7 C7 FM7 Bb7 Em7 Am7 Dm7 G7 CM7

ANALYSE

Dm7 U = 1.0

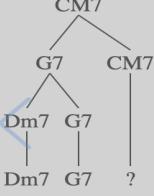
(0) 1.0


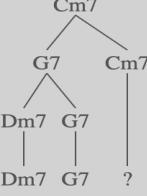
(1) 0.31746031746031744


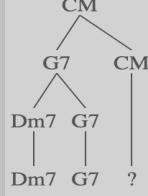
(2) 0.09615384615384616


>

Dm7 G7 U = 0.0901386748844376

(0) 0.0901386748844376


(1) 0.08021390374331551


(2) 0.07523510971786833


>

3.2 楽曲 CUTE の漸進的構造解析

17

ECSA での 解析結果



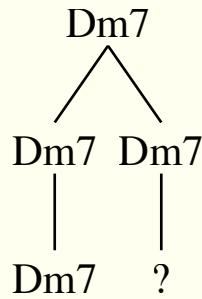
- Dm7

(順位*完全部分木) 生成確率値

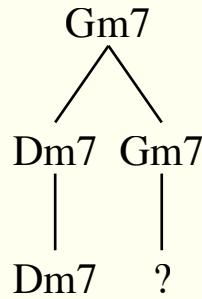
(1*)1.0



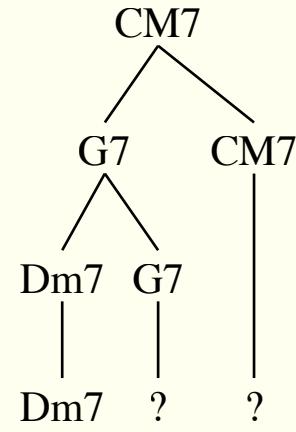
(2)0.317



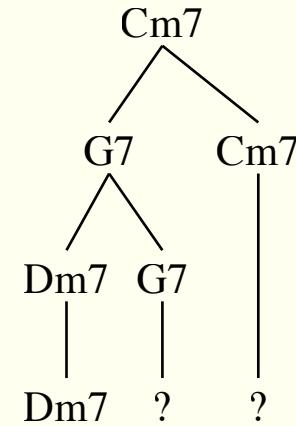
(3)0.0961



(4)0.0901



(5)0.0802



...

?

: 次に期待されるコード(カテゴリ)

完全部分木* : その時点で和声進行が完結(安定)

