

Search-Effectiveness Measures for Symbolic Music Queries in Very Large Databases

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Introduction

Match-Count Profiles



Musical Features

- We examined search characteristics of 14 musical features:

7 Pitch features

(examples below)



7 Rhythm features: (3 duration & 4 metric)

1. duration (37~74)
2. duration gross contour (3)
3. duration refined contour (5)
4. beat level (2)
5. metric level (10~14)
6. metric gross contour (3)
7. metric refined contour (5)



| | | |
|-----------------------|---|-----------|
| pitch name | pch: F A C C D E A F A G A A F E D F E F E D | 35 states |
| 12-tone pitch | 12p: 5 9 0 0 2 4 9 5 9 7 9 9 5 4 2 4 5 4 5 4 2 | 12 |
| musical interval | mi: +M3 +m3 p1 p1 +M2 -M2 -m3 -M3 +M3 -M2 +M2 p1 -M3 -m2 -M2 +M2 +m2 -m2 -m2 -M2 | 70/octave |
| 12-tone interval | 12i: +4 +3 0 0 +2 -2 -3 -4 +4 -2 +2 0 -4 -1 -2 +2 +1 -1 +1 -2 | 24/octave |
| scale degree | sd: 1 3 5 5 6 5 3 1 3 2 3 3 1 7 6 7 1 7 1 7 6 | 7 |
| pitch refined contour | prc: U U s s u d D D U d u s D d d u u d u d d | 5 |
| pitch gross contour | pgc: U U S S U D D D U D U S D D D U U D U D D | 3 |

- How do all these different features affect searching in a database?

Anchored vs. Unanchored Searches

Search Pattern: F A C

Two types of search methods, Examples:

Anchored Matches search only from the start of a database entries



Unanchored Matches search starting at any position in database entries



Example Feature Searches



| | Feature | Query (in Themefinder) | Anchored Matches | Unanchored Matches |
|-----------------------|------------|---------------------------|---------------------|-----------------------|
| pitch name | <i>pch</i> | F A C | 464 | 1,710 |
| 12-tone pitch | <i>l2p</i> | 5 9 0 | 464 | 1,710 |
| musical interval | <i>mi</i> | +M3 +m3 | 1,924 | 6,882 |
| 12-tone interval | <i>l2i</i> | +4 +3 | 1,925 | 6,894 |
| scale degree | <i>sd</i> | 1 3 5 | 2,009 | 7,024 |
| pitch refined contour | <i>prc</i> | U U | 4,677 | 17,712 |
| pitch gross contour | <i>pgc</i> | U U | 19,787 | 76,865 |

Searching a database of 100,000 melodic incipits/themes

Raw Data Extraction

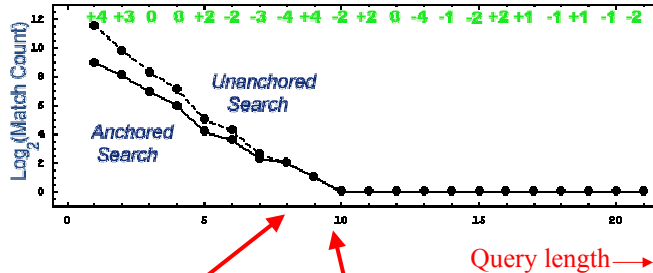
target incipit:



Individual Match-Count Profile

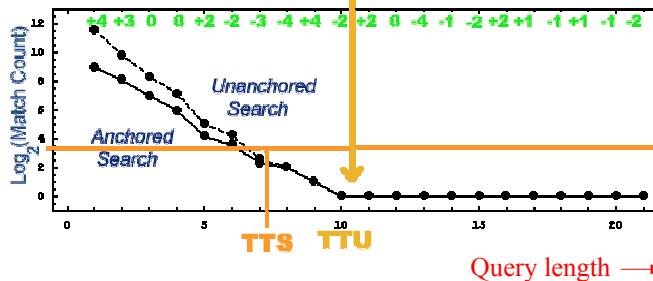


12-tone interval
features:



- Anchored and Unanchored searches merge at length = 8
- Unique match found at length = 10

Interesting Query Lengths



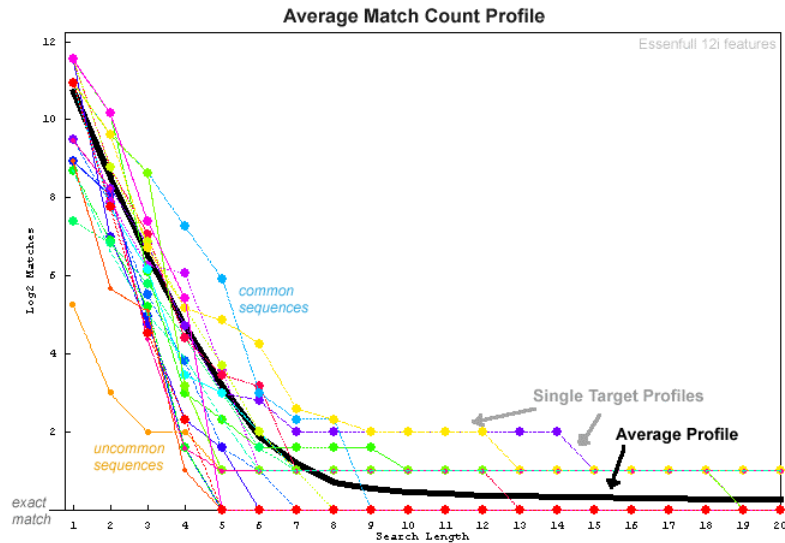
TTU = length of query yielding unique match

TTS = length giving matches under limit size

How long query length must be to generate a *sufficiently* small set of matches
e.g., first search-length which gives fewer than 10 matches

