INTERNATIONAL AUDIO LABORATORIES ERLANGEN
A joint institution of Fraunhofer IIS and Universität Erlangen-Nürnberg

Winter Term 2026/27

Selected Topics in Deep Learning for Audio, Speech, and Music Processing

Lecture

Nonnegative Music Audio Decomposition

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Friedrich-Alexander-Universität Erlangen-Nürnberg

Fraunhofer IIS

Source Separation

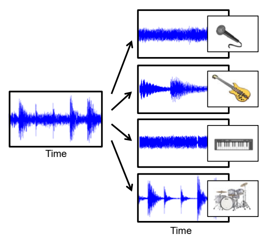
- Decomposition of audio stream into different sound sources
- Central task in digital signal processing
- “Cocktail party effect”

Source Separation

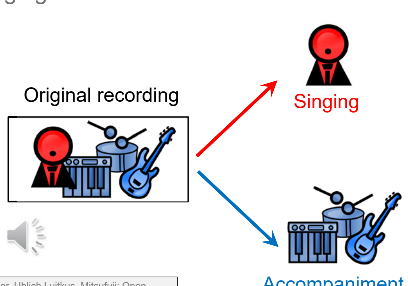
- Decomposition of audio stream into different sound sources
- Central task in digital signal processing
- “Cocktail party effect”
- Several input signals
- Sources are assumed to be statistically independent

Source Separation

- Main melody, accompaniment, drum track
- Instrumental voices
- Individual note events
- Only mono or stereo
- Sources are often highly dependent



Source Separation
Singing Voice

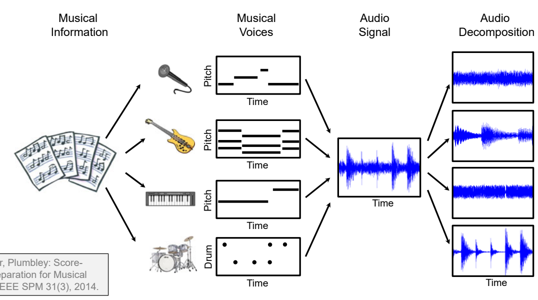


Reference
Signal Processing
AI

Reference
Signal Processing
AI

Stöter, Uhlich Luitkus, Mitsufuji: Open-Unmix – A Reference Implementation for Music Source Separation. JOSS, 2019.

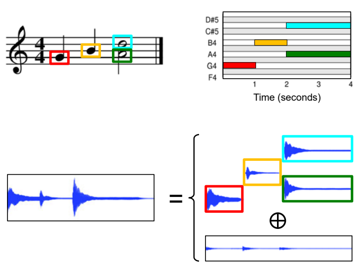
Score-Informed Source Separation
Exploit musical score to support decomposition process



Ewert, Pardo, Müller, Plumbley: Score-Informed Source Separation for Musical Audio Recordings. IEEE SPM 31(3), 2014.

Score-Informed Audio Decomposition

Driedger, Grohganz, Prätzlich, Ewert, Müller: Score-Informed Audio Decomposition and Applications. Proc. ACM Multimedia: 541–544, 2013



Score-Informed Audio Decomposition

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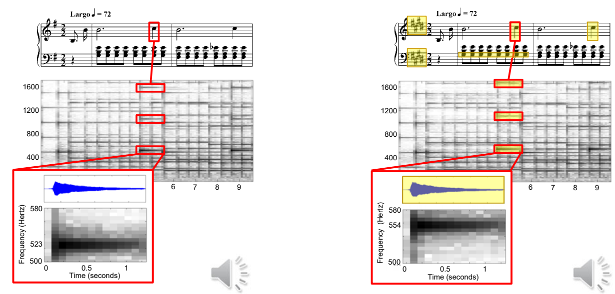
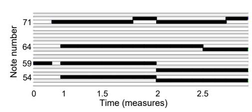


Score-Informed Audio Decomposition

Ewert, Pardo, Müller, Plumbley: Score-Informed Source Separation for Musical Audio Recordings. IEEE Signal Proc. Mag. 31(3): 116–124, 2014

Sheet music

Piano roll



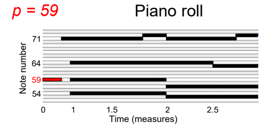
Score-Informed Audio Decomposition

Ewert, Pardo, Müller, Plumbley: Score-Informed Source Separation for Musical Audio Recordings. IEEE Signal Proc. Mag. 31(3): 116–124, 2014

Sheet music

p = 59

Piano roll



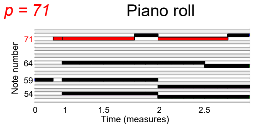
Score-Informed Audio Decomposition

Ewert, Pardo, Müller, Plumbley: Score-Informed Source Separation for Musical Audio Recordings. IEEE Signal Proc. Mag. 31(3): 116–124, 2014

Sheet music

p = 71

Piano roll



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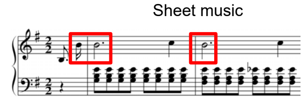
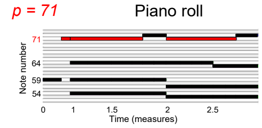
Sheet music

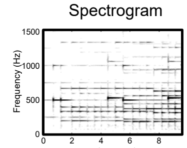


p = 71

Piano roll



Spectrogram



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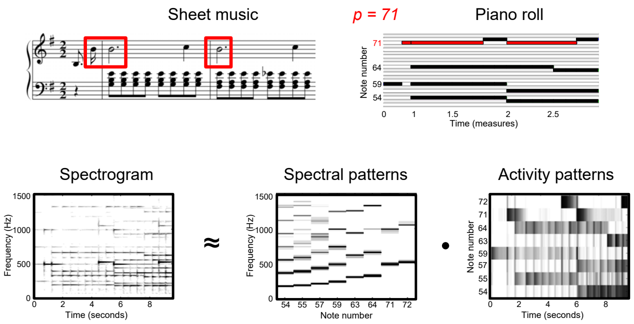