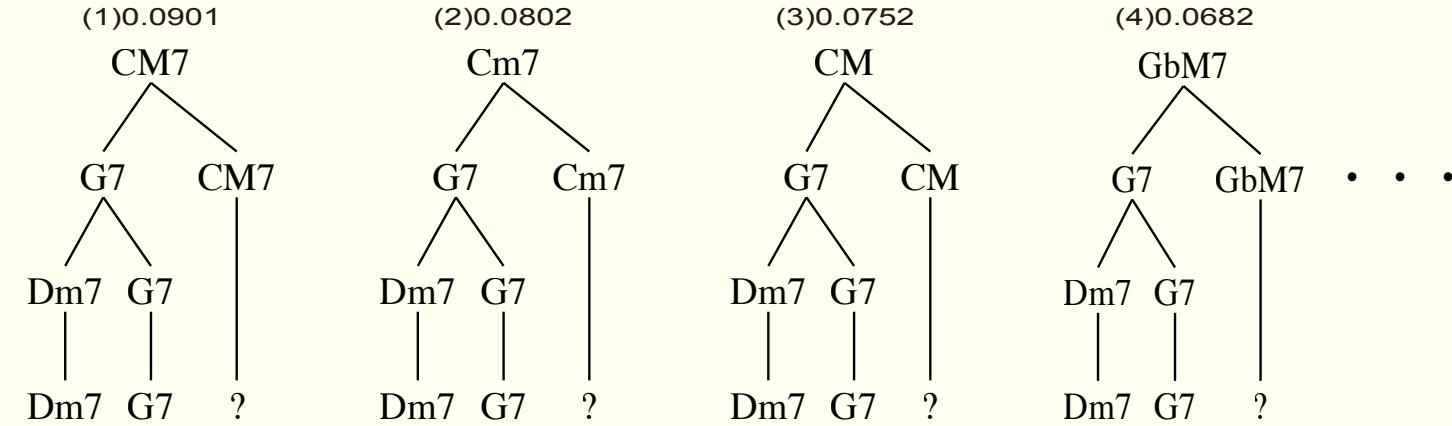
3.2 楽曲 CUTE の漸進的構造解析

18

ECSA での 解析結果



• Dm7 G7



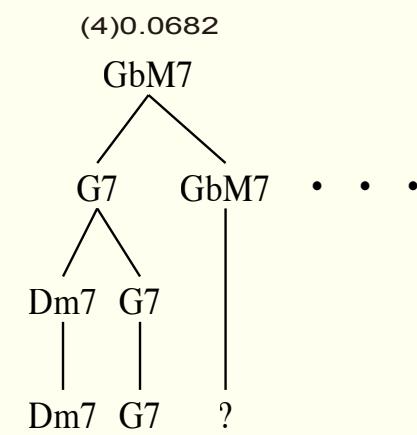
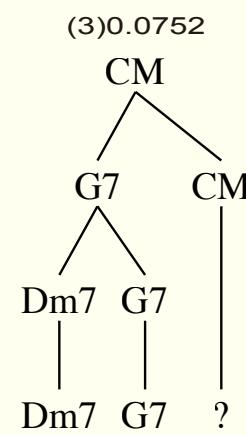
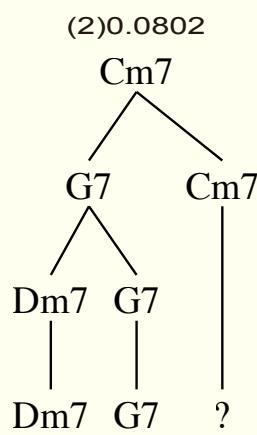
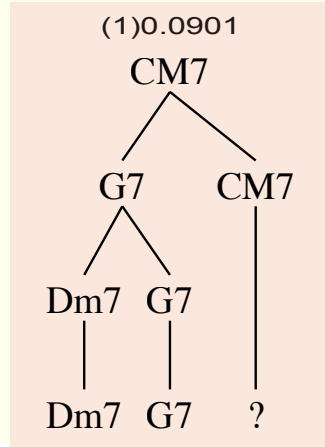
3.2 楽曲 CUTE の漸進的構造解析

