# Rhythm Analysis in Music

EECS 352: Machine Perception of Music & Audio

# Some Definitions

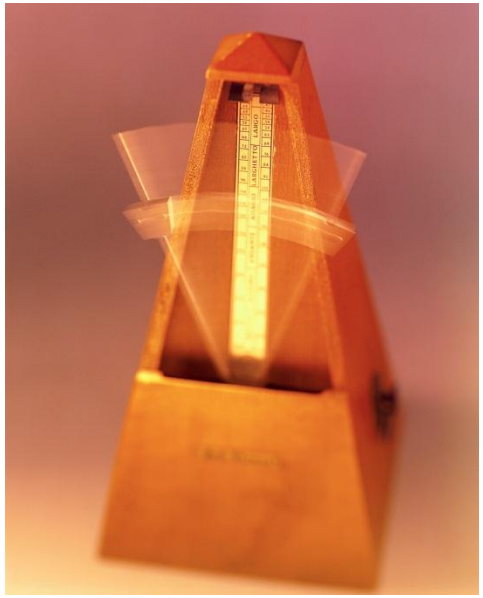
- Rhythm
  - "movement marked by the regulated succession of strong and weak elements, or of opposite or different conditions." [OED]

# Some Definitions

- Beat
  - Basic unit of time in music

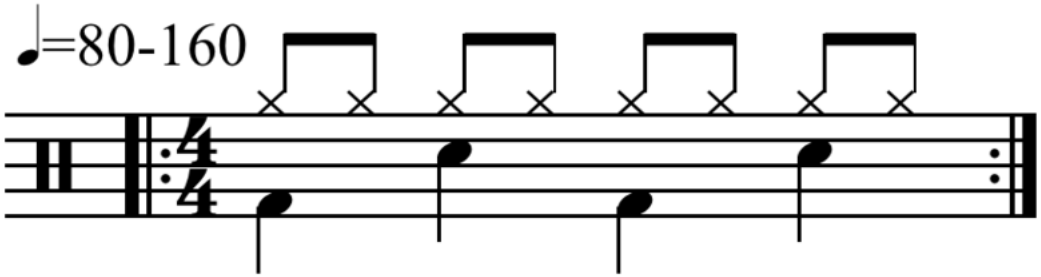
# Some Definitions

- Tempo
  - Speed or pace of a given piece, typically measured in beats per minute (BPM)



# Some Definitions

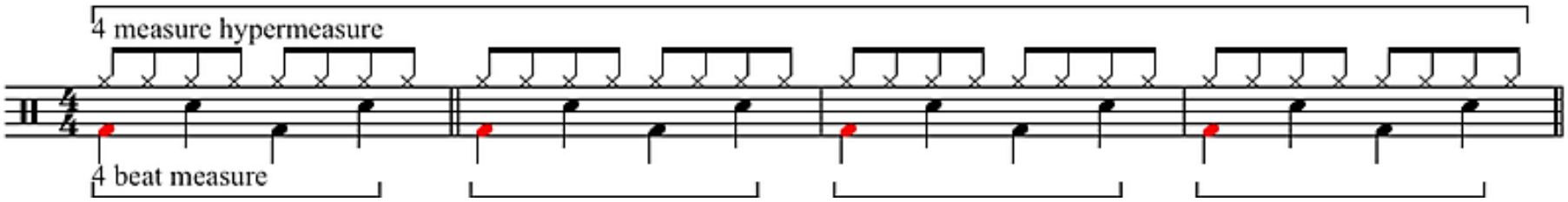
- Measure (or bar)
  - Segment of time defined by a given number of beats




A 4-beat measure drum pattern.
[http://en.wikipedia.org/wiki/Metre_(music)]

# Some Definitions

- Meter (or metre)
  - Organization of music into regularly recurring measures of stressed and unstressed beats



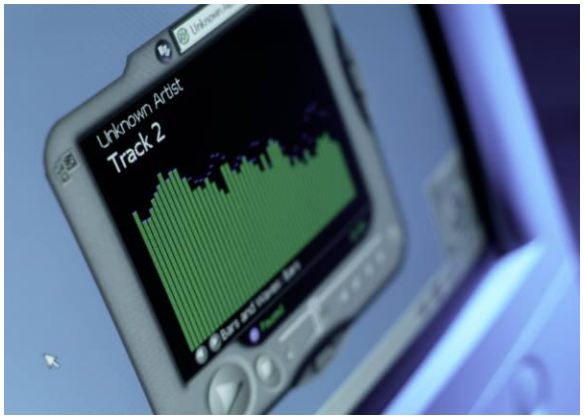

Hypermeter: 4-beat measure and 4-measure hypermeasure. Hyperbeats in red. [http://en.wikipedia.org/wiki/Metre_(music)]

# Rhythm Analysis Tasks

- Onset Detection
- Tempo Estimation
- Beat Tracking
- Higher-level Structures

# Practical Interest

- Identify/classify/retrieve by rhythmic similarity
- Music segmentation/summarization
- Audio/video synchronization
- And… Source separation!

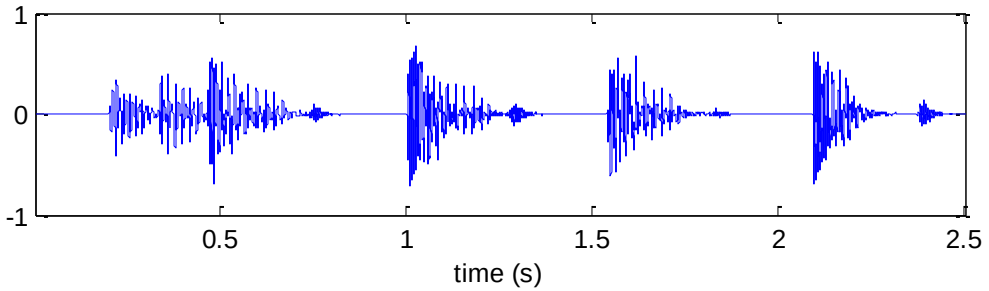


# Intellectual Interest

- "Music understanding" [Dannenberg, 1987]
- Music perception
- Music cognition
- And… Fun!

