Looking into Perfection
the Art and Science of Stradivarius Violins

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Stanford University, CA, USA
General trends:

- **Nearly-omnidirectional at low frequencies** (below ~700Hz)
- **More complex at high frequencies**
  - Acoustic shadow cast by body/head
  - Pattern complexity increases with frequency
    - “directional tone color” [Weinreich 1985]: each note perceived as coming from a different location

- **High similarity at similar frequencies**, even when excited by different strings, confirming results in [Wang 1999]
Spatial timbral features

A. Stradivari – “Il Cremonese” 1715

Guarneri del Gesù – “Stauffer” 1734

“Botticelli” vs. “Caravaggio”
Acoustic similarity

- Radiation pattern expressed as a Spherical Harmonic Expansion:

\[ D(\phi, \theta, \omega) = \sum_{n=0}^{N} \sum_{m=-n}^{n} a_{nm}(\omega)Y_n^m(\phi, \theta) \]

\[ \mathbf{a}(\omega) = [a_{1,-1}(\omega), a_{1,0}(\omega), a_{1,1}(\omega), \cdots, a_{N,N-1}(\omega), a_{N,N}(\omega)]^T \]

- Similarity metrics: normalized correlation index:

\[ r_{1,2}(\omega) = \frac{\mathbf{a}_1^T \mathbf{a}_2}{\|\mathbf{a}_1\| \cdot \|\mathbf{a}_2\|} \]
Pairwise similarity

G string

D string

A string

D string
Pairwise similarity

averaged over all strings

Largest correlation ($r=0.59$): “Twin” violins
All violin pairs turn out to have positive, though low (<0.3), correlation
- Similarities (mostly at low frequency)
  - They are all nearly-omnidirectional at low frequencies
  - They all have the acoustic shadow of the player (head and body)
- Dissimilarities (mostly at high frequency)
  - Different directionality (most exhibit a "sweet spot", but they tend to be different)

The radiation pattern is therefore peculiar of each violin → it can be seen as sort of an "acoustic signature"

The large correlation between the “twin” violins suggests that the geometry of the instrument is what characterizes it the most
<table>
<thead>
<tr>
<th>Year</th>
<th>Instrument</th>
<th>Maker</th>
<th>Model</th>
<th>Size</th>
<th>Notes</th>
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<td>N. Amati – &quot;Ex Collin&quot;</td>
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**Notes:**
- Late vs. Late Stradivarius
- Early vs. Late Stradivarius
- Guarneri vs. Guarneri
- Twin violins
- Contemporary school
- Before and after major revisions
- Late vs. Late Stradivarius
- Early vs. Late Stradivarius
- Guarneri vs. Guarneri
- Twin violins
- Contemporary school
- Before and after major revisions
“Twin” violins

- Made by the same luthier (Bardella, 2015) with
  - Same geometry
  - Same finishings (except for the final layer of varnish)

- Tests
  - Acoustic analysis (radiation pattern at different frequencies)
  - Timbral analysis
### Twin violins radiation patterns

<table>
<thead>
<tr>
<th>Twin violin A</th>
<th>Twin violin B</th>
<th>Correlation index</th>
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<tbody>
<tr>
<td><img src="image1.png" alt="Diagram 1" /></td>
<td><img src="image2.png" alt="Diagram 2" /></td>
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<td><img src="image3.png" alt="Diagram 3" /></td>
<td><img src="image4.png" alt="Diagram 4" /></td>
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<td><img src="image5.png" alt="Diagram 5" /></td>
<td><img src="image6.png" alt="Diagram 6" /></td>
<td>85.3%</td>
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</table>
- High positive correlation at all frequency bands
- Average correlation index: 59%
- A set of low-level descriptors extracted from recordings of the two violins
- Same acoustic conditions
- Execution protocol: open strings, played exercising constant force (mf)
A set of low-level descriptors extracted from recordings of the two violins

- Same acoustic conditions
- Execution protocol: open strings, played exercising constant force (mf)
Timbral analysis: capturing

- Feature-based analysis based on Machine learning algorithms
- Specific performance protocol
- Pre-selection of performance-invariant features
- Same violinist, bow and protocol
  - Free strings and single notes + chromatic scales
  - 7 excerpts from Paganini’s “capricci” No. 24 providing a selection of performative styles
Listening tests
Listening test

- Experts (musicians and luthiers)
- 7 scales ranging from 0 to 10 related to pairs of high-level descriptors (*High-Level Features, HLF*)
Identification of a set of Low-Level Features (LLF) to extract
Dataset split into Training set and Test set
Training phase:
- LLF extraction
- Regression training
Test phase:
- Use the trained model with the test set