18

ECSA での 解析結果



- Dm7 G7



各コードステップにおける認知構造を代表するものとして、
最大の生成確率を持つ木構造に注目する

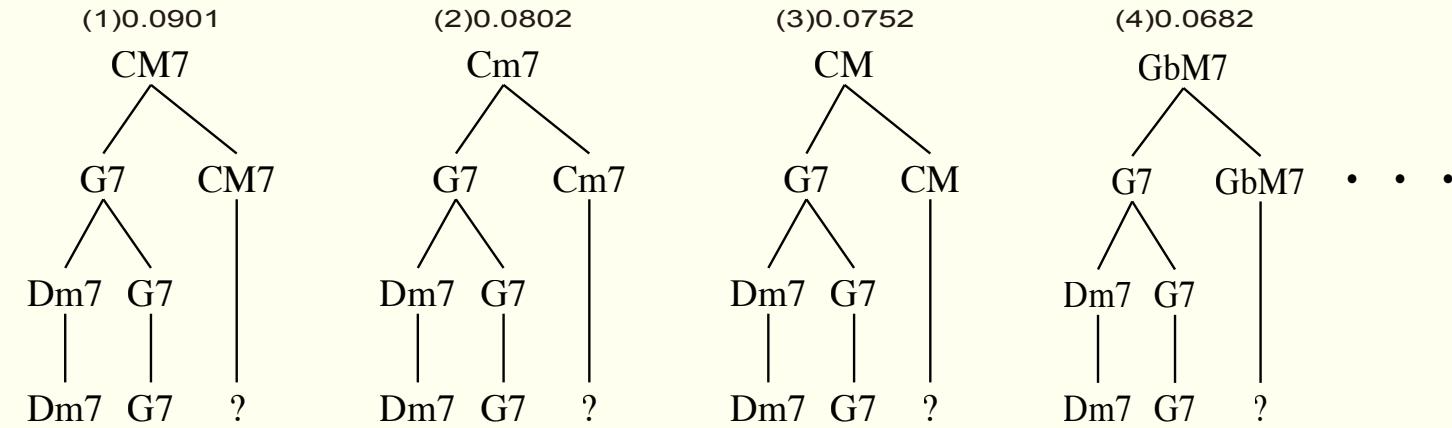
3.2 楽曲 CUTE の漸進的構造解析

18

ECSA での 解析結果



• Dm7 G7



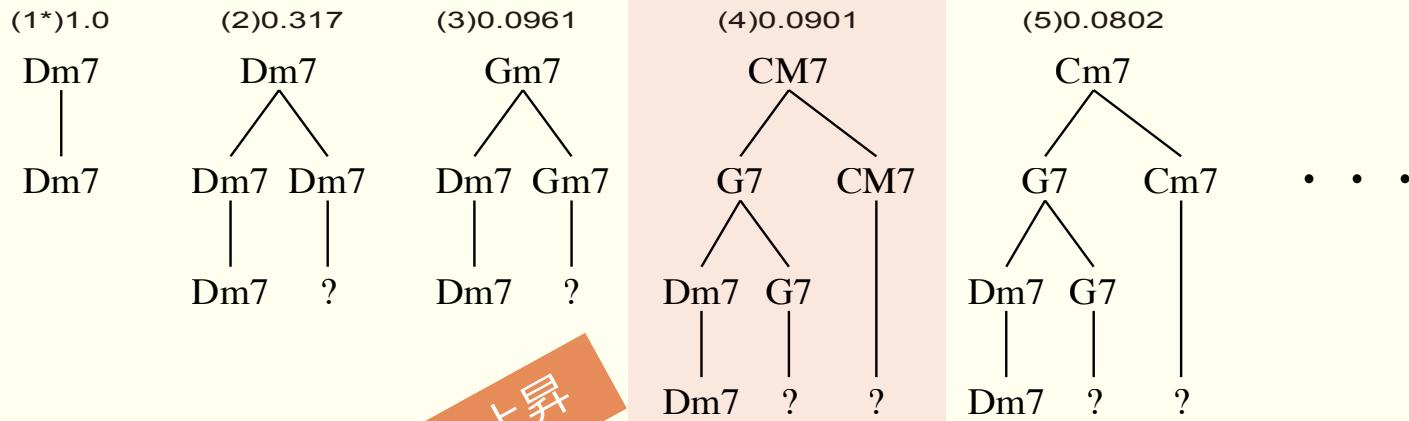