# Onset Detection (what?)

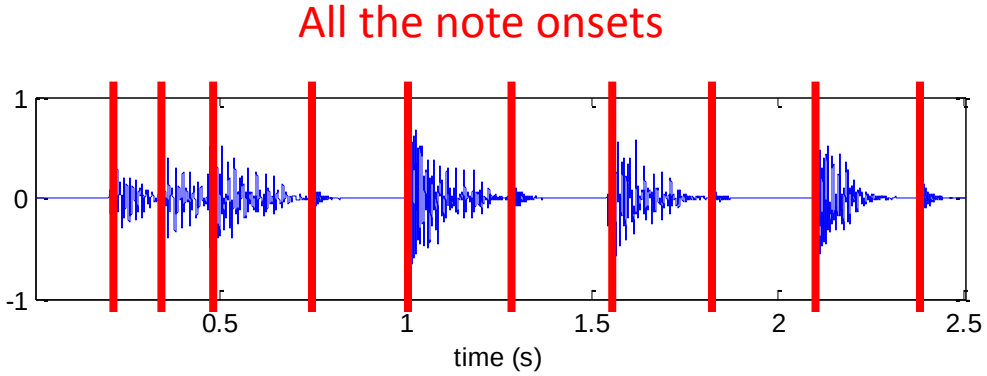
- Identify the starting times of musical elements
- E.g. notes, drum sounds, or any sudden change
- See *novelty curve* [Foote, 2000]




Beginning of *Another one bites the dust* by Queen.

# Onset Detection (how?)

- Analyze amplitude (drums have high energy!)
- Analyze other cues (e.g. spectrum, pitch, phase)
- Analyze self-similarity (see *similarity matrix*)

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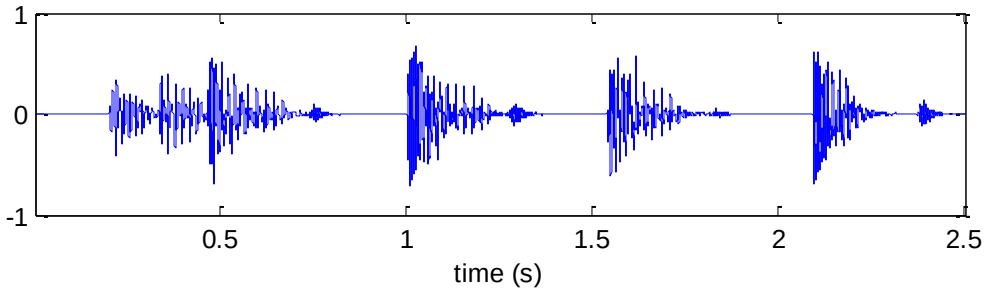
# Tempo Estimation (what?)

- Identify periodic or quasi-periodic patterns
- Identify some period of repetition
- See *beat spectrum* [Foote et al., 2001]

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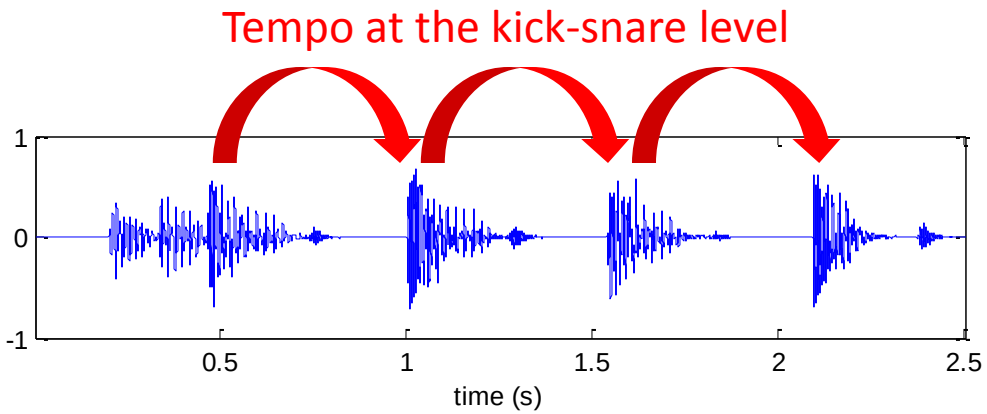
# Tempo Estimation (how?)

- Analyze periodicities using the *autocorrelation*
- Compare the onsets with a bank of comb filters
- Use the Short-Time Fourier Transform (STFT)

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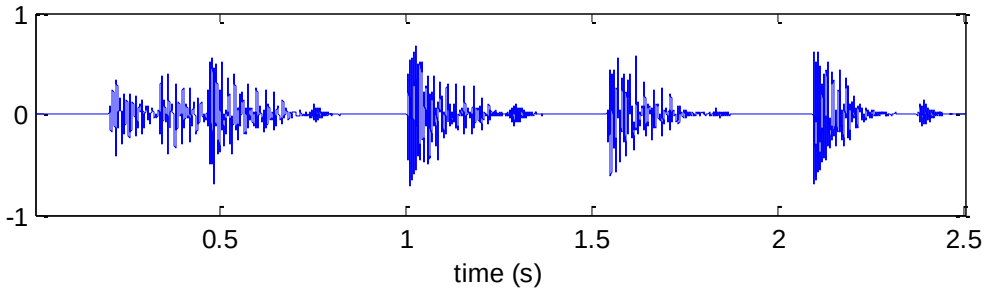
# Beat Tracking (what?)

- Identify the beat times
- Identify the times to which we tap our feet
- See (also) *beat spectrum*

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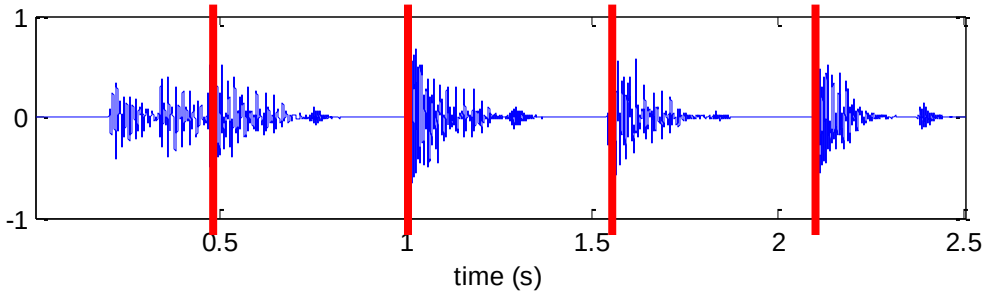
# Beat Tracking (how?)