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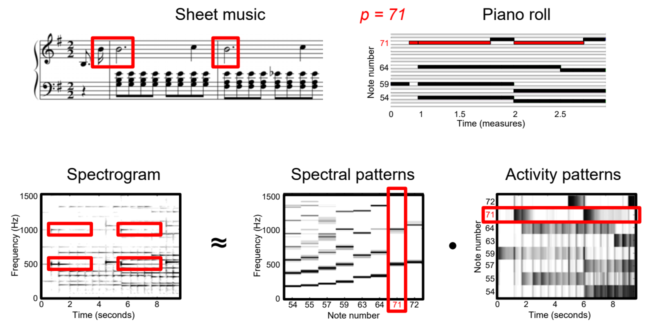
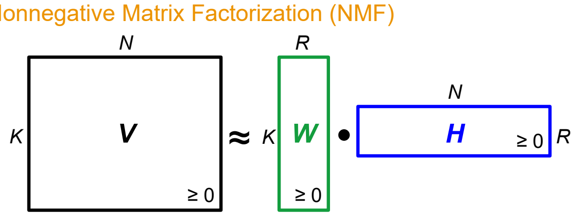
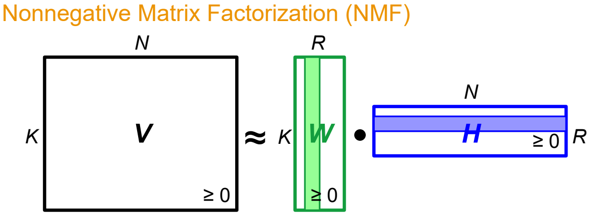


Nonnegative Matrix Factorization (NMF)



$V \in \mathbb{R}_{\geq 0}^{K\times N}$ $W \in \mathbb{R}_{\geq 0}^{K\times R}$ $H \in \mathbb{R}_{\geq 0}^{R\times N}$

Nonnegative Matrix Factorization (NMF)

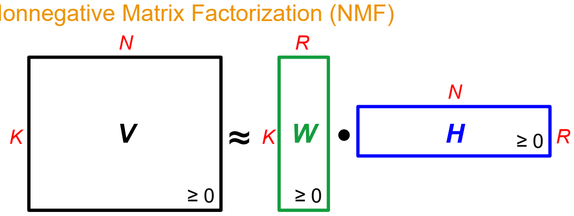


Magnitude Spectrogram **Templates** **Activations**

Templates: Pitch + Timbre "How does it sound"

Activations: Onset time + Duration "When does it sound"

Nonnegative Matrix Factorization (NMF)

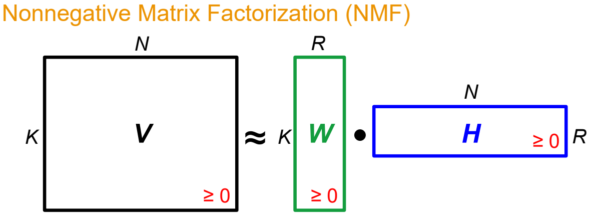


$V \in \mathbb{R}_{\geq 0}^{K\times N}$ $W \in \mathbb{R}_{\geq 0}^{K\times R}$ $H \in \mathbb{R}_{\geq 0}^{R\times N}$

Dimensionality reduction

- *K*, *N* typically much larger than *R* (maximal rank)
- Example: *N = 1000, K = 500, R = 20*
  K x N = 500,000, *K x R = 10,000,* *R x N = 20,000*

Nonnegative Matrix Factorization (NMF)



$V \in \mathbb{R}_{\geq 0}^{K\times N}$ $W \in \mathbb{R}_{\geq 0}^{K\times R}$ $H \in \mathbb{R}_{\geq 0}^{R\times N}$

Nonnegativity:

- Prevents mutual cancellation of template vectors
- Encourages semantically meaningful decomposition

NMF Optimization

Optimization problem:

Given $V \in \mathbb{R}_{\geq 0}^{K \times N}$ and rank parameter R minimize

$$\|V - WH\|^2$$

with respect to $W \in \mathbb{R}_{\geq 0}^{K \times R}$ and $H \in \mathbb{R}_{\geq 0}^{R \times N}$.

Optimization not easy:

- Nonnegativity constraints
- Nonconvexity when jointly optimizing W and H

Strategy: Iteratively optimize W and H via gradient descent

NMF Optimization

Computation of gradient with respect to H (fixed W)

$D := RN$

$\varphi^W : \mathbb{R}^D \to \mathbb{R}$

$\varphi^W(H) := \|V - WH\|^2$

Variables

$H \in \mathbb{R}^{R \times N}$

$H_{\rho\nu}$

$\rho \in [1:R]$

$\nu \in [1:N]$

NMF Optimization

Computation of gradient with respect to H (fixed W)

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$\varphi^W : \mathbb{R}^D \to \mathbb{R}$

$\varphi^W(H) := \|V - WH\|^2$

$$\frac{\partial \varphi^W}{\partial H_{\rho\nu}} = \frac{\partial \left(\sum_{k=1}^K \sum_{n=1}^N \left(V_{kn} - \sum_{r=1}^R W_{kr} H_{rn} \right)^2 \right)}{\partial H_{\rho\nu}}$$