3.2 楽曲 CUTE の漸進的構造解析

19

ECSA での 解析結果

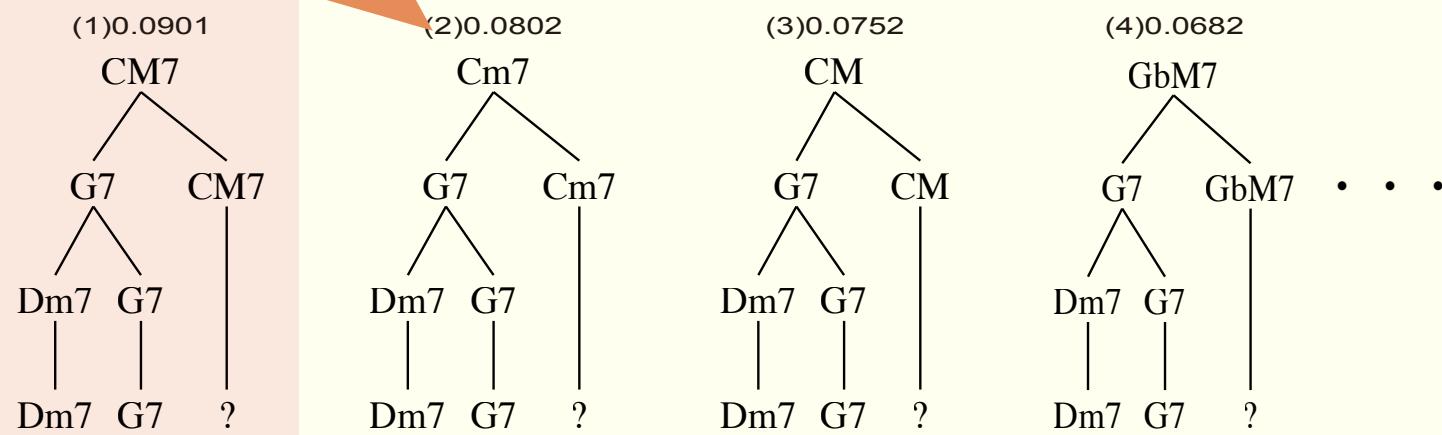


• Dm7



順位の上昇

• Dm7 G7



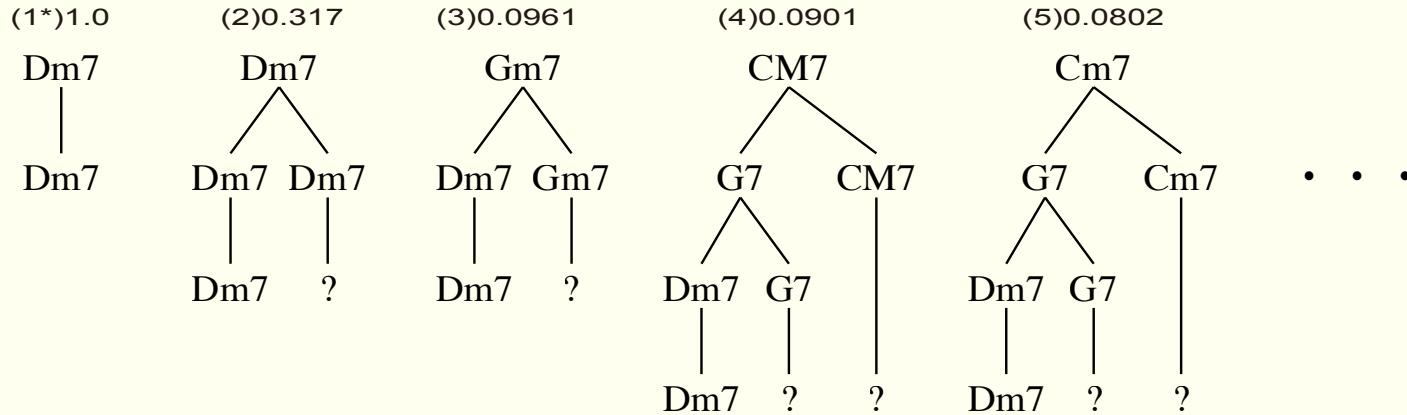
3.2 楽曲 CUTE の漸進的構造解析

20

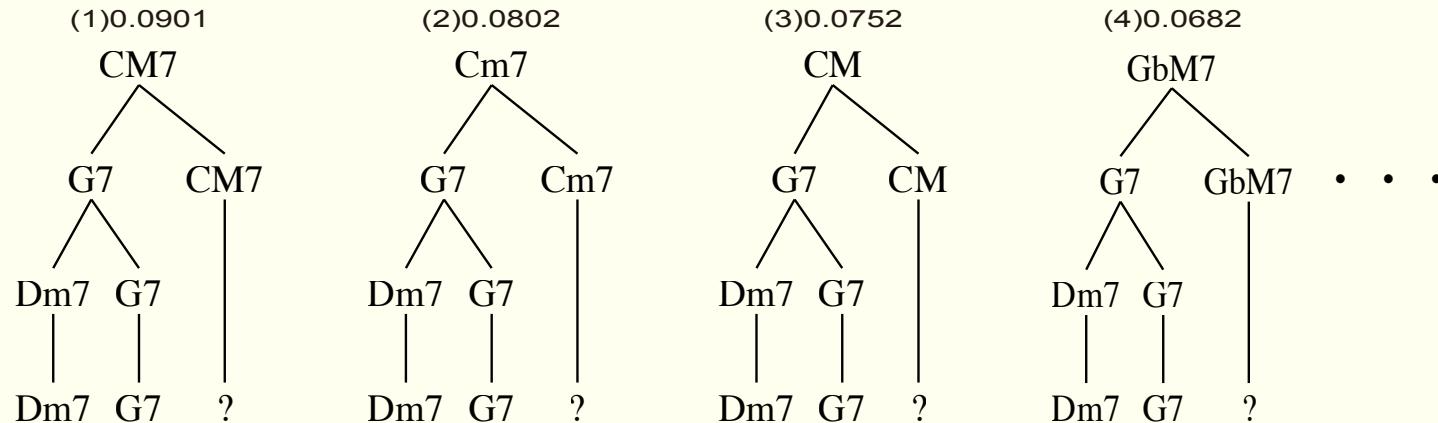
ECSA での 解析結果



