CTP431: Fundamentals of Computer Music

Time Scale Modification and Pitch Shifting

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Outlines

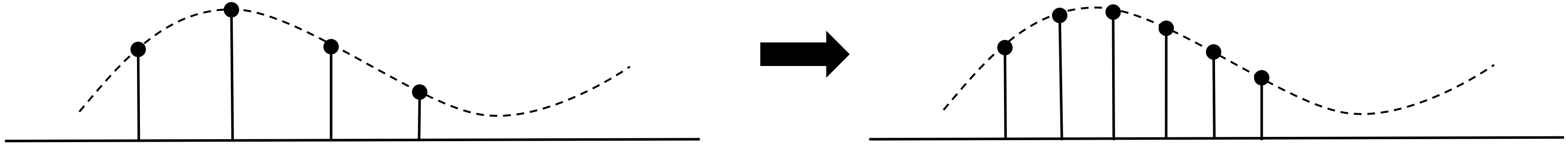
- Understanding the algorithms to change pitch or length (or time-scale) of audio waveforms
    - Resampling
    - Time-scale modification (or time stretching)
    - Pitch shifting

Resampling (Playback Rate Conversion)

- "Playback rate" is not necessarily equal to the recording rate
- Adjusting the playback rate given the recorded audio change the tone
  - Sliding tapes on the magnetic header in a variable speed
  - Speeding down: "monster-like"
  - Speeding up: "chipmunk-like"
  - It can be even negative rate: reverse playback
- Demo
  - https://musiclab.chromeexperiments.com/Voice-Spinner

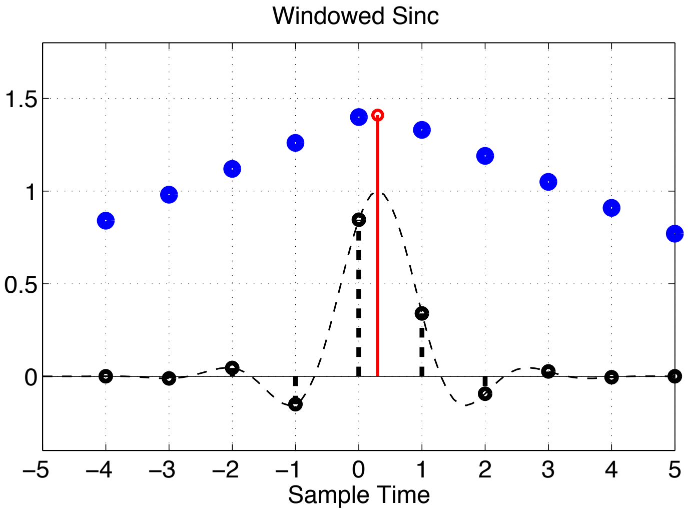
Playback Rate Conversion (Resampling)

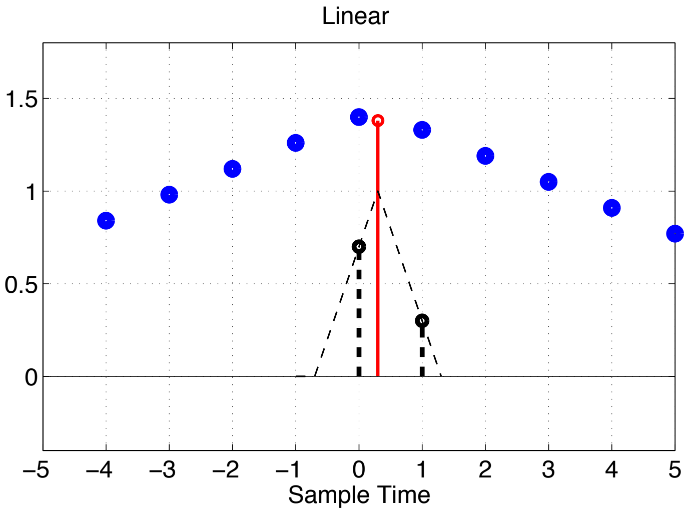
- Reconstruct the original signal and sample it with a new rate