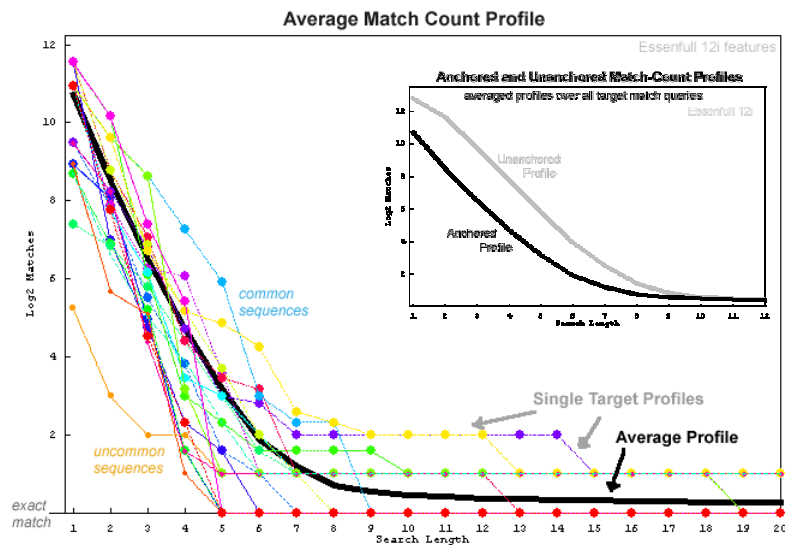
Average Match-Count Profiles

- Average all target profiles over entire database:



Average Match-Count Profiles

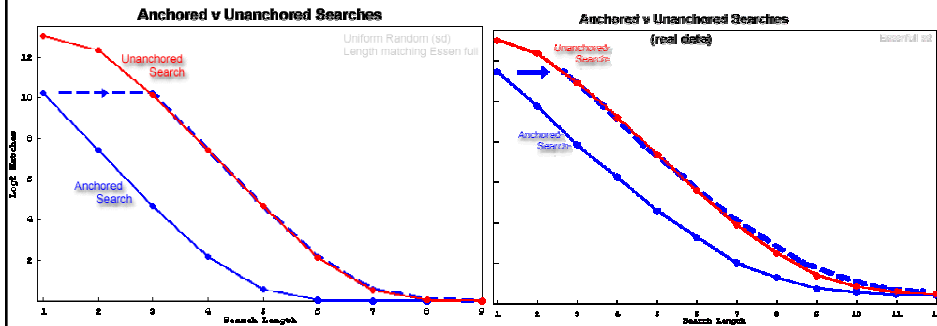
- Average all target profiles over entire database:



Anchored/Unanchored Profile Slopes

Synthetic Database

Real Database

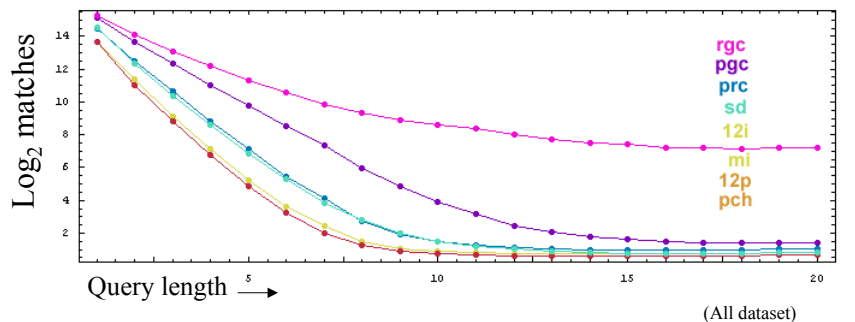


Anchored Searching: $O(\log N)$

Unanchored Searching: $O(N^2)$

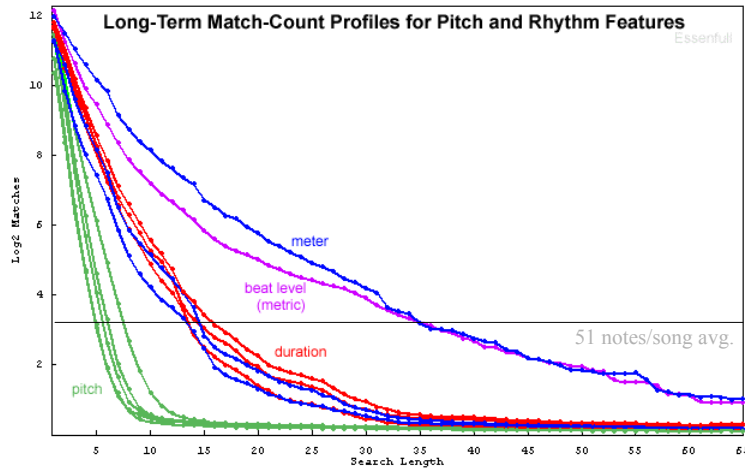
- Anchored/Unanchored slopes not much different.
- Anchored searching is much faster.

Match-Count Profiles for Pitch Features



- Steeper initial slope = more descriptive feature
- **Twelve-tone pitch** and **full pitch spelling** features are very identical (orange curve)
- Absolute **twelve tone pitch** and relative **twelve-tone interval** are close.
- 7-symbol **scale degree** features close to 5-symbol **refined pitch contour**.
- 3-symbol **pitch gross contour** more descriptive than 3-symbol **duration gross contour**.

Match-Count Profiles for All Features



- TTS for rhythm twice as long than pitch TTS.
- TTS for gross metric descriptions 5 times as long as pitch TTS values.
- Rhythm feature curves more crooked.
Phrase/meter effects?

Four Applications of Profiles:

- *Entropy & Entropy Rate*
- *Joint Feature Analysis*
- *Match Count Predictions*
- *Synthetic Database Analysis*

Entropy

- Entropy measures basic information content of a musical feature

entropy definition:

$$H(X) \triangleq - \sum_i P_i(X) \log_2 P_i(X)$$

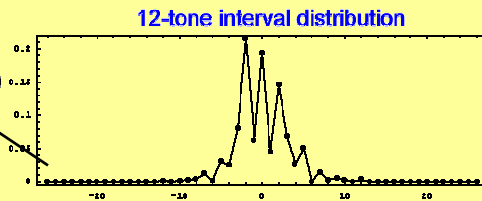
also called "Shannon Entropy" or "First-order Entropy"

Entropy (bits/symbol) Normalized probability distribution

- Example calculation:

$$H(X) = - \sum_i P_i(X) \log_2 P_i(X)$$

$$H(12i) = 3.41165 \text{ bits/pitch}$$



- 3.4 bits/note is the minimum symbol storage size needed to store sequences of 12-tone intervals (Folksong data set).

