On the Potential of AI and Machine Learning for Music Performance Analysis

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CONGRATULATIONS TO THE MAZURKA TEAM

OVERVIEW

Machine Learning for the Analysis of Music Performance Data

A. Search for common performance principles
   1. Discovering note-level rules
   2. Phrase-level learning
   3. A combined model

B. Search for characteristic differences (individual style)
   1. Pattern discovery
   2. Performer identification
   3. Automatic style imitation?

A new data-intensive project

Opportunities for cooperation computer science ↔ musicology

A RECENT RESEARCH PROJECT


Austrian Research Institute for Artificial Intelligence (OFAI), Vienna

funded by the Austrian National Science Foundation
PROJECT GOALS

• Performing **quantitative studies** of expressive music performance
• based on **large amounts** of 'real-world' performance data
• with AI / Machine Learning technology
  => 'data-intensive' bottom-up approach

**Possible advantages:**
• grounding of results in substantial empirical data
• not biased by pre-conceptions, can make surprising discoveries

**Possible problems:**
• little control over experimental conditions
• studies (must) generally remain at rather general level

TWO QUESTIONS

**Systematic similarities, general principles?**
What do 'reasonable' performances have in common?
What is predictable?

**Systematic stylistic differences between artists?**
What distinguishes great artists from each other?
Can this be characterised / quantified?

**RESTRICTIONS:**
• classical piano music
• expressive timing, dynamics, (articulation)
TWO QUESTIONS

Systematic similarities, general principles?
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RESTRICTIONS:
• classical piano music
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GENERAL PRINCIPLES?

Chopin: *Etude*, op. 10 no. 3, E major
GENERAL PRINCIPLES?

Chopin: *Etude*, op. 10 no. 3, E major

Pianists 1-22

Bösendorfer SE 290
STUDY 1: LEARNING NOTE-LEVEL PERFORMANCE RULES

The Data:
- 13 complete Mozart piano sonatas (> 100,000 notes)
- performed by concert pianist on a Bösendorfer SE290 computer-controlled grand piano
- plus explicit encoding of the musical score
- plus 1-to-1 correspondence between played notes and written notes

The Target:
- rules predicting the performer’s decisions in (local) timing, dynamics, and articulation
  - Timing: lengthen vs. shorten
  - Dynamics: louder vs. softer
  - Articulation: staccato vs. legato

THE LEARNING ALGORITHM

* G. Widmer
Artif. Intell. 146(2), 2003
### THE LEARNING ALGORITHM

Training Examples (notes with musical context and performance information)

![Diagram](image)

#### Learning Algorithm

Predictive Rules

---

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<thead>
<tr>
<th>Rule</th>
<th>Action</th>
<th>Conditions</th>
<th>pos. average</th>
<th>Precision pre</th>
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<td>95.53 %</td>
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<td>3,071</td>
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RULE TL2:

\textbf{lengthen IF}  
\textbf{abstr\_dur\_context = short-short-long \\ metr\_strength \leq 1}

“Given two notes of equal duration followed by a longer note, lengthen the note (i.e., play it more slowly) that precedes the final, longer one, if this note is in a metrically weak position.”

TP = 1,894 (14.12%), FP = 588 (2.86%), \( \pi = .763 \)

DISCOVERED RULES

rules generalise well to other performers and other musical styles!

QUANTITATIVE EVALUATION

Fit on training data (Mozart by R.Batik) vs. ...

... Mozart by P.Entremont

... Chopin by 22 pianists

rules generalise well to other performers and other musical styles!
RULE TL3: lengthen IF dir_next = up & 
   int_next > p4 & 
   metr_strength ≤ 2 & 
   int_prev ≤ maj2

“Lengthen a note if it precedes an upward melodic leap larger than a perfect fourth, if it is in a metrically weak position, and if it is preceded by (at most) stepwise motion.”

- slow: TP = 95 (2.60%), FP = 38 (0.64%), π = .714
- fast: TP = 164 (1.68%), FP = 94 (0.64%), π = .636
- all: TP = 259 (1.93%), FP = 132 (0.64%), π = .662

RULE AS3: staccato IF int_next > p4 & 
   dir_next = up & 
   metr_strength ≤ 2

“Insert a micropause after a note if it precedes an upward melodic leap larger than a perfect fourth and is metrically weak.”