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$$= \frac{\partial \left(\sum_{k=1}^K \left(V_{k\nu} - \sum_{r=1}^R W_{kr} H_{r\nu} \right)^2 \right)}{\partial H_{\rho\nu}}$$

Summand that does not depend on $H_{\rho\nu}$ must be zero

Variables

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$$= \sum_{k=1}^K 2 \left(V_{k\nu} - \sum_{r=1}^R W_{kr} H_{r\nu} \right) \cdot (-W_{k\rho})$$

Apply chain rule from calculus

Variables

$H \in \mathbb{R}^{R \times N}$

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NMF Optimization

Computation of gradient with respect to H (fixed W)

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$$= 2 \left(\sum_{r=1}^R \sum_{k=1}^K W_{k\rho} W_{kr} H_{r\nu} - \sum_{k=1}^K W_{k\rho} V_{k\nu} \right)$$

Rearrange summands

Variables

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Computation of gradient with respect to *H* (fixed *W*)

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$$\begin{aligned}
\frac{\partial \varphi^W}{\partial H_{\rho\nu}} &= \frac{\partial\left(\sum_{k=1}^K \sum_{n=1}^N \left(V_{kn} - \sum_{r=1}^R W_{kr}H_{rn}\right)^2\right)}{\partial H_{\rho\nu}}\\
&= \frac{\partial\left(\sum_{k=1}^K \left(V_{k\nu} - \sum_{r=1}^R W_{kr}H_{r\nu}\right)^2\right)}{\partial H_{\rho\nu}}\\
&= \sum_{k=1}^K 2\left(V_{k\nu} - \sum_{r=1}^R W_{kr}H_{r\nu}\right)\cdot(-W_{k\rho})\\
&= 2\left(\sum_{r=1}^R\sum_{k=1}^K W_{k\rho}W_{kr}H_{r\nu} - \sum_{k=1}^K W_{k\rho}V_{k\nu}\right)\\
&= 2\left(\sum_{r=1}^R\left(\sum_{k=1}^K W_{\rho k}^\top W_{kr}\right)H_{r\nu} - \sum_{k=1}^K W_{\rho k}^\top V_{k\nu}\right)
\end{aligned}$$

Introduce transposed $W^\top$

NMF Optimization

Computation of gradient with respect to *H* (fixed *W*)

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$\varphi^W(H) := \|V - WH\|^2$

Variables

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\frac{\partial \varphi^W}{\partial H_{\rho\nu}} &= \frac{\partial\left(\sum_{k=1}^K \sum_{n=1}^N \left(V_{kn} - \sum_{r=1}^R W_{kr}H_{rn}\right)^2\right)}{\partial H_{\rho\nu}}\\
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&= 2\left(\sum_{r=1}^R\sum_{k=1}^K W_{k\rho}W_{kr}H_{r\nu} - \sum_{k=1}^K W_{k\rho}V_{k\nu}\right)\\
&= 2\left(\sum_{r=1}^R\left(\sum_{k=1}^K W_{\rho k}^\top W_{kr}\right)H_{r\nu} - \sum_{k=1}^K W_{\rho k}^\top V_{k\nu}\right)\\
&= \boxed{2\left((W^\top WH)_{\rho\nu} - (W^\top V)_{\rho\nu}\right).}
\end{aligned}$$

NMF Optimization

Gradient descent

Initialization $H^{(0)} \in \mathbb{R}^{R\times N}$

Iteration for $\ell = 0, 1, 2, \ldots$

$$H_{rn}^{(\ell+1)} = H_{rn}^{(\ell)} - \gamma_{rn}^{(\ell)} \cdot \left(\left(W^\top WH^{(\ell)}\right)_{rn} - \left(W^\top V\right)_{rn}\right)$$

with suitable learning rate $\gamma_{rn}^{(\ell)} \geq 0$

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with suitable learning rate $\gamma_{rn}^{(\ell)} \geq 0$

Issues:

- How to do the initialization?
- How to choose the learning rate?
- How to ensure nonnegativity?

NMF Optimization

Gradient descent

Choose adaptive learning rate:

$$\gamma_{rn}^{(\ell)} := \frac{H_{rn}^{(\ell)}}{\left(W^\top WH^{(\ell)}\right)_{rn}}$$

Initialization $H^{(0)} \in \mathbb{R}^{R\times N}$

Iteration for $\ell = 0, 1, 2, \ldots$

$$\begin{aligned}
H_{rn}^{(\ell+1)} &= H_{rn}^{(\ell)} - \gamma_{rn}^{(\ell)} \cdot \left(\left(W^\top WH^{(\ell)}\right)_{rn} - \left(W^\top V\right)_{rn}\right)\\
&= H_{rn}^{(\ell)} \cdot \frac{\left(W^\top V\right)_{rn}}{\left(W^\top WH^{(\ell)}\right)_{rn}}
\end{aligned}$$

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Gradient descent

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&= H_{rn}^{(\ell)} \cdot \frac{\left(W^\top V\right)_{rn}}{\left(W^\top WH^{(\ell)}\right)_{rn}}
\end{aligned}$$

Issues:

- How to do the initialization?
- How to choose the learning rate?
- How to ensure nonnegativity?