• Dm7



• Dm7 G7



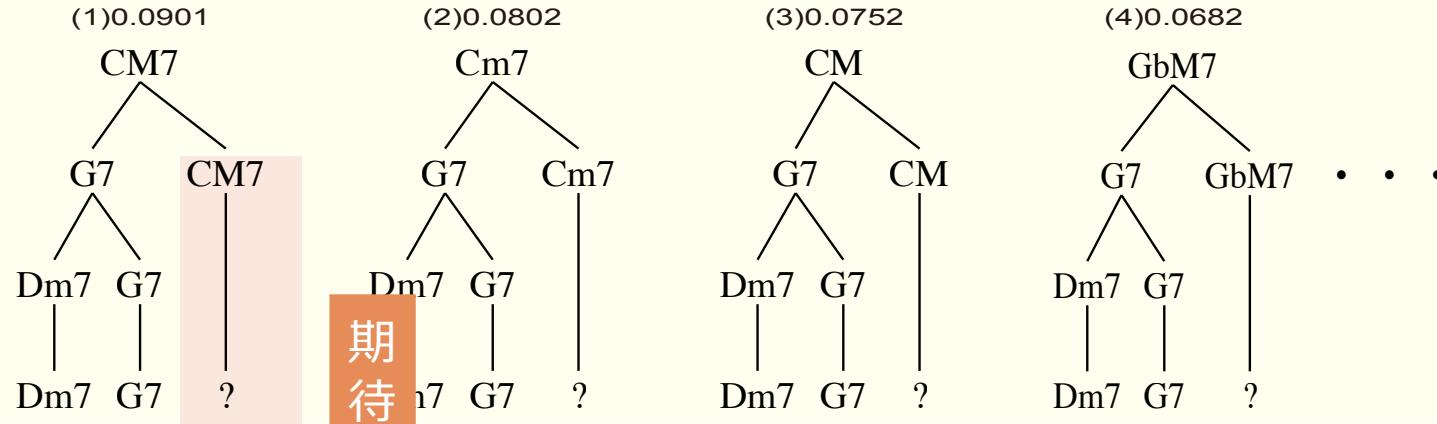
3.2 楽曲 CUTE の漸進的構造解析

20

ECSA での 解析結果

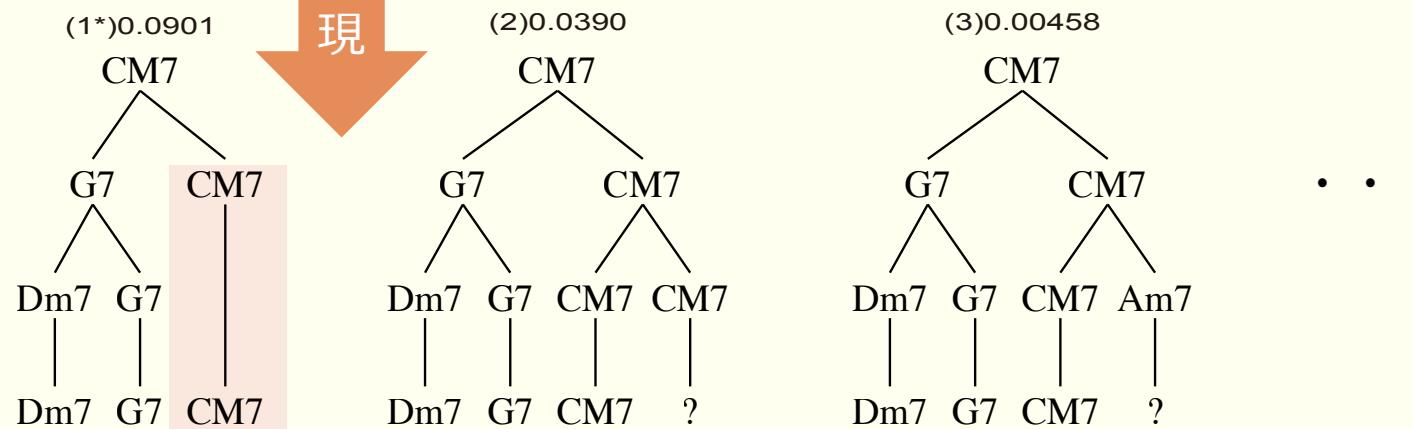


• Dm7 G7



期待の実現

• Dm7 G7 CM7



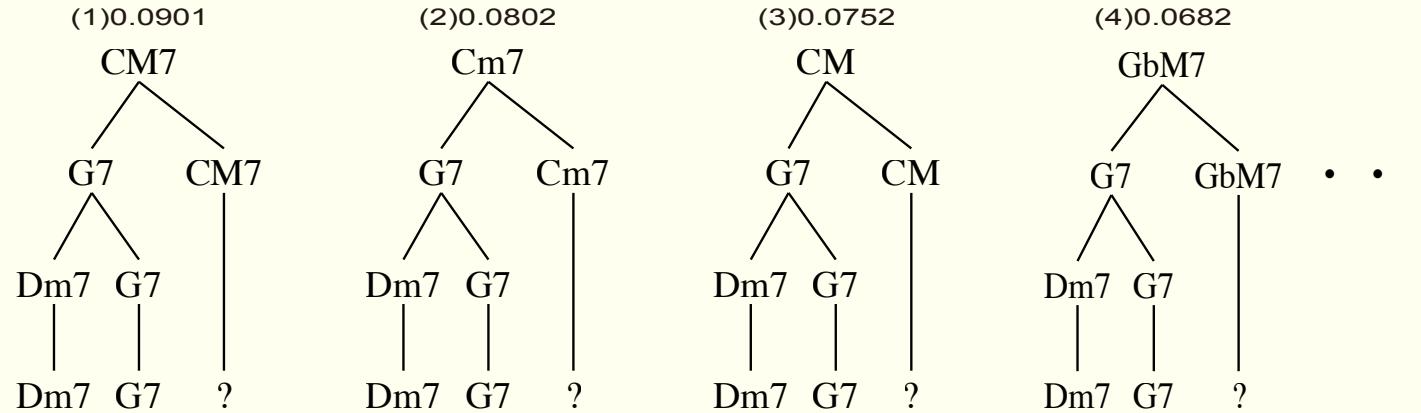