Entropy Rate

- Entropy is a contextless (memoryless) measure.
- Real music features are related to surrounding musical context.*
- Average entropy (entropy-rate) is more informative:

entropy-rate definition:

$$G(N) \triangleq \frac{H(X^N)}{N}$$

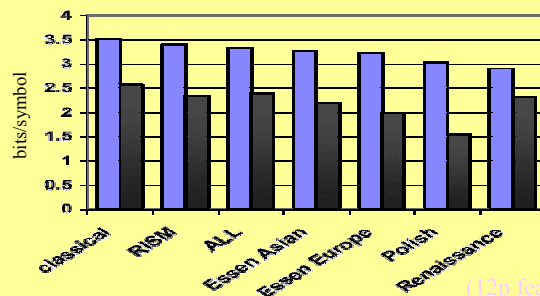
also called "Average Entropy"

Entropy rate (bits/symbol) N=Sequence length

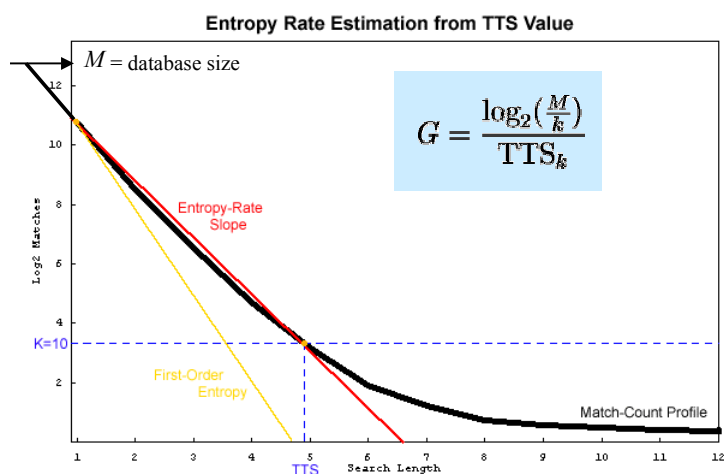
Entropy & entropy rate for various repertoires:

Note:

$$G(N) \leq H(X)$$



Entropy-Rate Estimation from TTS



- Entropy characterizes the minimum possible average TTS.
- Entropy-rate characterizes the actual average TTS.

- *Entropy & Entropy Rate*
- *Joint Feature Analysis*
- *Match Count Predictions*
- *Synthetic Database Analysis*

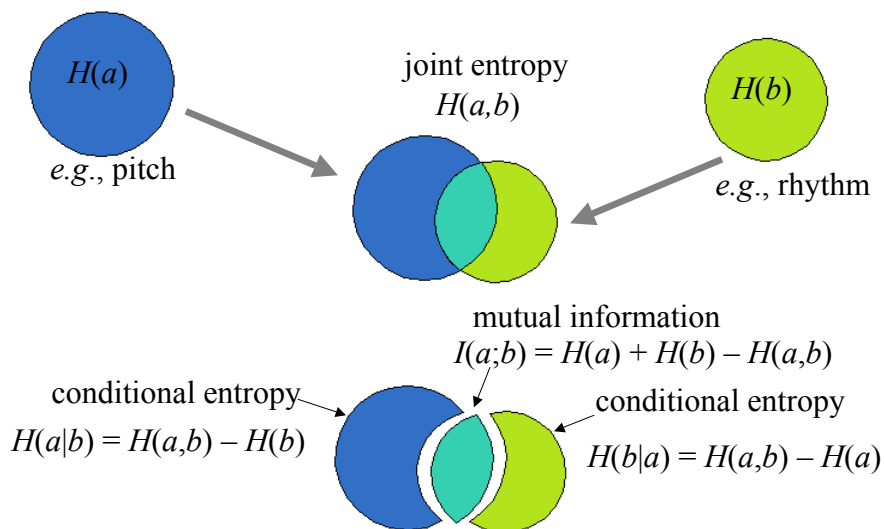
Joint Feature Analysis

Analyze
Pitch + Rhythm
as a combined feature

- How independent/dependent are pitch and rhythm features?
- What is the effect of searching pitch and rhythm features in parallel?

Mutual Information

- Measurement of the correlation of two types of features



Combining Pitch and Rhythm Searches



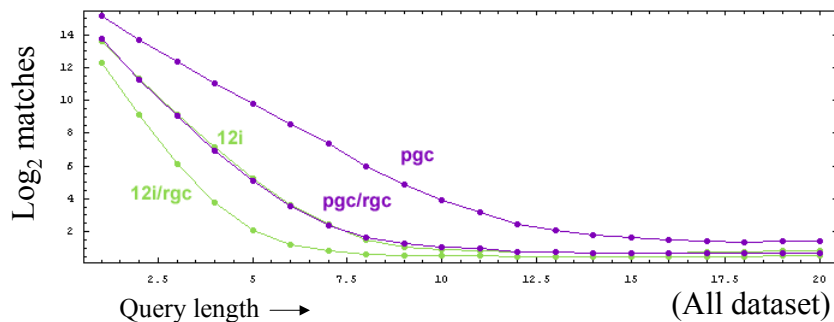
Individual Entropies: $H(\text{pgc}) = 1.5325$ $H(\text{rgc}) = 1.4643$

Joint Entropy: $H(\text{pgc}, \text{rgc}) = 2.9900$

Mutual Information: $I(\text{pgc}; \text{rgc}) = H(\text{pgc}) + H(\text{rgc}) - H(\text{pgc}, \text{rgc}) = 0.0068$
less than two orders of magnitude interaction