- Find optimal beat times given onsets and tempo
- Use Dynamic Programming [Ellis, 2007]
- Use Multi-Agent System [Goto, 2001]

Beats at the kick-snare level

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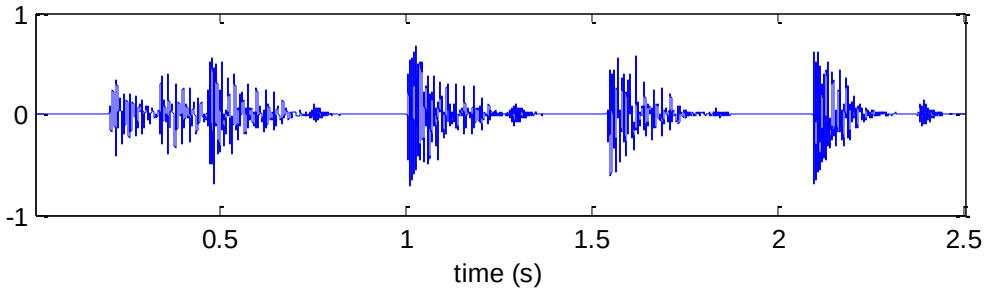
# Higher-level structures (what?)

- Rhythm, meter, etc.
- "Music understanding"
- See (again) *beat spectrum* and *similarity matrix*

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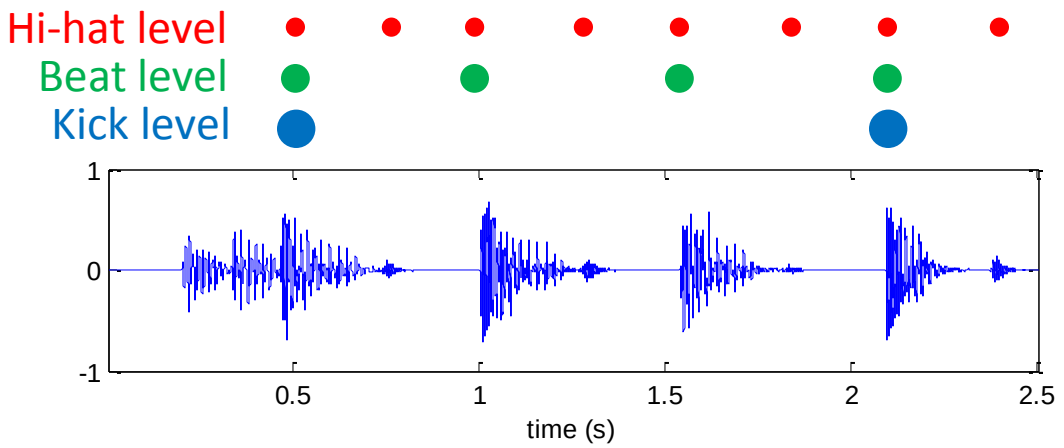
# Higher-level structures (how?)

- Extract onsets, tempo, beat
- Use/assume additional knowledge
- E.g. how many beats per measure? Etc.

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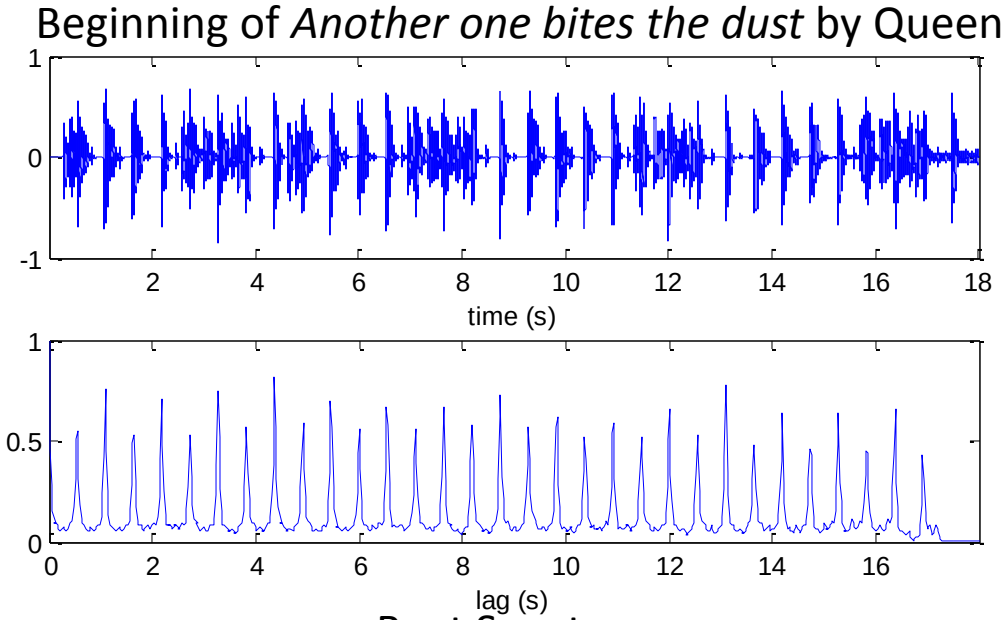
# State-of-the-Art

- Some interesting links
  - Dannenberg's articles on beat tracking: http://www.cs.cmu.edu/~rbd/bib-beattrack.html
  - Goto's work on beat tracking: http://staff.aist.go.jp/m.goto/PROJ/bts.html
  - Ellis' Matlab codes for tempo estimation and beat tracking: http://labrosa.ee.columbia.edu/projects/beattrack/
  - MIREX's annual evaluation campaign for Music Information Retrieval (MIR) algorithms, including tasks such as onset detection, tempo extraction, and beat tracking: http://www.music-ir.org/mirex/wiki/MIREX_HOME

# Foote's Beat Spectrum

- Definition
  - Using the autocorrelation function, we can derive the beat spectrum [Foote et al., 2001]