- For a digital system with a constant playback rate
  - **Up-sampling** makes the original sound **played slower**
  - **Down-sampling** makes the original sound **played faster**

Interpolation Filters





Windowed Sync

Linear Interpolation

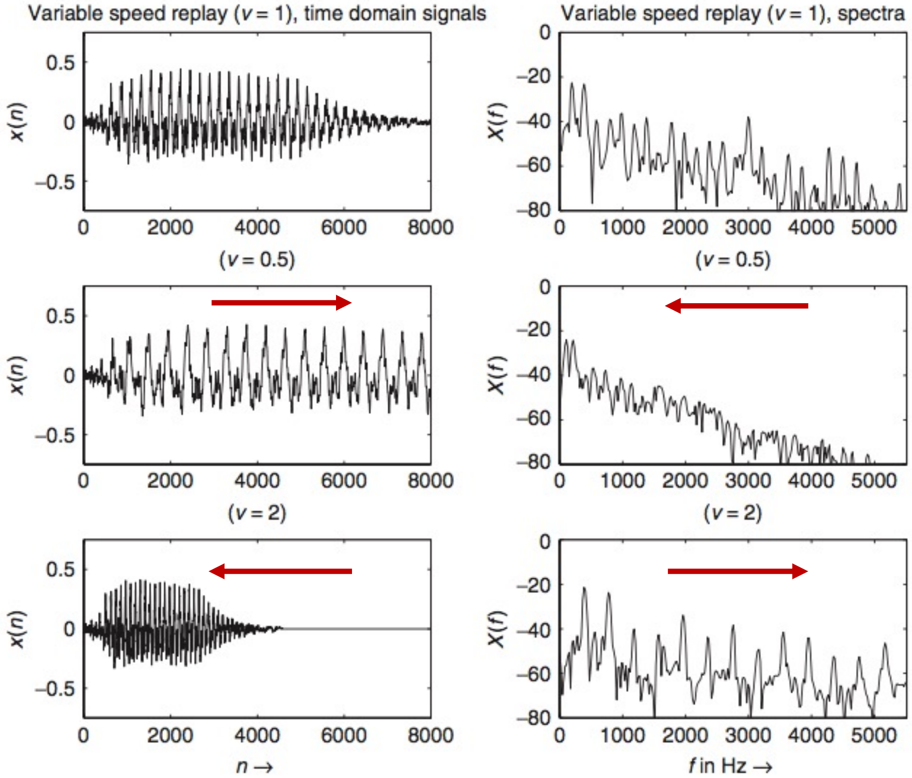
Resampling

- Resampling changes pitch, length and timbre at the same time!

Original

Speed Down
(Up-sampling)

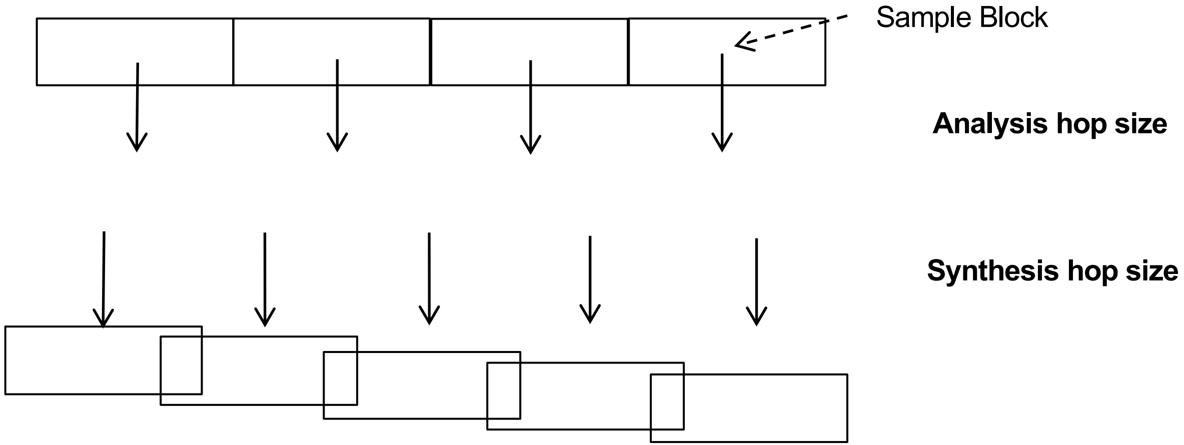
Speed Up
(Down-sampling)