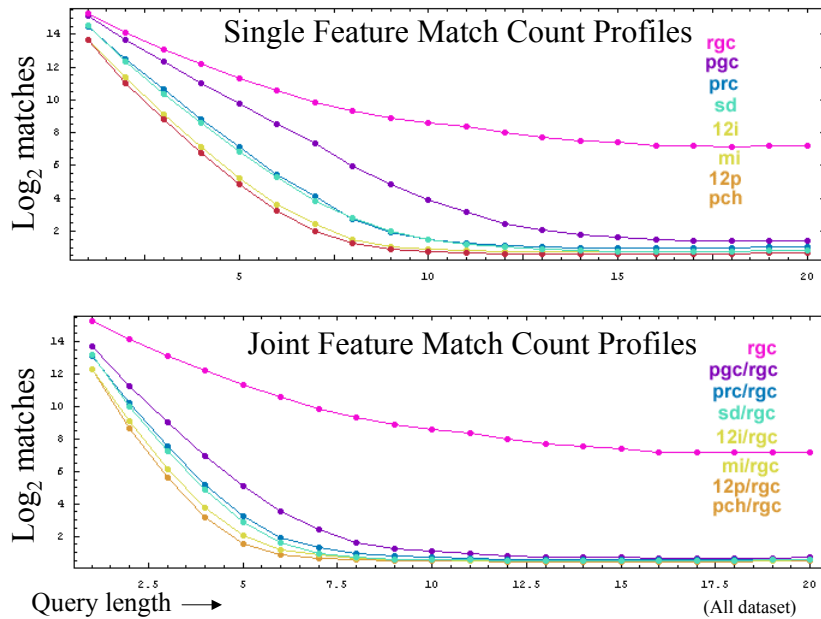
- Pitch and Rhythm are very independent features.
 (at least for **pgc+rgc** averaged over entire database)
- Therefore, combining independent search features should be effective.

Joint Feature Profiles for pgc/rgc vs. twelve-tone interval searching

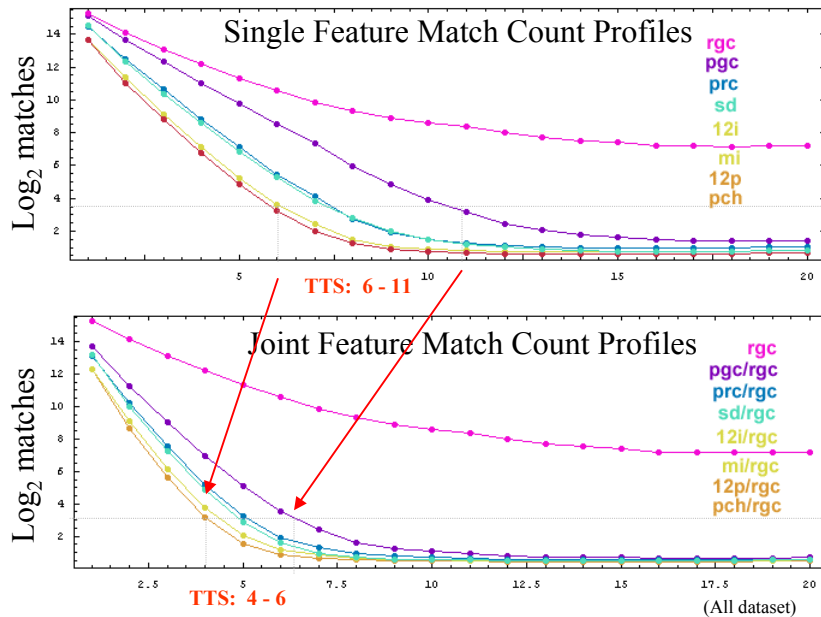


- 3*3 states work as well as 88 twelve-tone interval states.
- *pgc* and *rgc* are generic features less prone to query errors.

Joint Feature Search Effectiveness



Joint Feature Search Effectiveness



- *Entropy & Entropy Rate*
- *Joint Feature Analysis*
- *Match Count Predictions*
- *Synthetic Database Analysis*

Expectation Function

- Entropy Rate can be used to predict the number of matches:

$$E(n) = \frac{M}{R^n} \quad R = 2^H \quad (H = \text{measured entropy rate})$$

Expected match counts for an n -length query

database size

- Example:

- Consider a database of “best 3 out of 5” Heads/Tails coin flips:

H H T H T
 T H T T H
 H T T H H
 T T T T H
 H H H H H



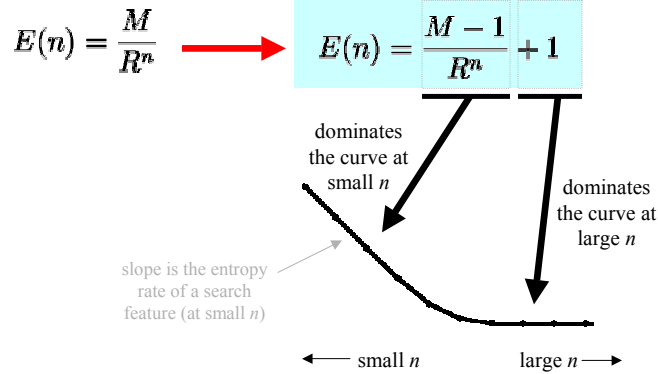
Entropy Rate = Entropy = $\log_2 2 = 1$ bit/symbol

Therefore $R = 2^{\log 2} = 2^1 = 2$

- Likelihood starting sequence is “H”: 50% → $E(1) = M/2^1 = M/2$
- Likelihood starting sequence is “H T”: 25% → $E(2) = M/2^2 = M/4$
- Likelihood starting sequence is “H H”: 25% → $E(2) = M/2^2 = M/4$