- Update rule become multiplicative
- Nonnegative values stay nonnegative

NMF Optimization

Lee, Seung: Algorithms for Non-Negative Matrix Factorization. Proc. NIPS, 2000

Algorithm: NMF ($V \approx WH$)

Input: Nonnegative matrix V of size $K \times N$
Rank parameter $R \in \mathbb{N}$
Threshold ε used as stop criterion

Output: Nonnegative template matrix W of size $K \times R$
Nonnegative activation matrix H of size $R \times N$

Procedure: Define nonnegative matrices $W^{(0)}$ and $H^{(0)}$ by some random or informed initialization. Furthermore set $\ell = 0$. Apply the following update rules (written in matrix notation):

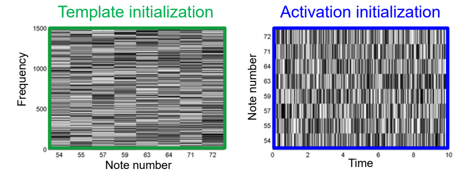
(1) $H^{(\ell+1)} = H^{(\ell)} \odot \left(\left((W^{(\ell)})^\top V\right) \oslash \left((W^{(\ell)})^\top W^{(\ell)} H^{(\ell)}\right)\right)$

(2) $W^{(\ell+1)} = W^{(\ell)} \odot \left(\left(V (H^{(\ell+1)})^\top\right) \oslash \left(W^{(\ell)} H^{(\ell+1)} (H^{(\ell+1)})^\top\right)\right)$

(3) Increase ℓ by one.

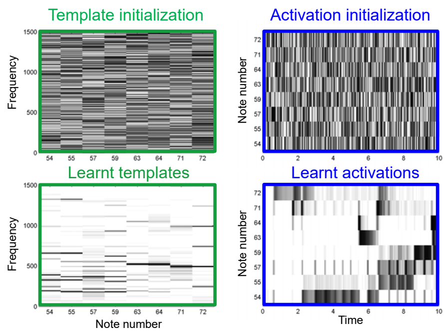
Repeat the steps (1) to (3) until $\|H^{(\ell)} - H^{(\ell-1)}\| \le \varepsilon$ and $\|W^{(\ell)} - W^{(\ell-1)}\| \le \varepsilon$ (or until some other stop criterion is fulfilled). Finally, set $H = H^{(\ell)}$ and $W = W^{(\ell)}$.

NMF-based Spectrogram Decomposition



Random initialization

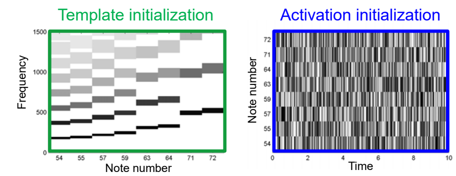
NMF-based Spectrogram Decomposition



Random initialization

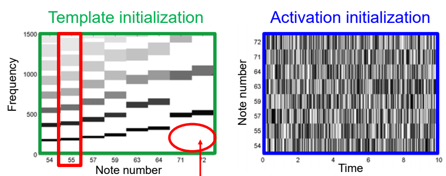
No semantic meaning

Constrained NMF: Templates



Enforce harmonic structure
with zero-valued entries

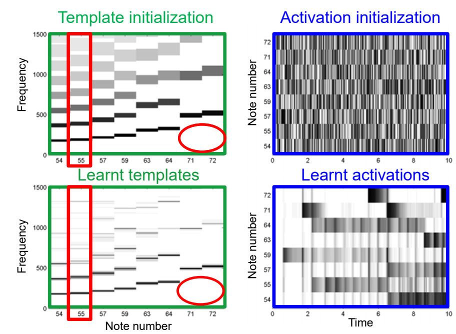
Constrained NMF: Templates



Template constraint for p=55

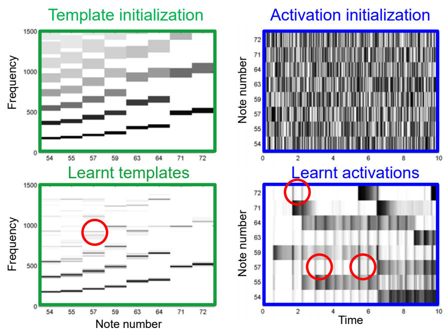
Enforce harmonic structure
with zero-valued entries

Constrained NMF: Templates



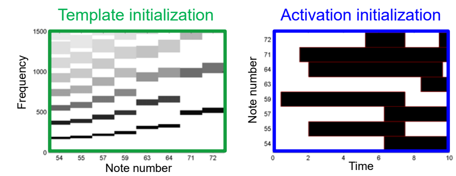
Zero-valued entries
remain zero-valued
entries!