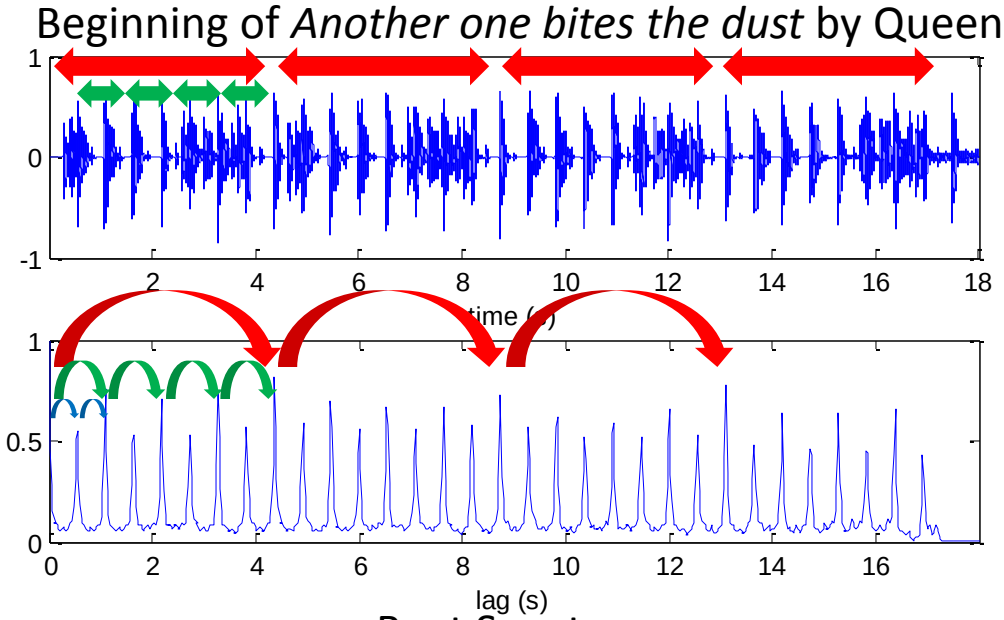
# Foote's Beat Spectrum

- Use
  - The beat spectrum reveals the hierarchically periodically repeating structure of the audio

Periodicity at the measure level

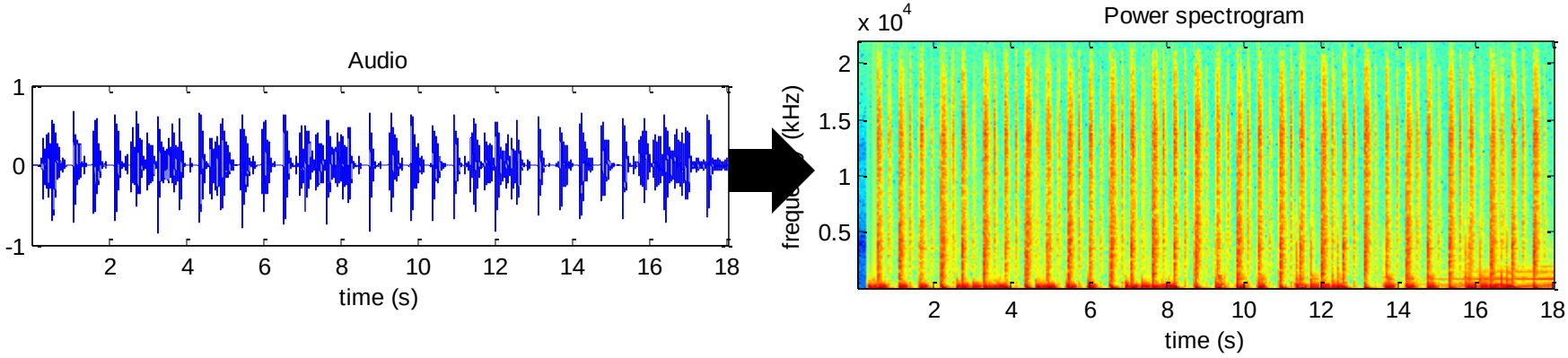
Sub-periodicity at the kick level

Sub-periodicity at the beat level



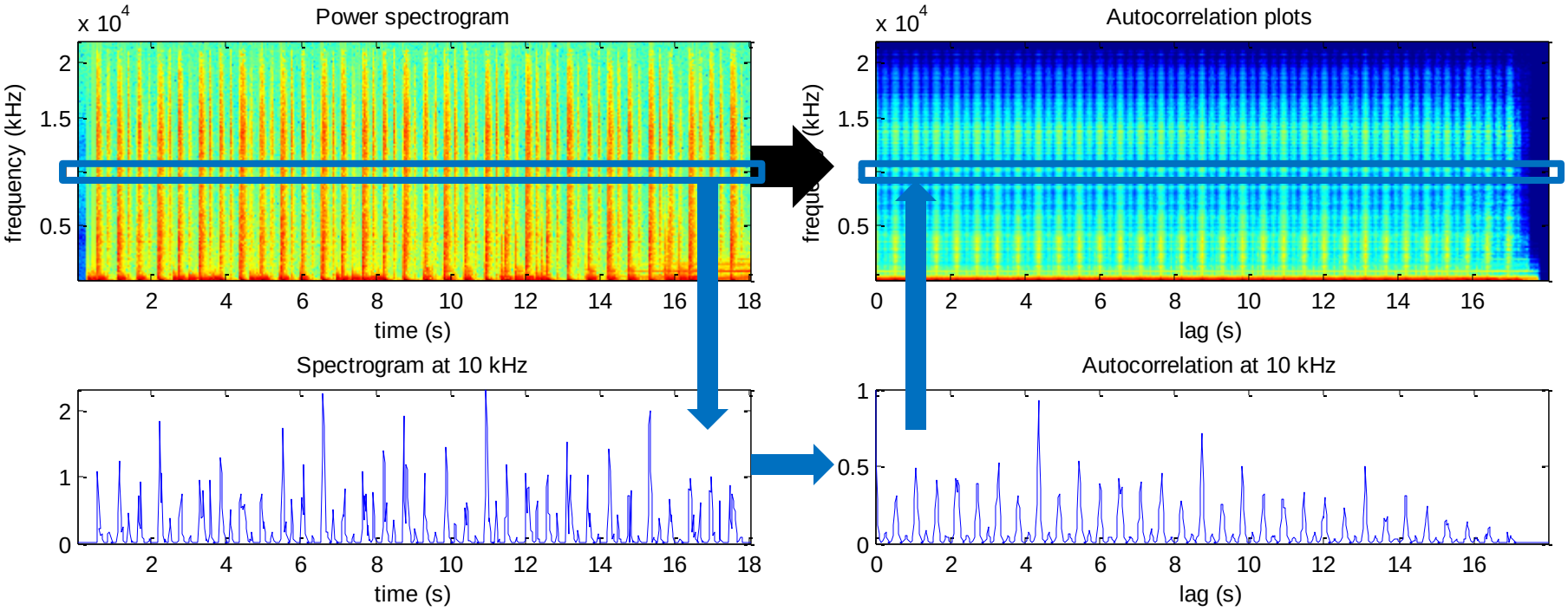
# Foote's Beat Spectrum

- Calculation
  - Compute the power spectrogram from the audio using the STFT (square of magnitude spectrogram)