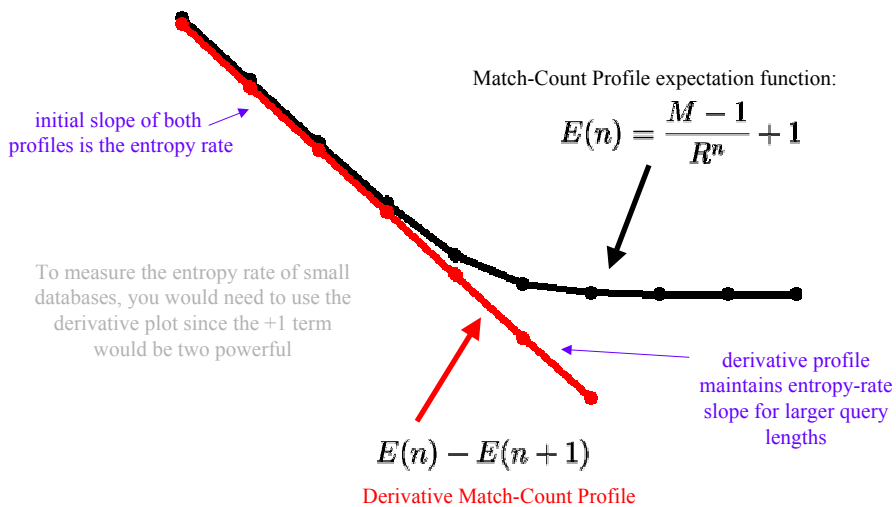
Match-Count Profile Constraint

- The match-count profile queries are constructed from database entries.
- Therefore at least one match is *always expected*.
- Steal this guaranteed match from M, and add as a constant to the expectation function:



- How to get rid of curvature caused by constant +1 term?

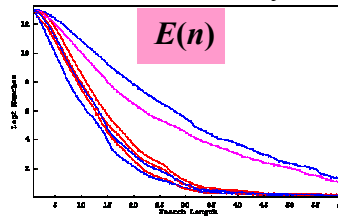
Match-Count and Derivative Profile Comparison



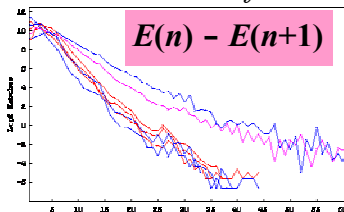
What about $E(n) - 1$?

Expectation Plot Functions

“Match-Count Profile”

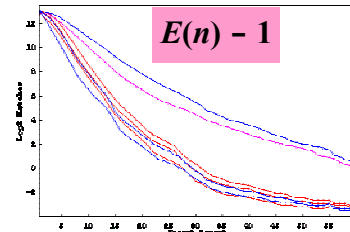


“Derivative Profile”



- Removes +1 curvature and *not* sensitive to duplicate entries in the database.
- Best method for measuring entropy-rate

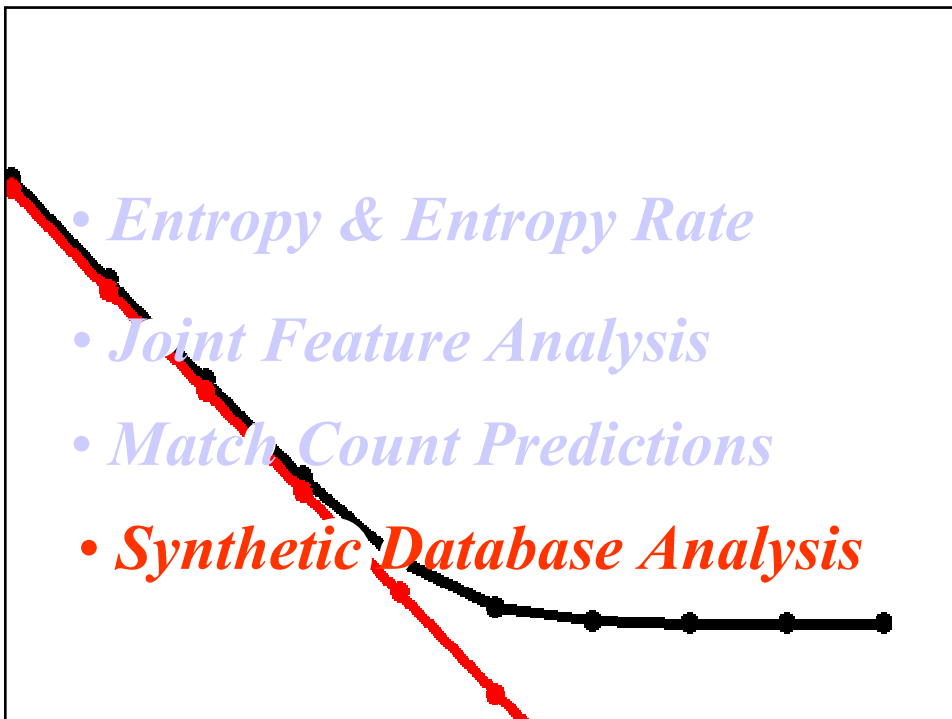
“Target-Exclusion Profile”



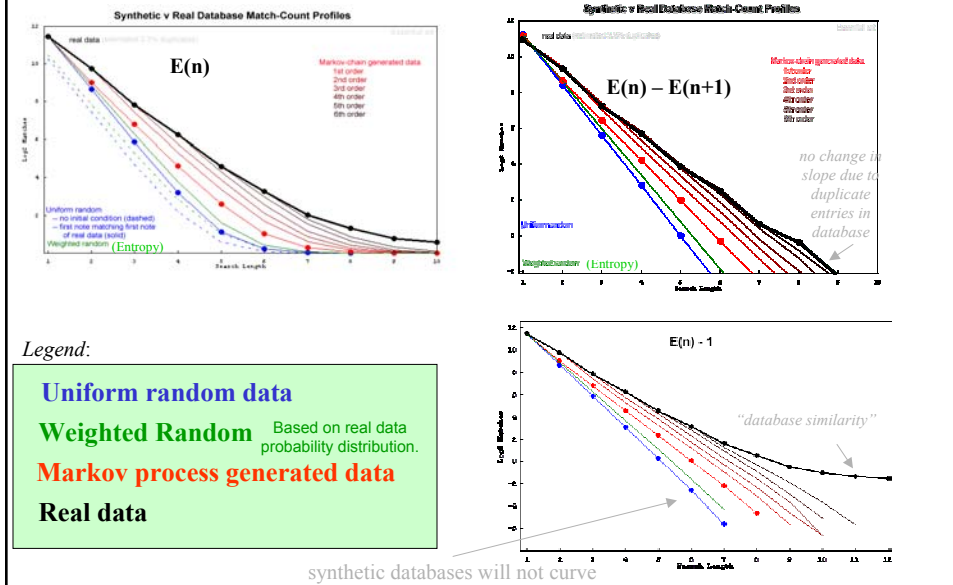
- Removes +1 curvature, but sensitive to duplicate entries in the database