3.2 楽曲 CUTE の漸進的構造解析

21

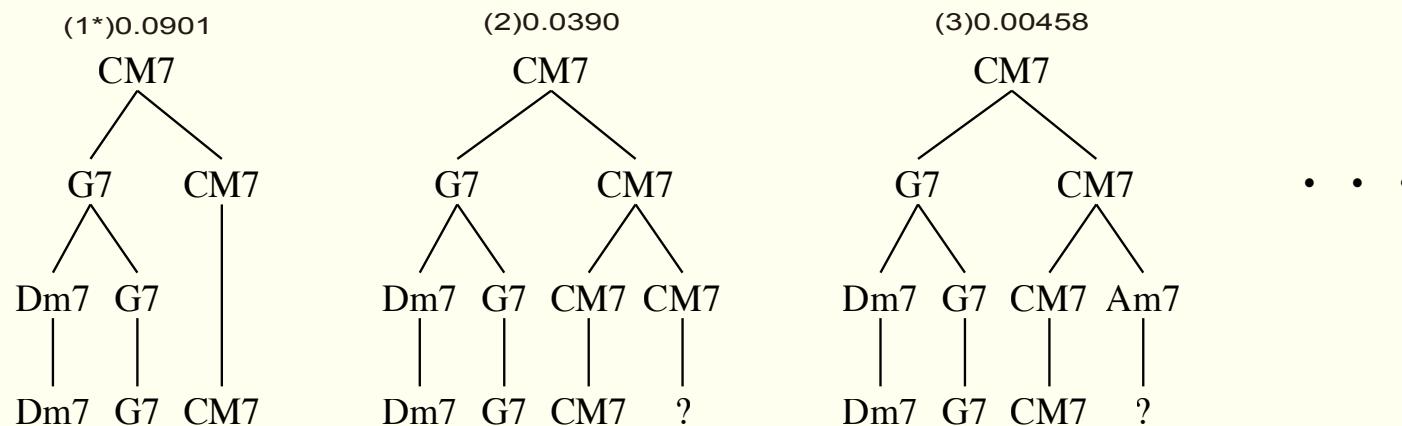
ECSA での 解析結果



• Dm7 G7



• Dm7 G7 CM7

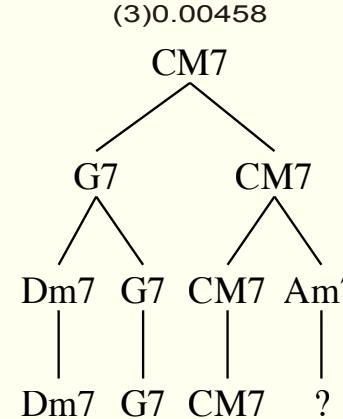
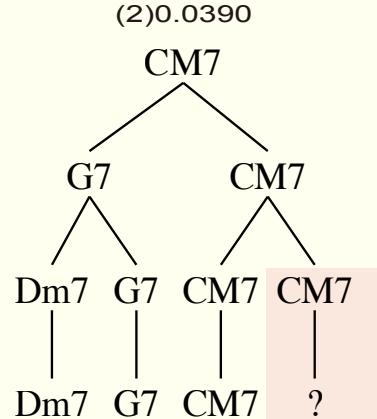
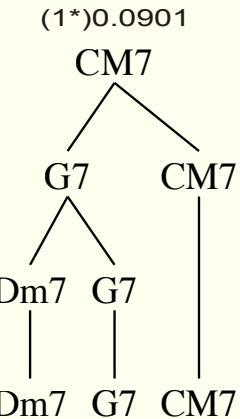