- slow: TP = 307 (6.27%), FP = 161 (2.31%), π = .656
- fast: TP = 930 (5.39%), FP = 239 (1.99%), π = .796
- all: TP = 1,237 (5.59%), FP = 400 (2.11%), π = .756

=> cf. “Leap Tone Duration” and “Leap Articulation” rules (Friberg, 1995)

RELATION TO SUNDBERG PERFORMANCE RULES

STUDY 2:
LEARNING PHRASE-LEVEL TIMING AND DYNAMICS
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LEARNING PHRASE-LEVEL TIMING AND DYNAMICS
Model class for phrase-level expressive ‘shapes’: quadratic functions ($2^{nd}$ degree polynomials)

$$y = ax^2 + bx + c$$

DERIVING TRAINING INSTANCES:
MULTI-LEVEL DECOMPOSITION

W.A. Mozart: Piano Sonata K. 279 (C major), 1st mvt., mm.31-38: dynamics

Multilevel decomposition (1)

Multilevel decomposition (2)

W.A. Mozart: Piano Sonata K. 279 (C major), 1st mvt., mm.31-38: dynamics
DERIVING TRAINING INSTANCES: MULTI-LEVEL DECOMPOSITION

Multilevel decomposition (3)

Multilevel decomposition (4)

W.A. Mozart: Piano Sonata K. 279 (C major), 1st mvt., mm. 31-38: dynamics

DERIVING TRAINING INSTANCES: MULTI-LEVEL DECOMPOSITION

Multilevel decomposition: All levels

W.A. Mozart: Piano Sonata K. 279 (C major), 1st mvt., mm. 31-38: dynamics
CASE-BASED LEARNING

new test piece:

training performances:

phrasal shapes:
‘prediction by analogy’
(nearest neighbour)

new test piece:

Table 1: Sonata movements used in experiments

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<th>sonata movement</th>
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<td>365</td>
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Table 1: Sonata movements used in experiments
### EXPERIMENTS: QUANTITATIVE RESULTS

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<th>MAEd</th>
<th>MAEl</th>
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</table>

**WMean**

|       | .0456| .0365| .1757| .1370| .6200 | .0282| .0326| .1106| .3202| .3600 |

Table 2: Results (by sonata sections) of cross-validation experiment with DISTALL (depth=2, k=1). Measures subscripted with D refer to the ‘default’ (mechanical, inexpressive) performance, those with L to the performance produced by the learner.

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### STUDY 3: A COMBINED MODEL

**Approximation of original curve by 4 levels of polynomial shapes**

=> "Residuals":

![Residuals Graph](image-url)
STUDY 3: A COMBINED MODEL

Training performances:

Phrase level

Phrasal shapes:
'prediction by analogy'

'residuals':

Note level

Rule learning algorithm PLCG

Note-level rules

THE COMBINED MODEL IN ACTION

W.A. Mozart, Piano Sonata K.280, F major, 1st Movement

Second Prize, RENCON Contest, Tokyo, Sept. 2003
INSIGHTS (1)

- There are predictable aspects of expressive performance
- Machine learning can (help us) discover some of them
- Expressive performance is a multi-level phenomenon and needs multi-level models
- Open question: the boundary of predictability …

TWO QUESTIONS

Systematic similarities, general principles?
  What do ‘reasonable’ performances have in common?
  What is predictable?

Systematic stylistic differences between artists?
  What distinguishes great artists from each other?
  Can this be characterised / quantified?
INTERACTIVE BEAT TRACKING

THE PERFORMANCE WORM

* Langner & Goebi, Comp.Mus.J. 27(4), 2003
PERFORMANCE TRAJECTORIES

Artur Rubinstein: Frédéric Chopin, Ballade op.27, A♭ major

PERFORMANCE ALPHABETS
PERFORMANCE ALPHABETS

SOME SIMPLE STATISTICS
Objective:
find subsequences \(\langle e_i, \ldots, e_j \rangle\) in a set of sequences \(\{S_1, \ldots, S_n\}\) of events that

- are frequent overall
- discriminate between different sequences/artists

Method:
- level-wise search for frequent item sets
  (Agrawal & Srikant, 1995; Mannila et al., 1995)
- combined with an information-theoretic heuristic for discrimination:
  \[ E(X) = \sum_y -n_y/N_i \times \log_2(n_y/N_i) \]