[Using unanchored rhythmic features for Essen-full]

- *Entropy & Entropy Rate*
- *Joint Feature Analysis*
- *Match Count Predictions*
- *Synthetic Database Analysis*

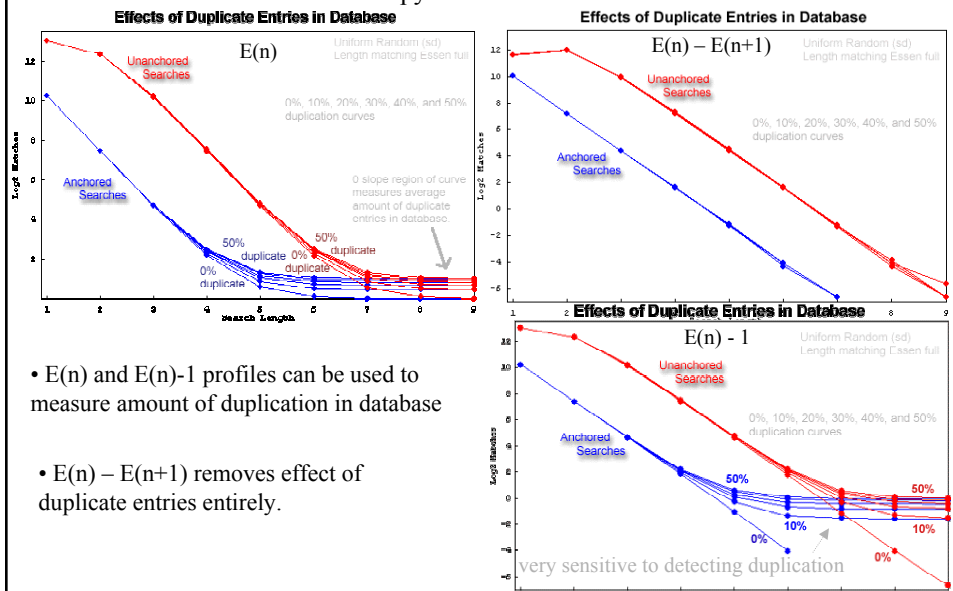


Synthetic vs. Real Database Profiles



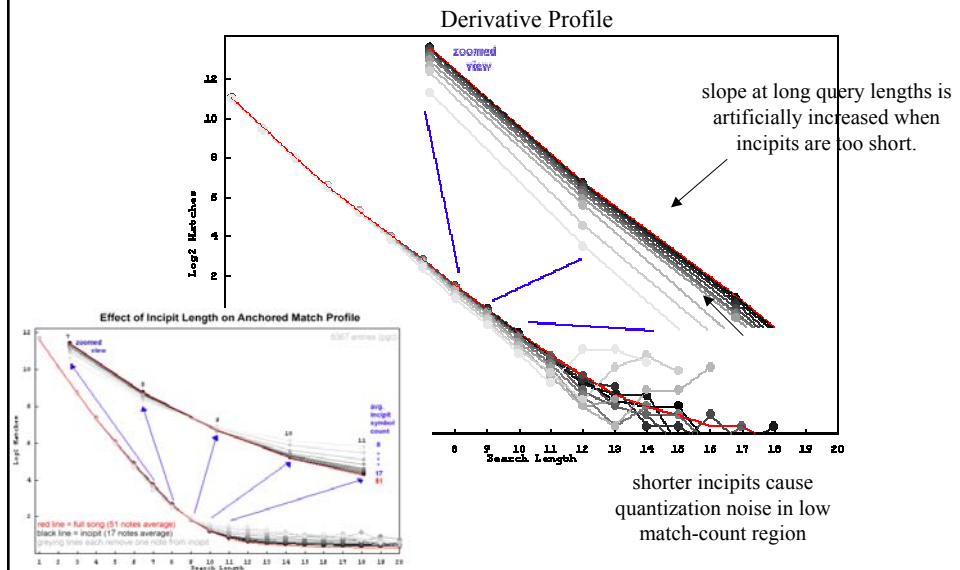
Effects of Duplicate Entries on Profiles

Duplicate entries in the database do not have a significant effect on entropy-rate measurements:



Effect of Incipit Length on Profiles

- An incipit is a short initial excerpt from a full composition
- How short is too short for a musical incipit?



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Summary

Interesting metrics for analyzing the effectiveness of search features:

- Match-Count Profiles:** Examines match characteristics of a musical feature for longer and longer queries.
- Entropy Rate:** Characterizes match count profiles well with a single number. Useful for predicting the expected average number of matches for a given length query.
- TTS:** The number of symbols in query necessary to generate a sufficiently small number of matches (average). TTU not as useful due to noise.

Proof for Derivative Plots

$$E(n) = \frac{M-1}{R^n} + 1 \quad (\text{expectation function for Match-Count Profiles})$$

$$E(n) - E(n+1) = \frac{M-1}{R^n} - \frac{M-1}{R^{n+1}} \quad (\text{subtract } n \text{ and } n+1 \text{ values of } E() \text{ to cancel } +1 \text{ term})$$

$$E(n) - E(n+1) = \frac{(R-1)(M-1)}{R R^n} \quad (\text{algebra manipulation})$$

plotting on a log scale, so take the log of both sides:

$$\log_2[E(n) - E(n+1)] = \log_2 \left[\frac{(R-1)(M-1)}{R} \right] - \log_2 R^n$$

$$\text{Let: } y = \log_2[E(n) - E(n+1)] \quad \text{and} \quad b = \log_2 \left[\frac{(R-1)(M-1)}{R} \right]$$

so the equation becomes:

