



Introduction to **Audio Content Analysis**

module 9.5: tempo detection

alexander lerch

introduction

overview

corresponding textbook section

section 9.5

■ lecture content

- introduction to tempo detection and beat tracking
- overview over basic approaches
- typical challenges

■ learning objectives

- discuss advantages and disadvantages for different approaches to tempo detection and beat tracking
- summarize the typical challenges of beat tracking systems



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tempo detection & beat tracking

problem statement

■ tempo detection

- detect speed of regular pulse (foot-tapping rate)

■ beat tracking

- detect the time instances the tempo pulses occur (beat phase)

tempo detection & beat tracking

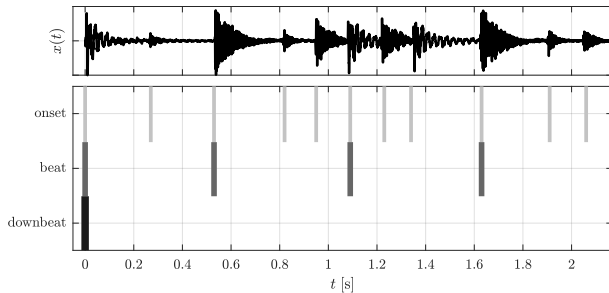
introduction

■ objectives

- 1 find the tempo from the novelty function/onsets
- 2 find the beat locations

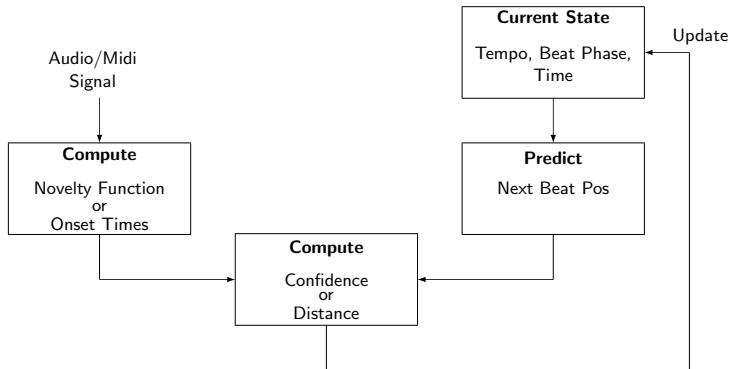
■ systematic problems:

- 1 distinguish *hierarchical levels*
 - ▶ meter
 - ▶ beat
 - ▶ subbeat/tatum
- 2 detect *beats without onsets*
- 3 recognize *onsets without beats*



tempo detection & beat tracking

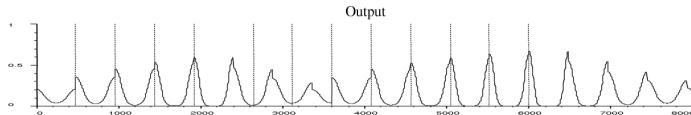
typical beat tracking system



tempo detection & beat tracking

oscillator approach

Beat tracking with an oscillator¹



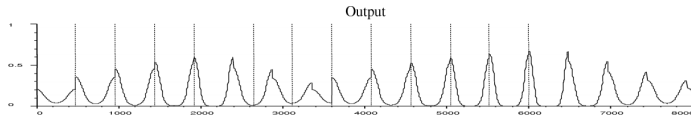
- 1 initialize pulse generator (tempo estimate, beat position estimate)
- 2 predict next beat location with pulse
- 3 adapt acc. to distance (predicted vs. real onset position)
 - beat period
 - beat phase
- 4 predict with adapted settings
- 5 adapt ...

¹E. W. Large, "Beat Tracking with a Nonlinear Oscillator," in *Proceedings of the 14th International Joint Conference on Artificial Intelligence (IJCAI)*, Montreal, Aug. 1995.