Constrained NMF: Templates

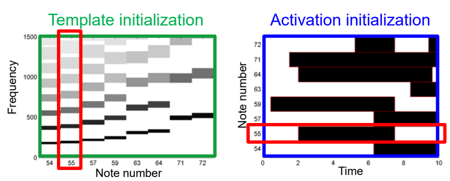


Pitch templates misused to represent onsets

Constrained NMF: Double Constraints



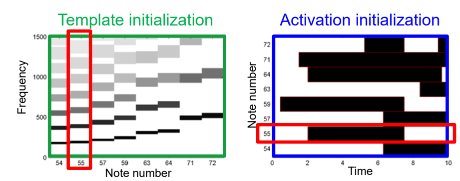
Constrained NMF: Double Constraints



Template constraint for p=55

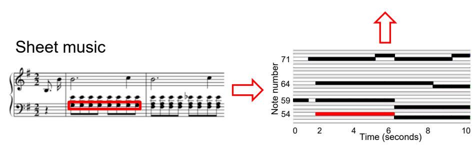
Activation constraints for p=55

Constrained NMF: Double Constraints



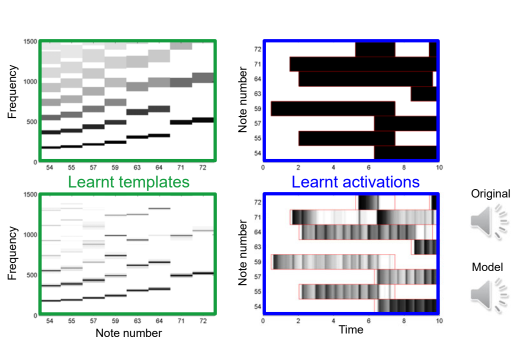
Template constraint for p=55

Activation constraints for p=55



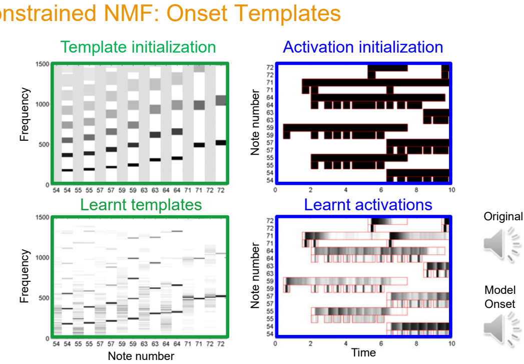
Such information may come from a synchronized score

Constrained NMF: Double Constraints



Significant gain, but onsets are missing

Constrained NMF: Onset Templates

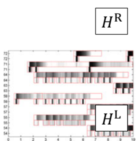


Onsets are sharper

Score-Informed Audio Decompostion

Application: Separating left and right hands for piano

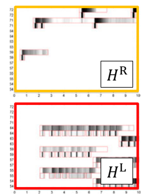
1. Split activation matrix



Score-Informed Audio Decompostion

Application: Separating left and right hands for piano

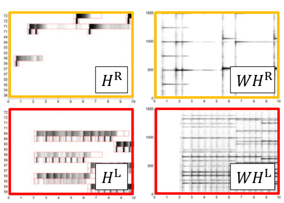
1. Split activation matrix



Score-Informed Audio Decompostion

Application: Separating left and right hands for piano

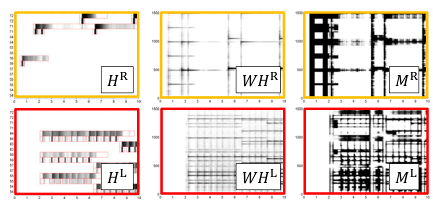
1. Split activation matrix
2. Model spectrogram for left/right



Score-Informed Audio Decompostion

Application: Separating left and right hands for piano

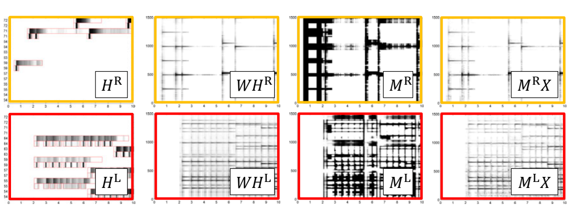
1. Split activation matrix
2. Model spectrogram for left/right
3. Separation masks for left/right



Score-Informed Audio Decompostion

Application: Separating left and right hands for piano

1. Split activation matrix
2. Model spectrogram for left/right
3. Separation masks for left/right
4. Estimated spectrograms for left/right



Score-Informed Audio Decompostion

Application: Separating left and right hands for piano

Ewert, Müller: Using Score-Informed Constraints for NMF-based Source Separation. Proc. ICASSP, 2012.

Chopin, Waltz Op. 64, No. 1

Original

Score-Informed Audio Decompostion

Application: Separating left and right hands for piano

Ewert, Müller: Using Score-Informed Constraints for NMF-based Source Separation. Proc. ICASSP, 2012.

Chopin, Waltz Op. 64, No. 1

Original

Left/right hand

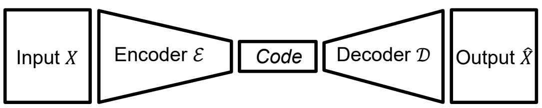
Right hand

Left hand

Conclusions (NMF)

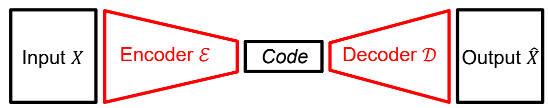
- NMF used for spectrogram decomposition
- Multiplicative update rules make it easy to constrain NMF model via zero initialization
- Exploiting score information to guide separation process (requires score–audio synchronization)
- Application: Separation of arbitrary note groups from given audio recording

Autoencoder



- Specific type of neural network
- Encoder: Compress input X into a low-dimensional code
- Decoder: Reconstruct output $\hat{X}$ from code

Autoencoder



- Specific type of neural network
- Encoder: Compress input X into a low-dimensional code
- Decoder: Reconstruct output $\hat{X}$ from code
- Goal: Learn parameters for encoder and decoder such that output is close to input with respect to some loss function:

$$\mathcal{L}(X, \hat{X}) \approx 0$$

NMF and Autoencoder (AE)

Smaragdis, Venkataramani: A Neural Network Alternative to Non-Negative Audio Models, Proc. ICASSP 2017.

NMF

$$V \approx W \cdot H = \hat{V}$$

$V \approx WH$ implies $W^{+}V \approx H$ with pseudoinverse W^{+}

NMF and Autoencoder (AE)

Smaragdis, Venkataramani: A Neural Network Alternative to Non-Negative Audio Models, Proc. ICASSP 2017.