Widmer et al., AI Magazine 24(3), 2003
DISCOVERING CHARACTERISTIC SUBSTRINGS

F. Chopin, Ballade no. 3 op.47, Ab major – Artur Rubinstein (1957)

DISCOVERING CHARACTERISTIC SUBSTRINGS

F. Chopin, Ballade no. 3 op.47, Ab major – Artur Rubinstein (1957)
Arthur Rubinstein plays Chopin …

Franz Schubert, Impromptu D.899/3, Gb major

Rubinstein
Horowitz

Guida
Pires
Lipatti
Uchida

Brendel
Kempff
Leonskaja
Maisenberg
Zimerman
Structural analysis of piece:

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<td>q</td>
<td>r</td>
<td>s</td>
<td>t</td>
<td>u</td>
<td>v</td>
<td>w</td>
<td>x</td>
<td>y</td>
<td>z</td>
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<td>Duration (positions)</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
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<td>19</td>
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<td>22</td>
<td>23</td>
<td>24</td>
<td>25</td>
<td>26</td>
</tr>
</tbody>
</table>

**Ranking pianists according to how similarly they play similar passages**

(Material: F. Schubert, Impromptu D.899 no.3, G♭ major)

<table>
<thead>
<tr>
<th>Rank</th>
<th>Recall</th>
<th>Precision</th>
<th>F-measure</th>
<th>St. dev</th>
<th>F-m</th>
<th>Pianist</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.613</td>
<td>0.725</td>
<td><strong>0.336</strong></td>
<td>0.000</td>
<td></td>
<td><strong>Barenboim</strong></td>
</tr>
<tr>
<td>2</td>
<td>0.538</td>
<td>0.765</td>
<td>0.368</td>
<td>0.091</td>
<td></td>
<td><strong>Horowitz</strong></td>
</tr>
<tr>
<td>3</td>
<td>0.476</td>
<td>0.717</td>
<td>0.427</td>
<td>0.049</td>
<td></td>
<td><strong>Lipatti</strong></td>
</tr>
<tr>
<td>4</td>
<td>0.408</td>
<td><strong>0.803</strong></td>
<td>0.460</td>
<td>0.029</td>
<td></td>
<td><strong>Maisenberg</strong></td>
</tr>
<tr>
<td>5</td>
<td>0.440</td>
<td>0.666</td>
<td>0.472</td>
<td>0.023</td>
<td></td>
<td><strong>Leonskaja</strong></td>
</tr>
<tr>
<td>6</td>
<td>0.459</td>
<td>0.605</td>
<td>0.478</td>
<td>0.084</td>
<td></td>
<td><strong>Kempff</strong></td>
</tr>
<tr>
<td>7</td>
<td>0.361</td>
<td>0.636</td>
<td>0.540</td>
<td>0.042</td>
<td></td>
<td><strong>Uchida</strong></td>
</tr>
<tr>
<td>8</td>
<td>0.380</td>
<td>0.539</td>
<td>0.555</td>
<td>0.044</td>
<td></td>
<td><strong>Brendel</strong></td>
</tr>
<tr>
<td>9</td>
<td>0.366</td>
<td>0.535</td>
<td>0.567</td>
<td>0.044</td>
<td></td>
<td><strong>Rubinstein</strong></td>
</tr>
<tr>
<td>10</td>
<td>0.338</td>
<td>0.505</td>
<td>0.597</td>
<td>0.093</td>
<td></td>
<td><strong>Pires</strong></td>
</tr>
<tr>
<td>11</td>
<td>0.308</td>
<td>0.340</td>
<td>0.678</td>
<td>0.050</td>
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<td><strong>Zimerman</strong></td>
</tr>
<tr>
<td>12</td>
<td>0.172</td>
<td>0.390</td>
<td>0.761</td>
<td>0.075</td>
<td></td>
<td><strong>Guida</strong></td>
</tr>
</tbody>
</table>

* Madsen & Widmer, IJAIT 2006
STUDY 2: AUTOMATIC PERFORMER IDENTIFICATION

### STUDY 2: AUTOMATIC PERFORMER IDENTIFICATION

Classification of performance strings with string kernels and support vector machines