[The DaFX book]

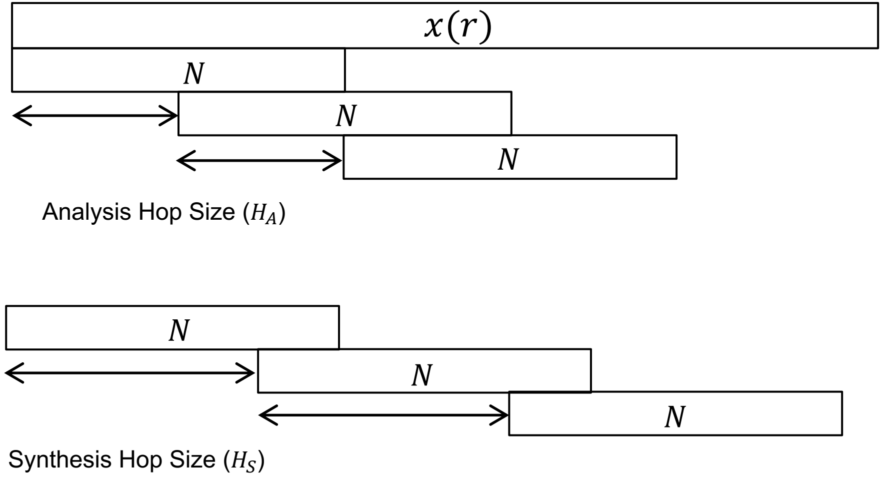
How can we control pitch and length independently?

- The secret is processing samples in frame-level instead of sample-level
  - The waveform is locally preserved within the frame
  - Analysis hop size and synthesis hop size are distinguished



Fundamental of Time-Scale Modification

- Analysis-Resynthesis approach in a frame-by-frame manner



$$x_m(r) = \begin{cases} x(r + mH_A), & \text{if } r \in [-\frac{N}{2} : \frac{N}{2} - 1] \\ 0, & \text{otherwise.} \end{cases}$$

$$\downarrow$$

$$\mathcal{F}: x_m(r) \to y_m(r)$$

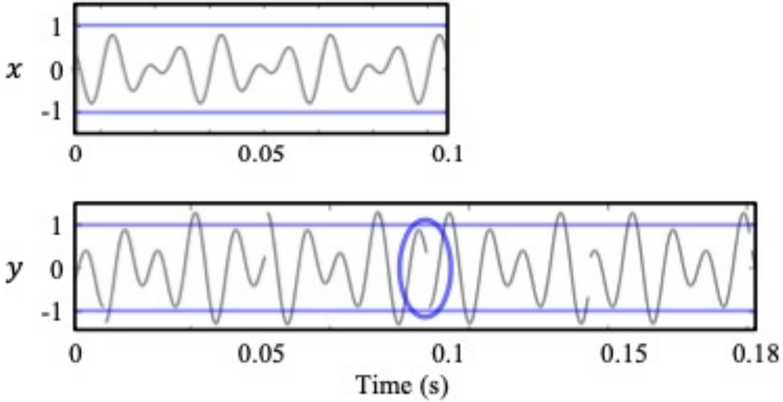
$$\downarrow$$

$$y(r) = \sum_{m \in \mathbb{Z}} y_m(r - mH_S)$$

  - Time-stretching ratio: $\alpha = \frac{H_S}{H_A}$ (H_S: synthesis hop size, H_A : analysis hop size)
  - If $\alpha > 1$, increase the length, If $\alpha < 1$, reduce the length