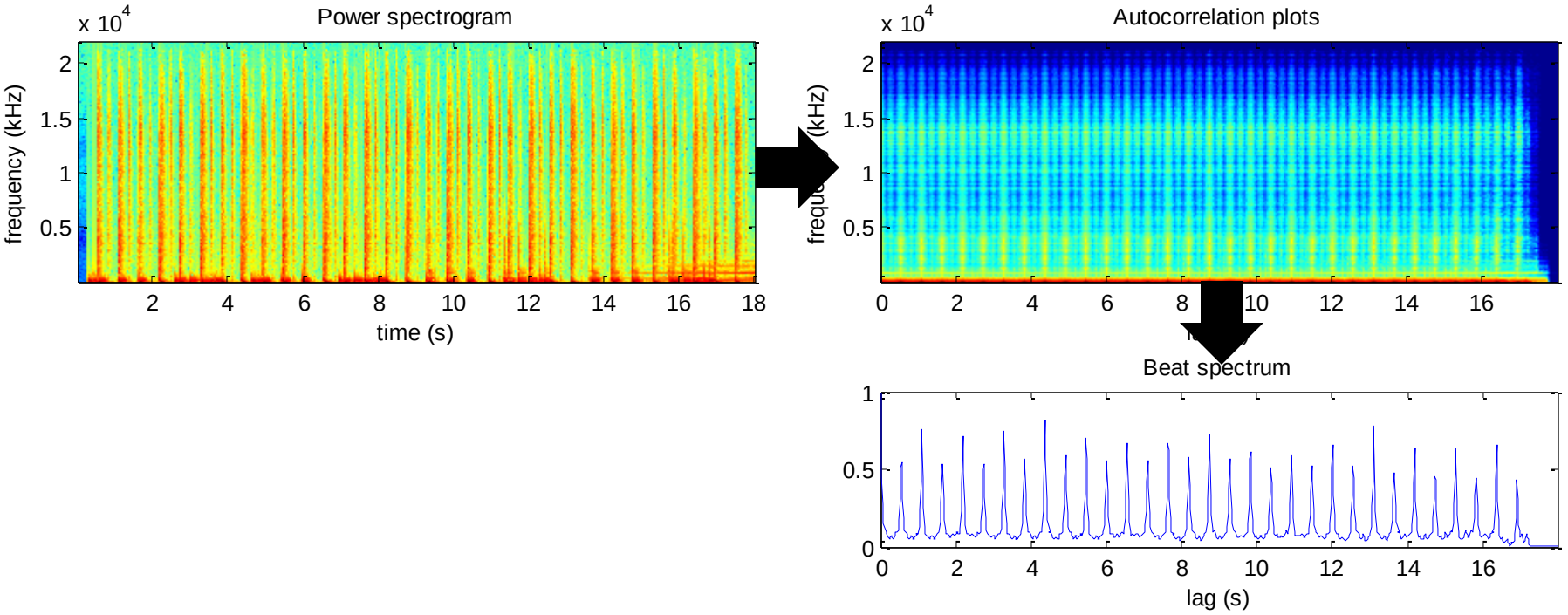
# Foote's Beat Spectrum

- Calculation
  - Compute the autocorrelation of the rows of the spectrogram



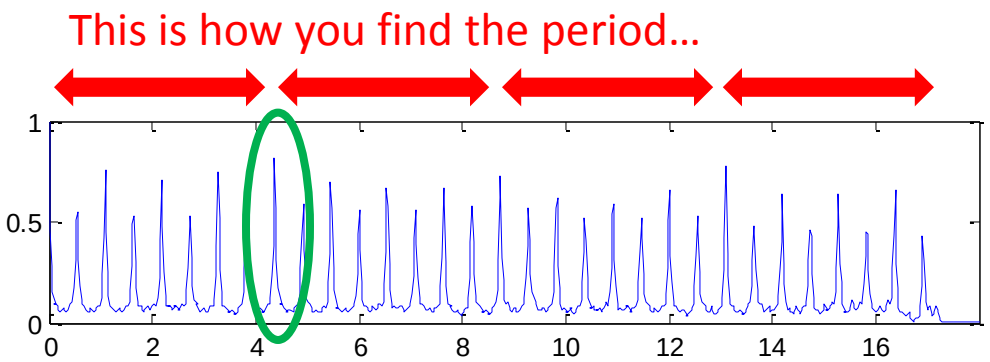
# Foote's Beat Spectrum

- Calculation
  - Compute the mean of the autocorrelations (of the rows)