$$y = b - \log_2 R^n$$

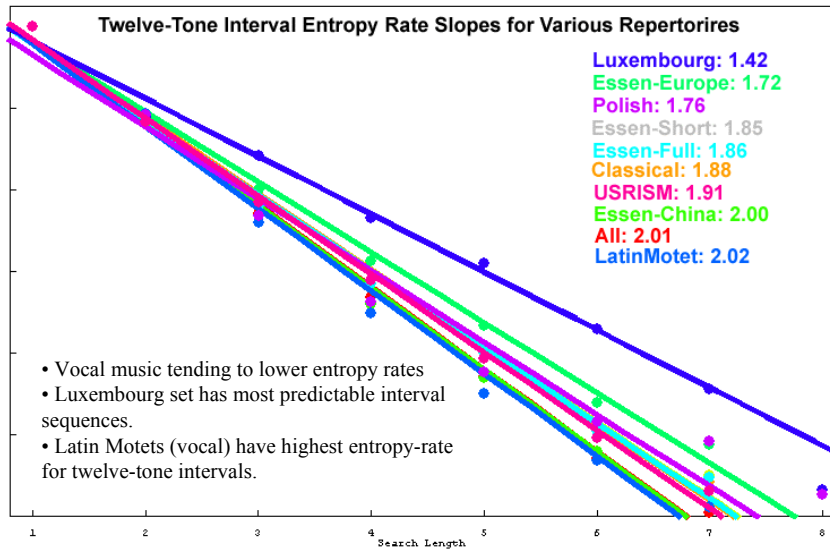
$$y = b - \log_2 2^{Hn} \quad \text{since } R = 2^H$$

Let: $x = n$

$$y = \underbrace{-H}_{\text{slope}} x + b$$

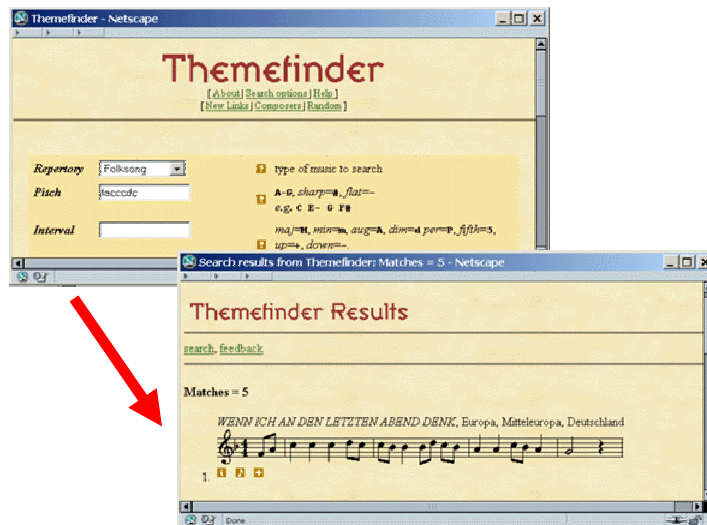
which is a line with a slope proportional to the entropy (rate)

Derivative Plots for 12i features



Themefinder Website

<http://www.themefinder.org>



Themefinder Collections

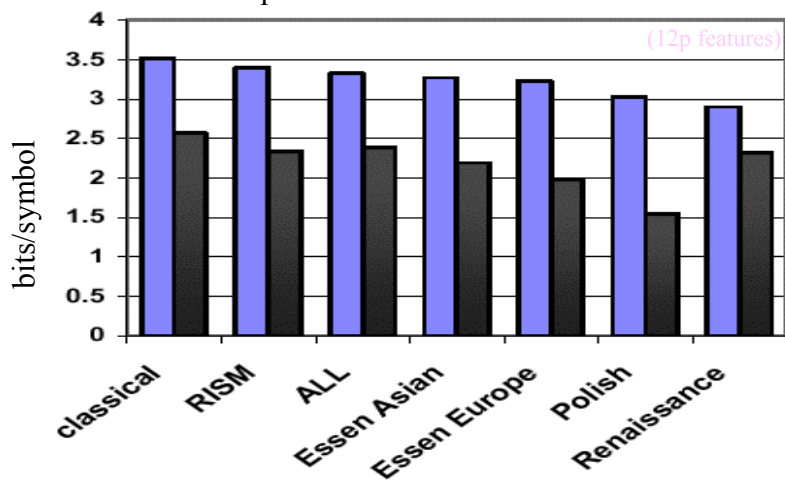
| Data set | Count | Web Interface |
|---------------|---------|--|
| Classical | 10,718 | themefinder.org |
| Folksong | 8,473 | themefinder.org |
| Renaissance | 18,946 | latinmotet.themefinder.org |
| US RISM A/II | 55,490 | |
| Polish | 6,060 | |
| Luxembourg | 612 | lux.themefinder.org |
| <i>total:</i> | 100,299 | |