<table>
<thead>
<tr>
<th>Pair</th>
<th>Classifier 2 [%]</th>
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<tbody>
<tr>
<td>Gould-Barenboim</td>
<td>21 87.5</td>
</tr>
<tr>
<td>Barenboim-Batik</td>
<td>22 <strong>91.7</strong></td>
</tr>
<tr>
<td>Pires-Barenboim</td>
<td>18 75.0</td>
</tr>
<tr>
<td>Pires-Batik</td>
<td>22 <strong>91.7</strong></td>
</tr>
<tr>
<td>Pires-Gould</td>
<td>23 <strong>95.8</strong></td>
</tr>
<tr>
<td>Schiff-Barenboim</td>
<td>19 79.2</td>
</tr>
<tr>
<td>Schiff-Batik</td>
<td>23 <strong>95.8</strong></td>
</tr>
<tr>
<td>Schiff-Gould</td>
<td>18 75.0</td>
</tr>
<tr>
<td>Schiff-Pires</td>
<td>23 <strong>95.8</strong></td>
</tr>
<tr>
<td>Uchida-Barenboim</td>
<td>15 62.5</td>
</tr>
<tr>
<td>Uchida-Batik</td>
<td>17 70.8</td>
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<tr>
<td>Uchida-Gould</td>
<td>19 79.2</td>
</tr>
<tr>
<td>Uchida-Pires</td>
<td>19 79.2</td>
</tr>
<tr>
<td>Uchida-Schiff</td>
<td>18 75.0</td>
</tr>
<tr>
<td></td>
<td><strong>81.9</strong></td>
</tr>
</tbody>
</table>

*Saunders, Hardoon, Shawe-Taylor & Widmer, Proc. ECML’2004

### STUDY 3: STYLE IMITATION


<table>
<thead>
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<th>compared with</th>
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<tbody>
<tr>
<td></td>
<td>DB</td>
</tr>
<tr>
<td>learned from</td>
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<tr>
<td>Barenboim</td>
<td>DB</td>
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<td></td>
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</tr>
<tr>
<td>Batik</td>
<td>RB</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td>Gould</td>
<td>GG</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td>Pires</td>
<td>MP</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td>Schiff</td>
<td>AS</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td>Uchida</td>
<td>MU</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
INSIGHTS (2)

- Visualisation helps to understand differences in performance
- There are systematic differences between great artists that machines can pick up
- Some characteristic patterns can be discovered, but their statistical (and musical!) significance is difficult to establish

A NEW PROJECT


funded by the Austrian National Science Foundation
**STARTING POINT:**

**A NEW SOURCE OF PERFORMANCE DATA**

Nikita Magaloff

* 1912 (St. Petersburg)
† 1992 (Vevey)

Recorded almost complete solo piano works by Frederic Chopin on a Bösendorfer computer-monitored piano (1989)

---

**THE DATA**

Nocturnes op. 9, 15, 27, 32, 37, 48, 55, 62
Mazurkas op. 6, 7, 17, 24, 30, 33, 41, 50, 56, 59, 63
Polonaises op. 26, 40, 44, 53, 61
Waltzes op. 34, 42, 64
Etudes op. 10, 25
Scherzi op. 31, 39, 54
Impromptus op. 29, 36, 51
Ballades op. 38, 47, 51
Sonatas op. 4, 35, 58
+ miscellaneous piano works (e.g., Fantaisie F minor, op.49)

9:04:23 hours total playing time
301.679 played notes
1.5 million sustain pedal events
RESOURCES

- **Magaloff**
  - Audio recordings (complete Chopin)
  - Direct time index
  - Match

- **Scores in kern or MIDI format**
  - Score-performance matching

Other famous pianists:
- Manually annotated (beats) by Mazurka team

**RESOURCES**

- **Magaloff**
  - Audio recordings (complete Chopin)
  - Direct time index
  - Match

- **Scores in kern or MIDI format**
  - Score-performance matching

**MATCH**
- Detailed information about expressive "deviations"
Research on music (audio) analysis:
  • more precise extraction of performance details from audio recordings
  • better matching and annotation
  • quantification of achievable accuracy

Research in machine learning:
  • interpretable probabilistic models

Music-related research:
  • detailed studies on specific performance aspects (ritardando, pedalling, ornaments, …)
  • intra-performer stylistic consistency
  • inter-performer differences

RESEARCH QUESTIONS

CONCLUSIONS

AI / Machine Learning can help in analysing large amounts of empirical data, but you still need to
  • pose the right questions
  • provide appropriate data representations
  • interpret the results in a musical context

=> need input and help from musicology