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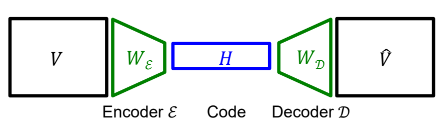
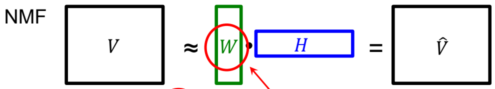


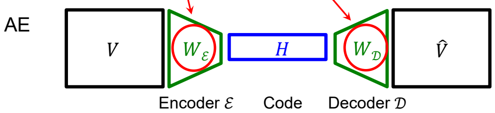
1. Layer: $H = W_{\mathcal{E}}\, V$
2. Layer: $\hat{V} = W_{\mathcal{D}}\, H$

NMF and Autoencoder (AE)

Smaragdis, Venkataramani: A Neural Network Alternative to Non-Negative Audio Models, Proc. ICASSP 2017.



$V \approx WH$ implies $W^+V \approx H$ with pseudoinverse W^+

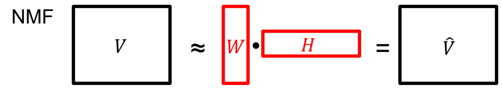


1. Layer: $H = W_\mathcal{E}\, V$
2. Layer: $\hat{V} = W_\mathcal{D}\, H$

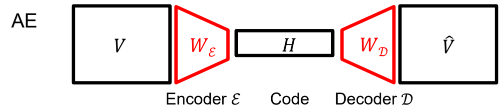
Fully connected network

NMF and Autoencoder (AE)

Smaragdis, Venkataramani: A Neural Network Alternative to Non-Negative Audio Models, Proc. ICASSP 2017.



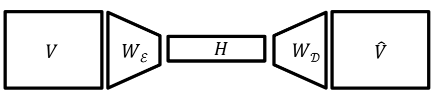
$V \approx WH$ implies $W^+V \approx H$ with pseudoinverse W^+



1. Layer: $H = W_\mathcal{E}\, V$
2. Layer: $\hat{V} = W_\mathcal{D}\, H$

NMF: Learn H and W
AE: Learn $W_\mathcal{E}$ and $W_\mathcal{D}$

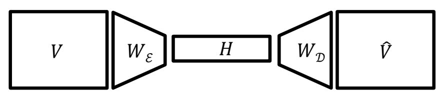
Nonnegative Autoencoder (NAE)



1. Layer: $H = W_\mathcal{E}\, V$
2. Layer: $\hat{V} = W_\mathcal{D}\, H$

- How can one adjust the AE to simulate NMF?
- How can one achieve nonnegativity?
- How can one incorporate musical knowledge?
- …

Nonnegative Autoencoder (NAE)

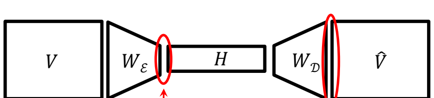


1. Layer: $H = W_\mathcal{E}\, V$
2. Layer: $\hat{V} = W_\mathcal{D}\, H$

$\mathcal{L}(V,\hat{V}) = \|V - \hat{V}\|^2$

- Loss function: same as in NMF

Nonnegative Autoencoder (NAE)

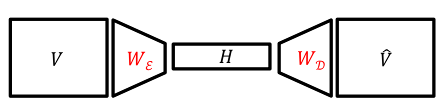


1. Layer: $H = \max(W_\mathcal{E}\, V, 0)$
2. Layer: $\hat{V} = \max(W_\mathcal{D}\, H, 0)$

$\mathcal{L}(V,\hat{V}) = \|V - \hat{V}\|^2$

- Loss function: same as in NMF
- Activation function (ReLU) makes H and $\hat{V}$ nonnegative

Nonnegative Autoencoder (NAE)



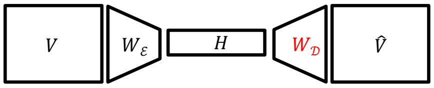
1. Layer: $H = \max(W_\mathcal{E}\, V, 0)$
2. Layer: $\hat{V} = \max(W_\mathcal{D}\, H, 0)$

$\mathcal{L}(V,\hat{V}) = \|V - \hat{V}\|^2$

$$W_\mathcal{D} \leftarrow \max\left(W_\mathcal{D} - \gamma \frac{\partial \mathcal{L}}{\partial W_\mathcal{D}}, 0\right)$$

- Loss function: same as in NMF
- Activation function (ReLU) makes H and $\hat{V}$ nonnegative
- Projected gradient descent can be used to keep $W_\mathcal{D}$ (and $W_\mathcal{E}$) nonnegative

Musical Constraints



$H = \max(W_{\mathcal{E}}\, V, 0)$
$\hat{V} = \max(W_{\mathcal{D}}\, H, 0)$

- Template constraints: Project certain entries in $W_{\mathcal{D}}$ to zero values (using projected gradient decent)

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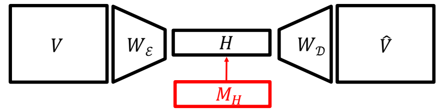
Musical Constraints

Ewert, Sandler: Structured Dropout for Weak Label and Multi-Instance Learning and Its Application to Score-Informed Source Separation. Proc. ICASSP, 2017.



$H' = H \odot M_H$
$\hat{V} = \max(W_{\mathcal{D}}\, H', 0)$

- Template constraints: Project certain entries in $W_{\mathcal{D}}$ to zero values (using projected gradient decent)
- Activation constraints: Use structured dropout by applying pointwise multiplication with binary mask M_H

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NAE with Multiplicative Update Rules

- Multiplicative update rules in NMF:
  - Preserve nonnegativity
  - Lead to fast convergence
- Question: Can one introduce multiplicative update rules to train network weights for NAE?
- Use in additive gradient descent $W^{(\ell+1)} = W^{(\ell)} - \gamma \cdot \dfrac{\partial \mathcal{L}}{\partial W}$

  a suitable (adaptive) learning rate γ.