3.2 楽曲 CUTE の漸進的構造解析

21

ECSA での 解析結果

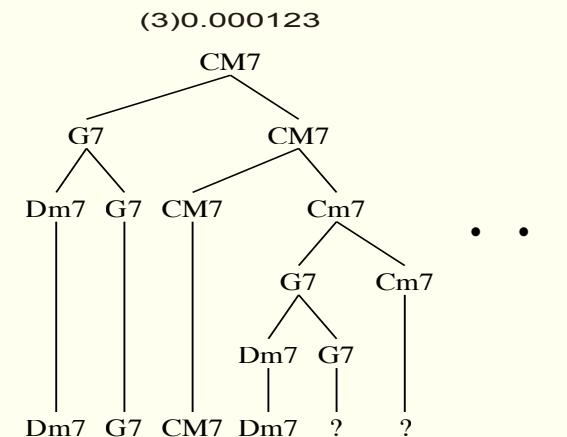
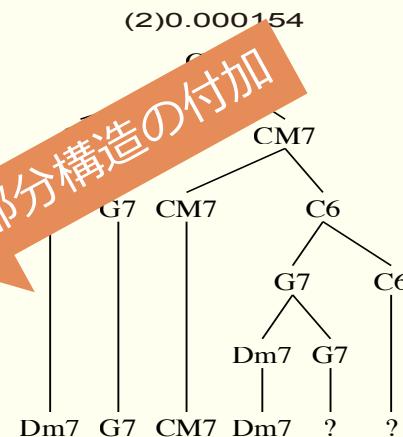
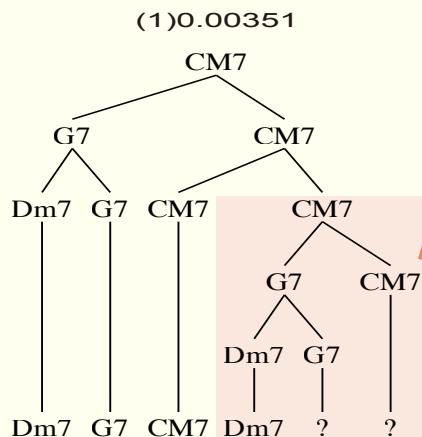
- Dm7 G7 CM7



...



- Dm7 G7 CM7 Dm7



部分構造の付加

...