# Foote's Beat Spectrum

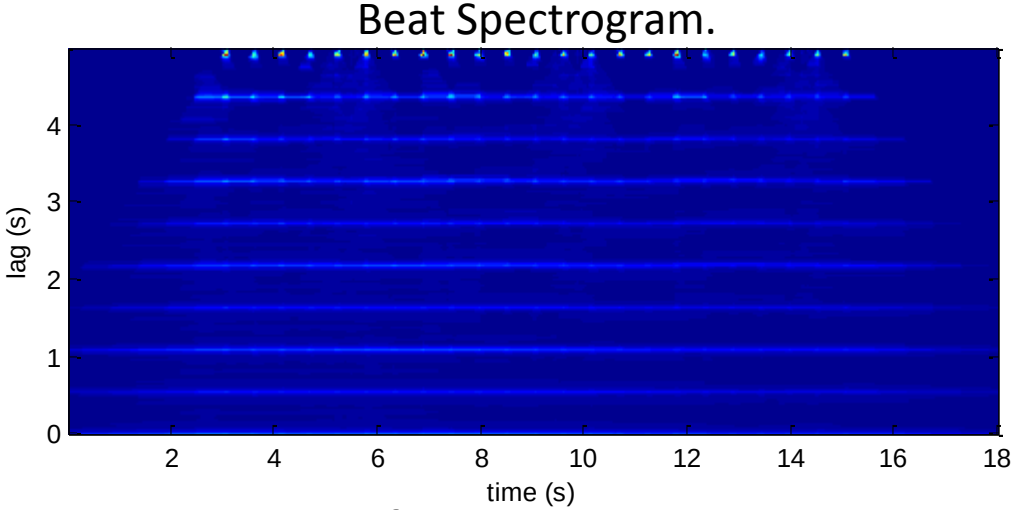
- Notes
  - The first highest peak in the beat spectrum does not always correspond to the repeating period!
  - The beat spectrum does not indicate where the beats are or when a measure starts!




Beat Spectrum.

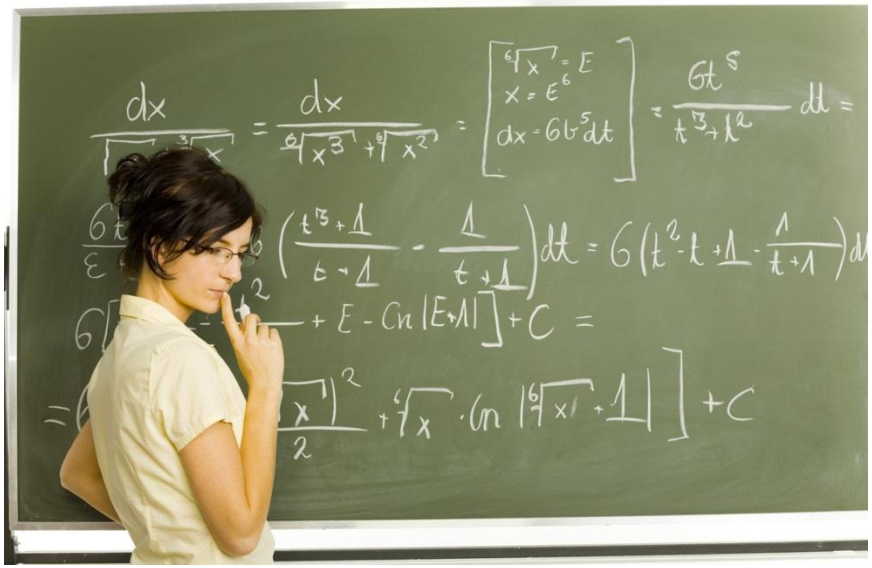
# Foote's Beat Spectrum

- Notes
  - The beat spectrum can also be built using the *similarity matrix* [Foote et al., 2001]
  - A *beat spectrogram* can also be built using successive beat spectra [Foote et al., 2001]



# Foote's Beat Spectrum

- Question
  - Can we use the beat spectrum for source separation?...
  - To be continued…



# References


- R. B. Dannenberg, “Music Understanding by Computer,” *1987/1988 Computer Science Research Review*, Carnegie Mellon School of Computer Science, pp. 19-28, 1987.
- J. Foote, “Visualizing Music and Audio using Self-Similarity,” in *7th ACM International Conference on Multimedia (Part 1)*, Orlando, FL, USA, pp. 77-80, October 30-November 05, 1999.
- J. Foote, “Automatic Audio Segmentation using a Measure of Audio Novelty,” in *IEEE International Conference on Multimedia and Expo*, New York, NY, USA, vol.1, pp. 452-455, July 30-August 02, 2000.
- J. Foote and S. Uchihashi, “The Beat Spectrum: A New Approach to Rhythm Analysis,” in *IEEE International Conference on Multimedia and Expo*, Tokyo, Japan, pp. 881-884, August 22-25, 2001.
- M. Goto, “An Audio-based Real-time Beat Tracking System for Music With or Without Drum-sounds,” *Journal of New Music Research*, vol. 30, no. 2, pp. 159-171, 2001.
- D. P. W. Ellis, “Beat Tracking by Dynamic Programming,” *Journal of New Music Research*, vol. 36, no. 1, pp. 51-60, 2007.
- M. Müller, D. P. W. Ellis, A. Klapuri, and G. Richard, “Signal Processing for Music Analysis,” *IEEE Journal of Selected Topics in Signal Processing*, vol. 5, no. 6, pp. 1088-1110, October 2011.
- Wikipedia, “Rhythm,” http://en.wikipedia.org/wiki/Rhythm, 2012.
- Wikipedia, “Meter,” http://en.wikipedia.org/wiki/Metre_(music), 2012.

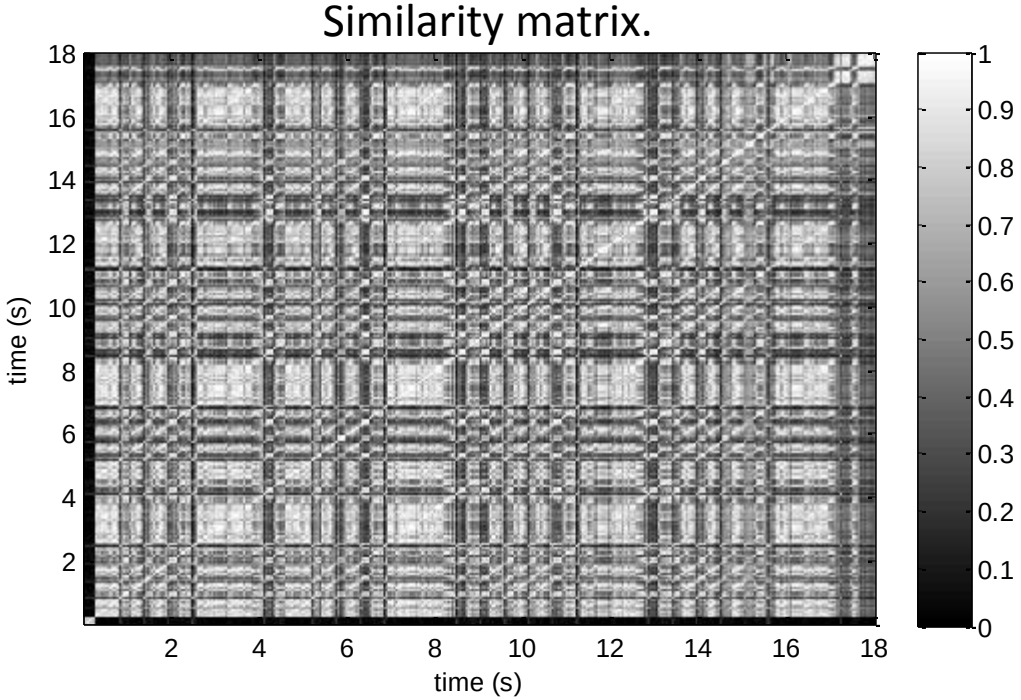
# The Similarity Matrix

- Calculation
  - The similarity matrix S of X is basically the matrix multiplication between transposed X and X, after (generally) normalization of the columns of X