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NAE with Multiplicative Update Rules

Özer, Hansen, Zunner, Müller: Investigating Nonnegative Autoencoders for Efficient Audio Decomposition. Proc. EUSIPCO, 2022.

- Encoder:

  $H = W_{\mathcal{E}} V$
- Structured Dropout:

  $H' = H \odot M_H$
- Decoder:

  $\hat{V} = W_{\mathcal{D}} H'$

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NAE with Multiplicative Update Rules

Özer, Hansen, Zunner, Müller: Investigating Nonnegative Autoencoders for Efficient Audio Decomposition. Proc. EUSIPCO, 2022.

- Encoder:

  $H = W_{\mathcal{E}} V$

$$\boxed{W_{\mathcal{E},rk}^{(\ell+1)} = W_{\mathcal{E},rk}^{(\ell)} \cdot \frac{\left(\left(\left(W_{\mathcal{D}}^{\top} V\right) \odot M_H\right) V^{\top}\right)_{rk}}{\left(\left(\left(W_{\mathcal{D}}^{\top} W_{\mathcal{D}} H'^{(\ell)}\right) \odot M_H\right) V^{\top}\right)_{rk}}}$$

- Structured Dropout:

  $H' = H \odot M_H$
- Decoder:

  $\hat{V} = W_{\mathcal{D}} H'$

$$\boxed{W_{\mathcal{D},kr}^{(\ell+1)} = W_{\mathcal{D},kr}^{(\ell)} \cdot \frac{\left(V H'^{\top}\right)_{kr}}{\left(W_{\mathcal{D}}^{(\ell)} H' H'^{\top}\right)_{kr}}}$$

Similar idea and computation as for NMF.

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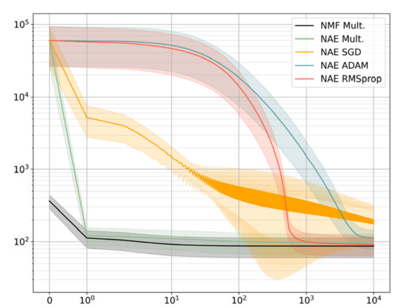
Approximation Loss

Özer, Hansen, Zunner, Müller: Investigating Nonnegative Autoencoders for Efficient Audio Decomposition. Proc. EUSIPCO, 2022.



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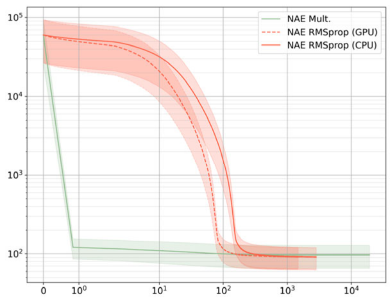
Approximation Loss

Özer, Hansen, Zunner, Müller: Investigating Nonnegative Autoencoders for Efficient Audio Decomposition. Proc. EUSIPCO, 2022.

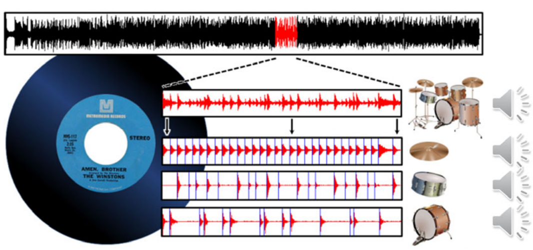


Conclusions (NAE)

- Simulation of NMF:
  - Decoder corresponds to NMF templates
  - Encoder learns a kind of pseudo-inverse
  - Code corresponds to NMF activations
- Nonnegativity can be achieved via
  - activation function (ReLU)
  - projected gradient descent
  - multiplicative update rules
- Musical knowledge can be integrated via
  - removing network weights (template constraints)
  - structured dropout (activation constraints)

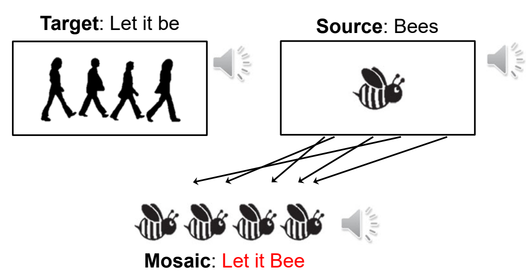
Informed Drum-Sound Decomposition

Dittmar, Müller: Reverse Engineering the Amen Break — Score-Informed Separation and Restoration Applied to Drum Recording. IEEE/ACM TASLP, 24(9): 1531–1543, 2016



NMF-Inspired Audio Mosaicing

Driedger, Prätzlich, Müller: Let It Bee — Towards NMF-Inspired Audio Mosaicing. ISMIR, 350–356, 2015



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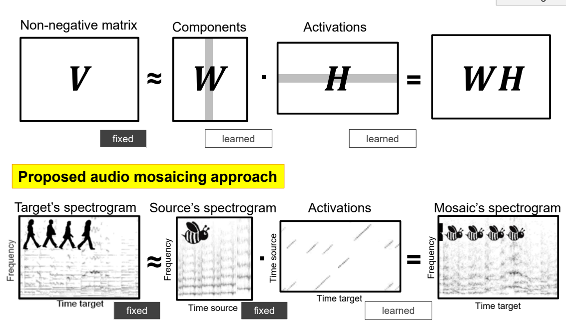