Matches on First Seven Notes



Entropy and Entropy Rate

for various repertoires in the Themefinder database



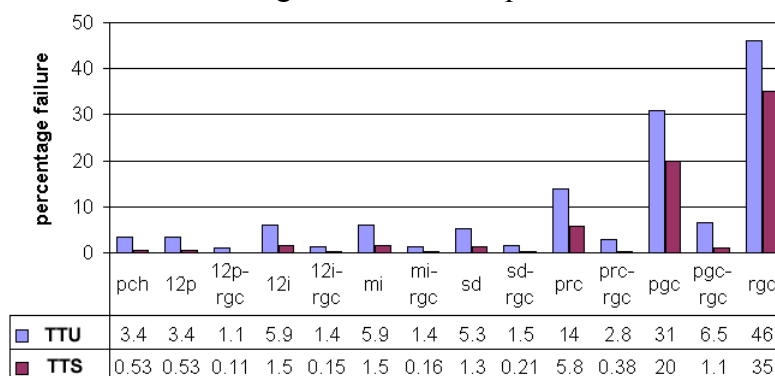
$$G(N) \leq H(X)$$

Entropy rate less than or equal to the Entropy

Search Failure Rates

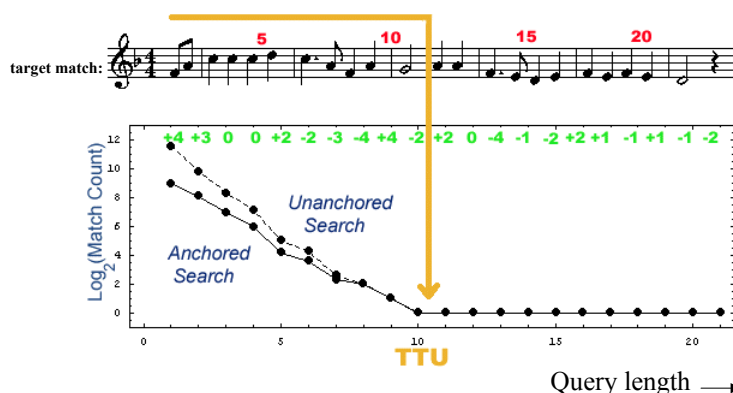
Database size: 100,299

Average note count/incipit: 16



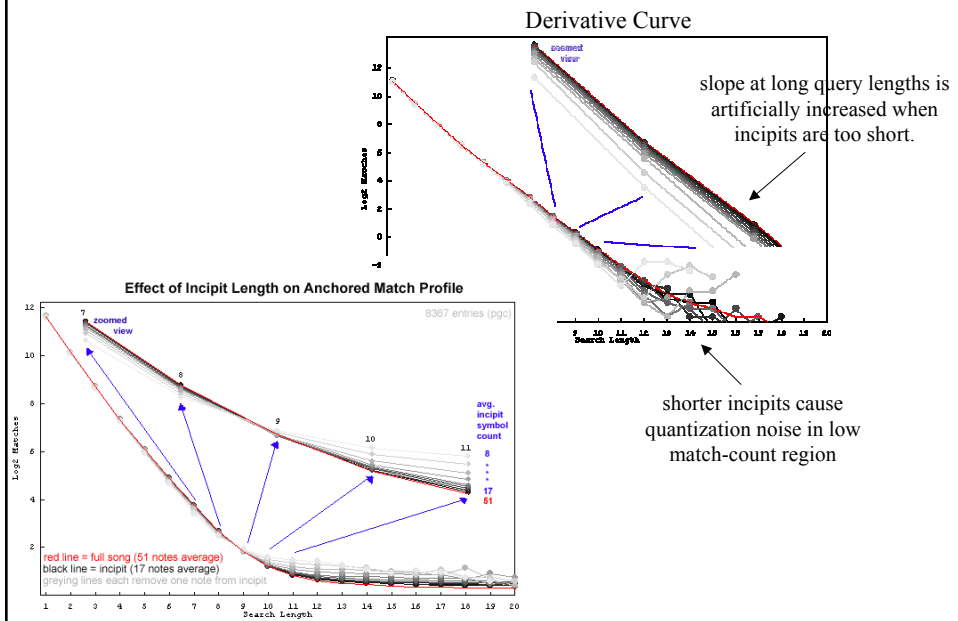
- Plot measures how often a search produces too many matches for query sequences as long as the database entry.

Time To Uniqueness



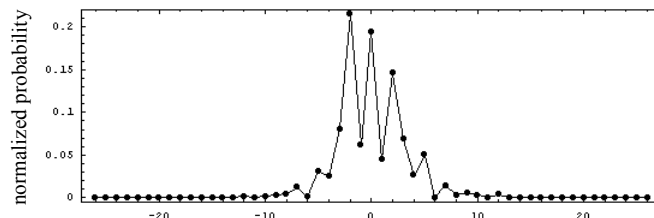
TTU = the number of query symbols needed to find the exact match in the database. Turns out to not be very useful since it is more susceptible to noise in the data.

Effect of Incipit Length on Profiles



Probability Distributions

12-tone interval distribution



$$H(X) = - \sum_i P_i(X) \log_2 P_i(X)$$

$$H(12i) = 3.41165$$

3.4 bits/note is the lower symbol storage size limit needed to store sequences of 12-tone intervals (Folksong data set).

- Entropy can be used as a basic estimate for how many notes are necessary to find a unique/sufficient match in the database, but ...

Expectation Function

M = database size

$E(n)$ = average expected match counts for an n -length query

$R = 2^H$ where H is the entropy rate of the feature being searched for (Entropy rate is assumed to be constant)

In general: $E(n) = \frac{M}{R^n}$

For example, consider sequences created with a uniform random distribution of three states (the next symbol in the sequence is equally likely to be any of the three states).

Then, the entropy of the sequence is: $H = \log_2 3$ which makes $R = 2^{\log_2 3} = 3$

and the formula for the expected match counts becomes: $E(n) = \frac{M}{3^n}$

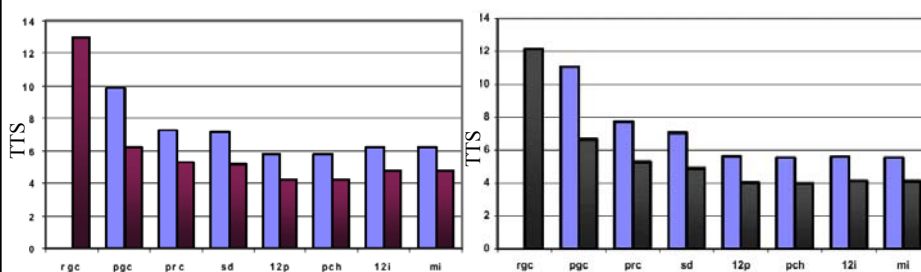
then 1/3 of the database entries should be matched with a one-length query on the average:

$$E(1) = \frac{M}{3^1} = \frac{M}{3}$$

and a length-two query should return 1/9 of the database on the average:

$$E(2) = \frac{M}{3^2} = \frac{M}{9}$$

Joint Pitch/Rhythm Effects on TTS



Chinese Folksongs dataset

Classical dataset

- Adding *rgc* to pitch features usually reduces the search length by 2 notes.
- Combining *rgc* and *pgc* reduces search length by 4 notes.