$$S(j_1, j_2) = \frac{\sum_{k=1}^{n} X(k,j_1)X(k,j_2)}{\sqrt{\sum_{k=1}^{n} X(k,j_1)^2}\sqrt{\sum_{k=1}^{n} X(k,j_2)^2}}$$

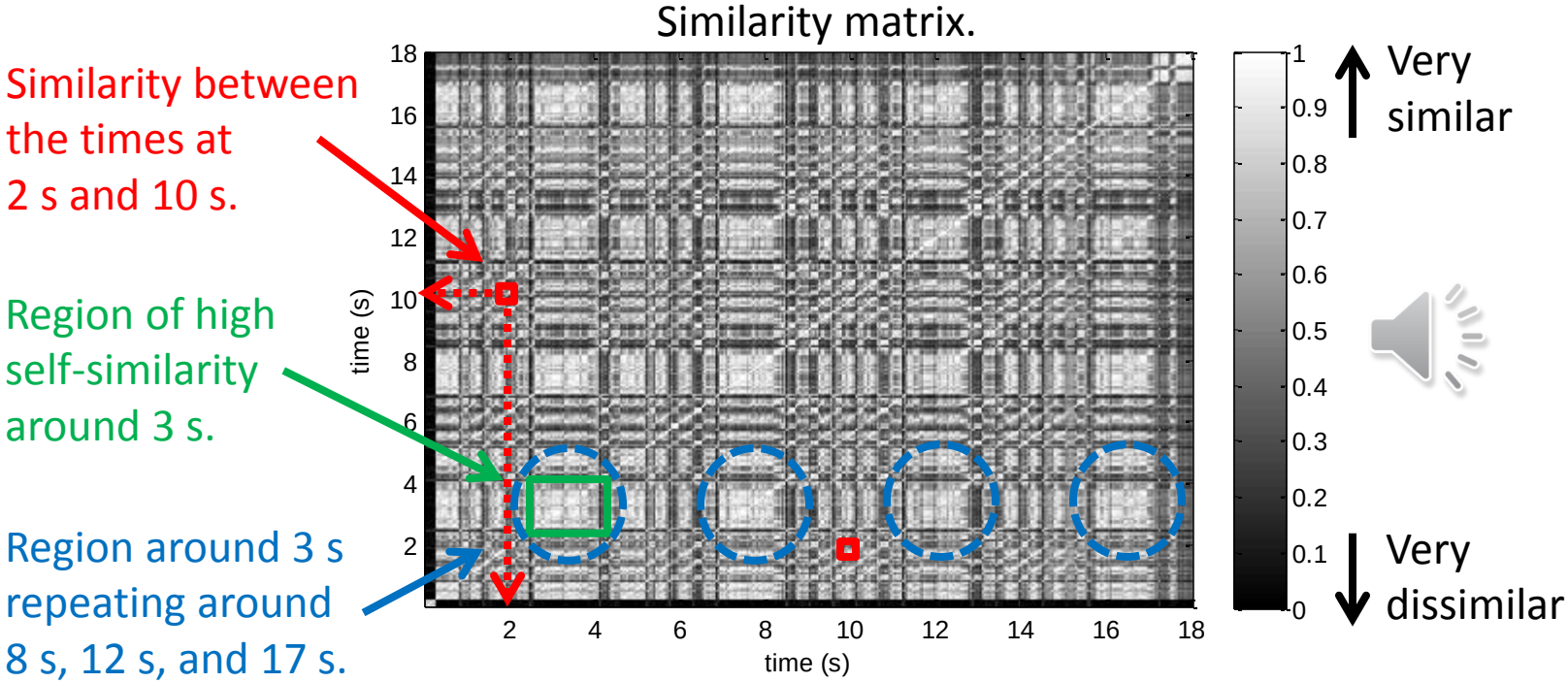
# The Similarity Matrix

- Definition
  - Matrix where each point measures the similarity between any two elements of a given sequence



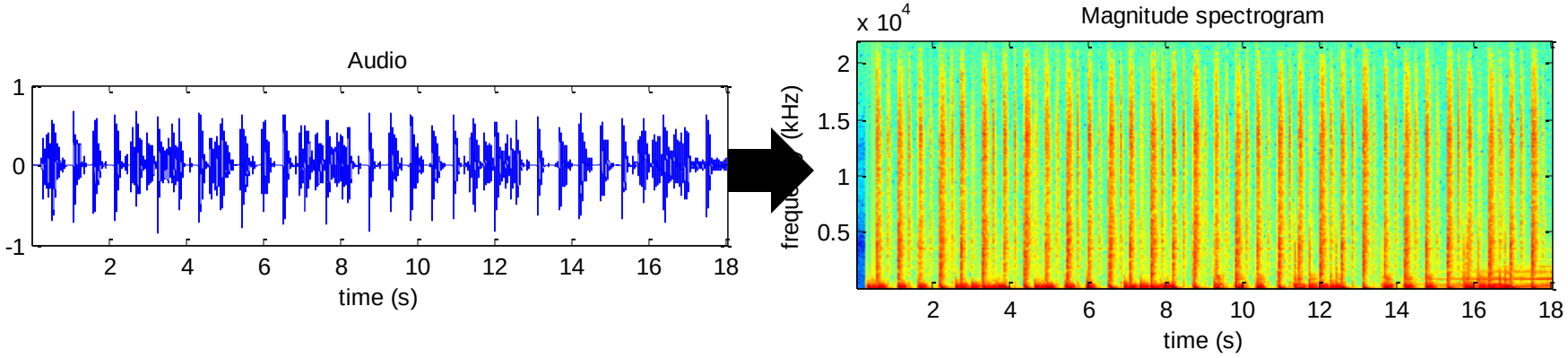
# The Similarity Matrix

- Use
  - Visualize time structure of an audio [Foote, 1999]
  - Identify repeating/similar patterns