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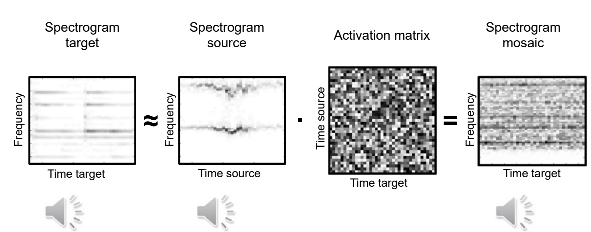

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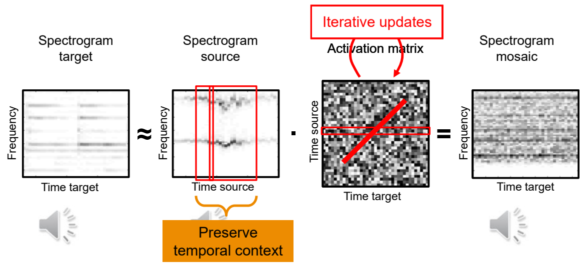
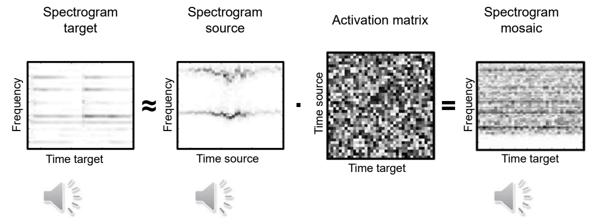


Core idea: support the development of sparse diagonal activation structures

NMF-Inspired Audio Mosaicing

Driedger, Prätzlich, Müller: Let It Bee — Towards NMF-Inspired Audio Mosaicing. ISMIR, 350–356, 2015



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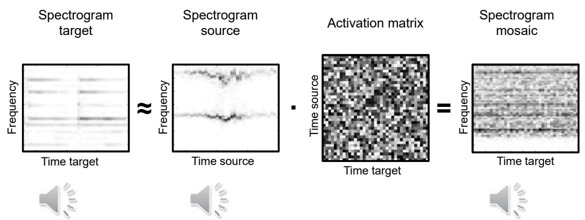

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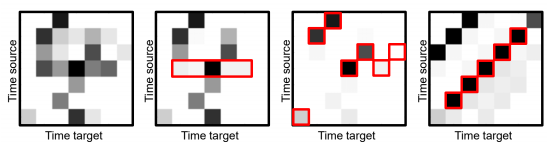
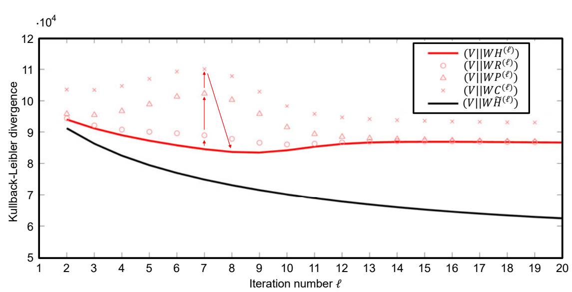


Activation matrix	Repetition-restricted activation matrix	Polyphony-restricted activation matrix	Continuity-enhanced activation matrix
	Neighborhood constraints	Column constraints	Diagonal smoothing

- Constraints are enforced by additional update rules
- Additional rules are interleaved with standard NMF update rules
- Soft alternative to NMFD

NMF-Inspired Audio Mosaicing

Driedger, Prätzlich, Müller: Let It Bee — Towards NMF-Inspired Audio Mosaicing. ISMIR, 350–356, 2015



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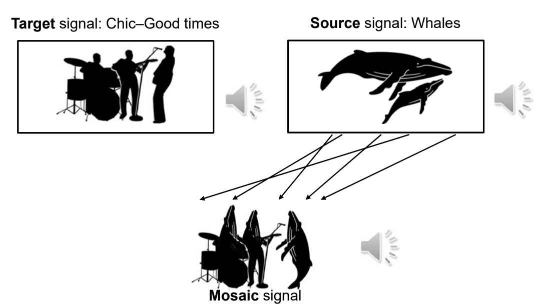

NMF-Inspired Audio Mosaicing

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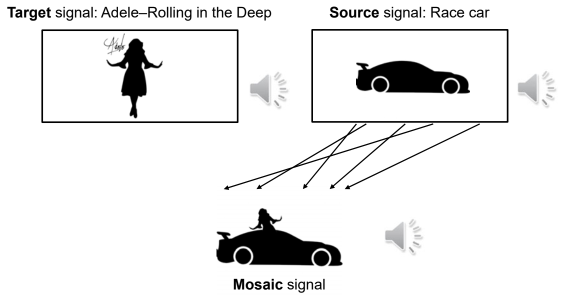

Conclusions (Nonnegative Music Audio Decomposition)

- Spectrogram decomposition using NMF
- Integration of musical knowledge through constrained NMF
- Simulation of NMF using nonnegative autoencoders (NAEs)
- Related Topics:
  - Resynthesize of sound components
    - Differentiable Digital Signal Processing (DDSP)
    - Diffusion-based music synthesis
  - Generation of musical knowledge
    - Automatic music transcription
    - Dataset curation

References (NMF, NAE)

- Daniel Lee, Sebastian Seung: Algorithms for Non-Negative Matrix Factorization. Proc. NIPS, 2000.
- Sebastian Ewert, Meinard Müller: Using Score-Informed Constraints for NMF-Based Source Separation. Proc. ICASSP, 2012.
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- Meinard Müller: Fundamentals of Music Processing. Springer, 2021.
- Yigitcan Özer, Jonathan Hansen, Tim Zunner, Meinard Müller: Investigating Nonnegative Autoencoders for Efficient Audio Decomposition. Proc. EUSIPCO, 2022.