Low-Level Features
<table>
<thead>
<tr>
<th>Spectral Centroid</th>
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<tbody>
<tr>
<td>Spectral Spread</td>
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<tr>
<td>Spectral Skewness</td>
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<tr>
<td>Spectral Kurtosis</td>
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<td>Spectral Brightness</td>
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<td>Spectral Rolloff</td>
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<td>Spectral Irregularity</td>
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<td>Spectral Roughness</td>
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<tr>
<td>Spectral Contrast</td>
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<td>Spectral Flux</td>
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<td>RMS</td>
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<td>ZCR</td>
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<tr>
<td>Mel-Frequency Cepstral Coefficients</td>
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</tbody>
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HLF modeling using deep learning

- Each descriptor modeled as a monodimensional space
- HLF modeled with regression techniques
- LLF learned with a 3 layers Deep Belief Network
  - It detects the features that describe the input

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DBN: Deep Belief Network
RBM: Restricted Boltzmann Machine

Some comparisons

Historical violins

Contemporary violins
winners of the world triennial violin-making competition
Some comparisons
The choice of materials (woods and finishings) has a strong impact on the final timbre.

3 finishing steps
- Untreated (blank)
- Ground coated
- Varnished

Results
- Forward shifting of some modes
- Enhancement of LLF that account for perceived brightness
- The ground coat creates a shell that stiffens the structure

Impact of varnish and ground coat

- $t_1$: blank
- $t_2$: with ground coat
- $t_3$: with varnish
Optical microscopy images (20X) of the cross section after applying ground coat and varnish (t3):

- Visible light (a) and UV induced fluorescence (b)
- Anatomical wooden structures: medullary ray (mr)
- Resin canal (rc), tracheid and/or fiber tracheid (tr)
- Electronic microscopy image (1000X) of the cross section after applying ground coat (t2): red line represents the trajectory of the semi-quantitative energy-dispersive X-ray microanalysis (EDX) (a)
- Electronic microscopy image (1000X) of the cross section after applying ground coat and varnish (t₃): thickness of varnish layer (b).
Penetration depth (µm) of Calcium:
• Calcium concentration measured through semi-quantitative energy-dispersive X-ray microanalysis (EDX)
• Concentration drops to its minimum at 30 µm of depth
Impact of varnish and ground coat

Total thickness variation (percentage) of the top (left) and back plate (right)
Impact of varnish and ground coat

Average of all point-to-point frequency response (FRF) over 7 locations of the soundboard (multiple excitations)
Timbral analysis of the impact of finishings

- Feature selection
  - Discard non discriminant features
  - Retain those that are less sensitive to performance
  - Timbral analysis confirms a similar enhancement of high frequencies

- Untreated violin: loud and unbalanced

- Ground coat reduces the radiated energy, despite its limited thickness. Calcium caseinate polymerizes and turns into a rigid shell. This causes numerous partials to cluster around the bridge-hill region and boosts high frequencies (very aggressive and harsh sound)

- Varnish layers gradually reduce the impact of the ground coat (enabling the violin maker to fine tune the timbre)
Let the Messiah sing...

- Acoustic measurements on the Stradivarius Messiah (Courtesy of the Ashmolean Museum of Oxford, UK)
- The only “unaltered and unplayed” Stradivarius violin
- Touchless vibrometric and acoustic measurements at the PoliMI Labs
- Hybrid analytic-synthetic model based on bridge admittance and radiance pattern (in collaboration with Esteban Maestre, McGill Univ.)
- Final goal: virtual Messiah (in progress)
Preparation of the instrument

Stradivari “Messia” (1716) - courtesy of Ashmolean Museum, Oxford UK
Positioning the instrument (with laser reference)

Stradivari “Messia” (1716) - courtesy of Ashmolean Museum, Oxford UK
Simultaneous capturing of radiance pattern and bridge admittance

Stradivari “Messia” (1716) - courtesy of Ashmolean Museum, Oxford UK
Simultaneous capturing of radiance pattern and bridge admittance

Stradivari “Messia” (1716) - courtesy of Ashmolean Museum, Oxford UK
Checklist

- Bridge admittance measurement ✔
- Radiance reconstruction (≈✔)
- Extrapolate bridge admittance corresponding to full tensioned strings
  - Using similar measurements based on other Strads (Clisbee, Cremonese and Vesuvius) at various string tension levels
- Virtual restoration of soundboard
- Build model
- Capture violin motion
- Listen...
Dictionary-based equivalent source method for near-field acoustic holography

See ICASSP 2017 paper
Credits

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