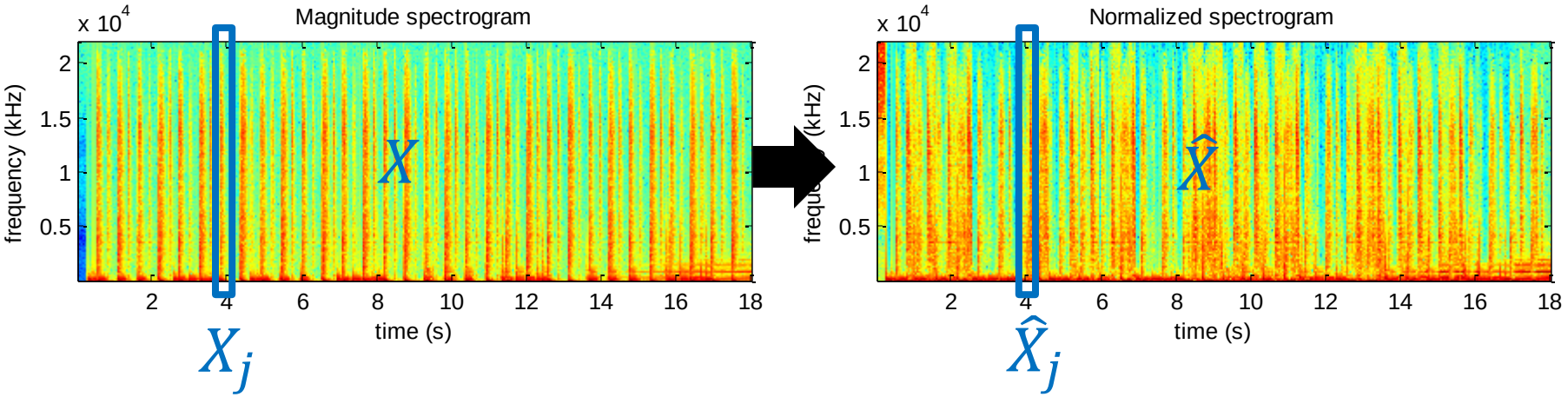
# The Similarity Matrix

- Calculation
  - Compute the magnitude spectrogram from the audio using the STFT



# The Similarity Matrix

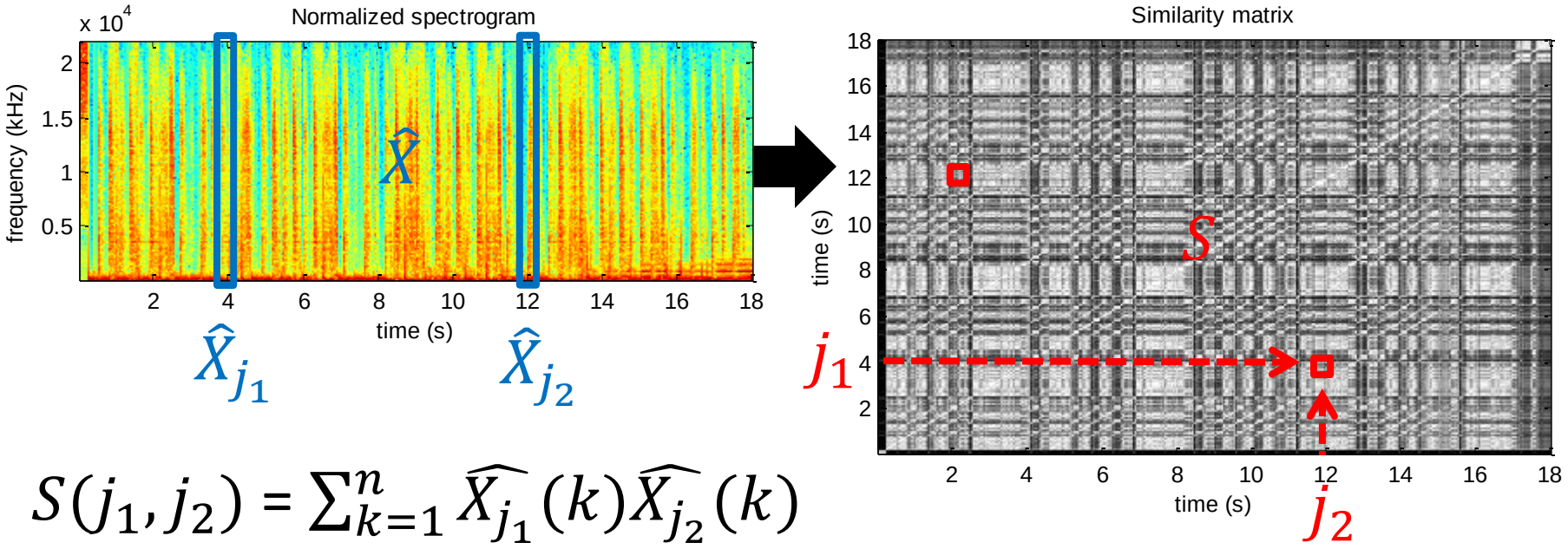
- Calculation
  - Normalize the columns of the spectrogram by dividing them by their Euclidean norm




$$\hat{X}_j(i) = \frac{X_j(i)}{\sqrt{\sum_{k=1}^{n} X_j(k)^2}}$$

# The Similarity Matrix

- Calculation
  - Compute the dot product between any two pairs of columns and save them in the similarity matrix




$$S(j_1, j_2) = \sum_{k=1}^{n} \widehat{X_{j_1}}(k)\widehat{X_{j_2}}(k)$$

# The Similarity Matrix

- Notes
  - The similarity matrix can also be built from other features (e.g. MFCCs, chromagram, pitch contour)
  - The similarity matrix can also be built using other measures (e.g. Euclidean distance)