tempo detection & beat tracking

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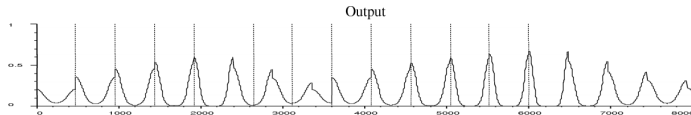
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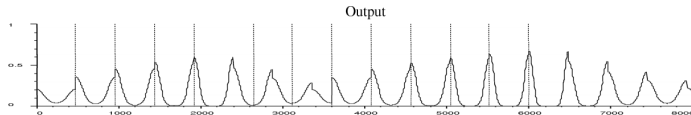
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tempo detection & beat tracking

oscillator approach: initialization

How to estimate the initial tempo



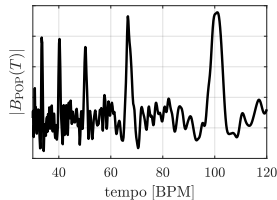
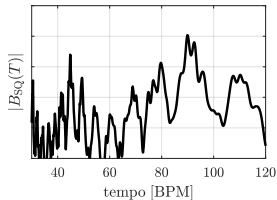
tempo detection & beat tracking

oscillator approach: initialization



How to estimate the initial tempo

- location of maximum of **ACF** of novelty function
- maximum of **IOI histogram**



- maximum of **beat spectrum/histogram**
- ...

tempo detection & beat tracking

multi-agent approach

1 run **multiple beat trackers** with different parameters

- initial tempo
- initial beat phase
- adaptation speed

2 compute reliability/**confidence** criteria:

- match beat and onset times
- tempo stability
- majority of different agents
- ...

3 choose **most reliable agent** (or path between agents)

tempo detection & beat tracking

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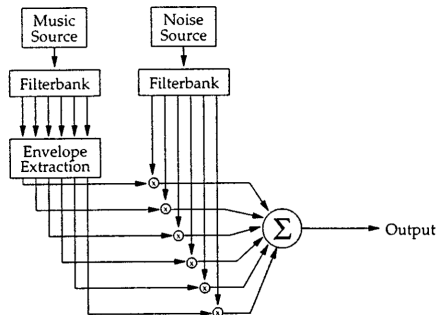
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tempo detection & beat tracking

filterbank approach

- 1 design **filterbank** (e.g. comb resonators spaced 1 beat)
- 2 compute filter output energy
- 3 pick maximum



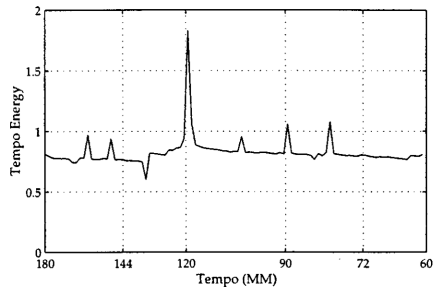
plots by Scheirer²

²E. D. Scheirer, "Tempo and beat analysis of acoustic musical signals," *Journal of the Acoustical Society of America (JASA)*, vol. 103, no. 1, pp. 588–601, 1998.

tempo detection & beat tracking

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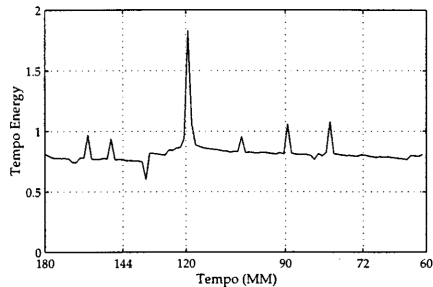
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tempo detection & beat tracking

template-based approach

- 1 define set of **template pulses** in all tempi
- 2 compute CCF between novelty function (or its ACF) and all templates
- 3 choose template with highest correlation as tempo
- 4 choose lag with highest correlation as beat phase

tempo detection & beat tracking

typical problems

- 1 tempo: detection of **double/half tempo** (triple, ...)
- 2 phase: detection of **off-beats**
- 3 tempo & phase: strongly depends on **initialization values**
- 4 tempo & phase: only **slow adaptation** — no sudden tempo changes

example: challenges with adaptation speed



tempo detection & beat tracking

evaluation

■ evaluation of **constant tempo**

- match within tempo range \Rightarrow classification metrics

■ evaluation of **beat tracking**

- ground truth can be subjective (double/half tempo, deviations)
- each beat matched against ground truth
 - ▶ challenge 1: tolerance window definition (tempo dependent or not?)
 - ▶ challenge 2: slightly different tempo might lead to gap between metrics and perceptual severity

■ **typical errors**

- double/half tempo (sometimes also 3/2 relationships)
- off-beat
- problems with abrupt tempo changes

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summary

lecture content

■ tempo analysis

- similar to pitch detection on a different scale
 - ▶ periodicity analysis of novelty function
 - ▶ time or spectral domain

■ typical approaches

- oscillator
- histogram/beat spectrum
- template correlation

■ main challenges

- double/half tempo
- adaptation to sudden tempo changes