3.3 意外性の考察

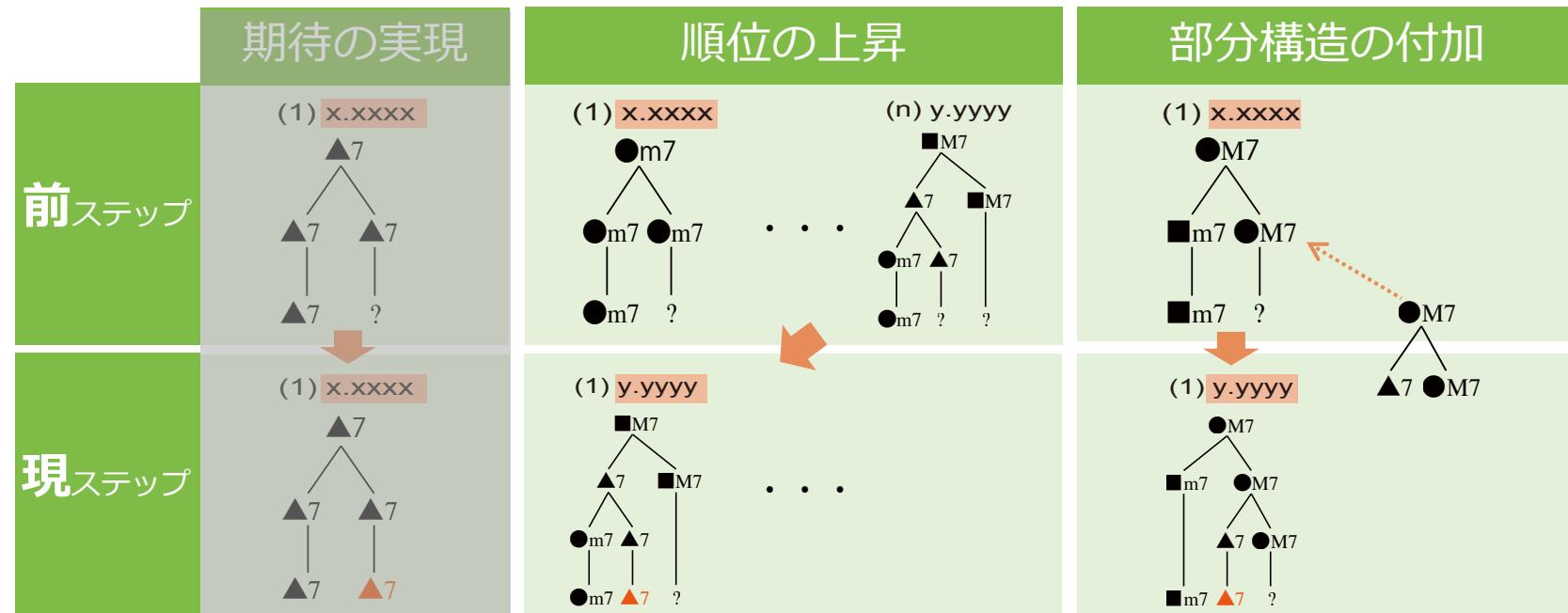
CUTE の意外性を考察する

あるコードステップの意外性 (unexpectedness) U ($0 < U \leq 1$) を以下で与える

$U = \text{前ステップでの希少度合い} \times \text{新しく付加された部分木の確率}$

$$= \frac{\text{導出元木構造の生成確率}}{\text{前ステップ1位の生成確率}} \times \frac{\text{現ステップ1位の生成確率}}{\text{導出元木構造の生成確率}}$$

小さいほど意外性がある



3.3 意外性の考察

23

CUTE

各コードステップにおいてU(unexpectedness)を計算

The image displays four staves of musical notation, each representing a different chord progression. Above each staff, the chords are labeled. The notation uses a treble clef and a 4/4 time signature.

- Staff 1:** Dm7, G7, CM7. The notes are: rest, C, D, E, G, A, B, rest, rest.
- Staff 2:** Dm7, G7, Gm7, C7. The notes are: rest, C, D, E, G, A, B, rest, rest.
- Staff 3:** FM7, B♭7, Em7, Am7. The notes are: rest, F, G, A, B, C, D, E, rest, rest.
- Staff 4:** Dm7, G7, CM7. The notes are: rest, C, D, E, G, A, B, rest, rest.

Each staff includes a calculation for 'U' (unexpectedness) below the staff line, consisting of a fraction and a percentage value.

Staff	Chord Progression	U
1	Dm7, G7, CM7	$\frac{1}{2}$ 50%
2	Dm7, G7, Gm7, C7	$\frac{1}{2}$ 50%
3	FM7, B♭7, Em7, Am7	$\frac{1}{2}$ 50%
4	Dm7, G7, CM7	$\frac{1}{2}$ 50%

3.3 意外性の考察

23

CUTE

各コードステップにおいてU(unexpectedness)を計算

The musical score consists of four staves of music in 4/4 time with a treble clef. It shows various chords and their calculated unexpectedness (U) values:

- Top staff: Dm7 U=1.00, G7 U=0.09, CM7 U=1.00
- Second staff: Dm7 U=0.03, G7 U=1.00, Gm U=0.00088, C7 U=0.04 (highlighted in green)
- Third staff: FM7 U=1.00, B♭7 U=0.05, Em7 U=0.00081, Am7 U=0.14 (highlighted in green)
- Bottom staff: Dm7 U=1.00, G7 U=0.33, CM7 U=1.00

Notes: The Gm chord in the second staff and the FM7 chord in the third staff have very low U values, while the Am7 chord in the third staff has a relatively high U value of 0.14.

4. まとめ・今後の展望

まとめ

本研究の概要

- 音楽的期待に基づくジャズ和声解析手法の提案
- 確率文脈自由文法による漸進的解析により
樂曲途中の認知構造を表示
- 木構造の比較によって意外性の生じるポイントを議論

今後の展望

- 意外性Uの認知的リアリティの調査
- 複数楽曲間における意外性Uの比較