Fundamental of Time-Scale Modification (TSM)

- If the analysis frame $x_m(r)$ is the same as the synthesis frame $y_m(r)$?
  - Discontinuity at the boundary of the unmodified frames
  - Overlapping of the synthesis frame changes the amplitude



Time-scale modification with α=1.8 [Driedger and Müller, 2016]

OverLap-and-Add (OLA)

- Enforce a smooth transition between frames and compensate the amplitude change
  - Applying a window function w to the analysis frame: e.g. Hann window

$$w(r) = \begin{cases} 0.5(1 - \cos(\dfrac{2\pi(r + N/2)}{N-1})), & \text{if } r \in [-\frac{N}{2} : \frac{N}{2} - 1] \\ 0, & \text{otherwise.} \end{cases}$$

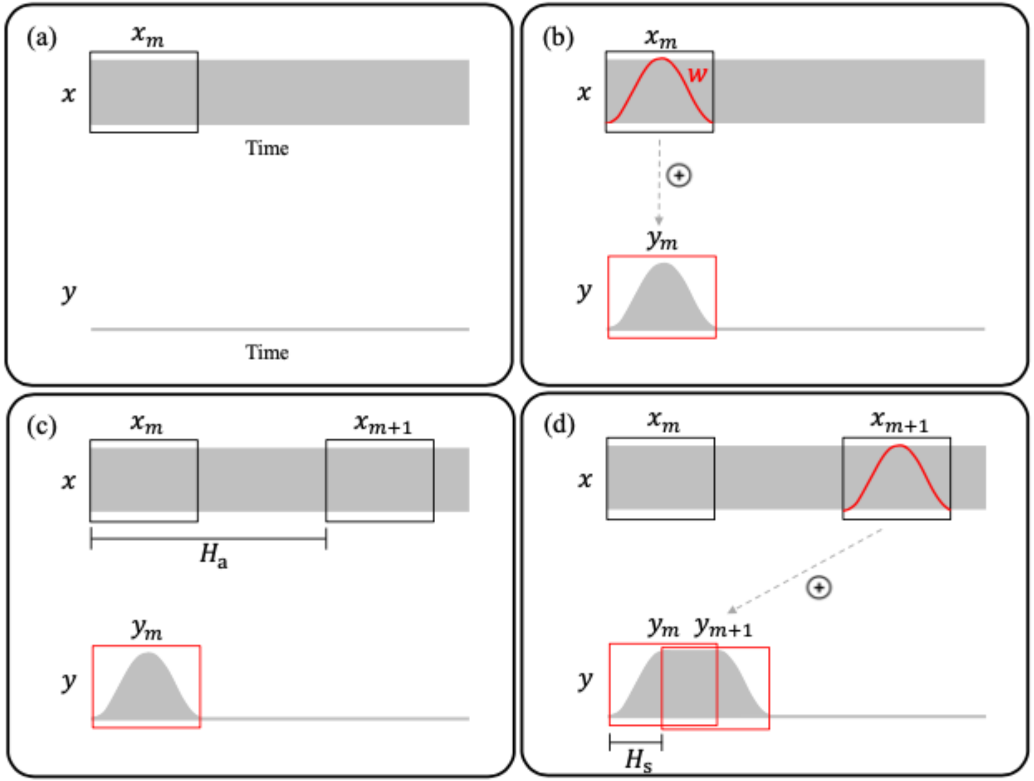
  - The Hann window has the following property for all r ∈ $\mathbb{Z}$

$$\sum_{n \in \mathbb{Z}} w\ (r - n\frac{N}{2}) = 1$$

  - The synthesis frame is computed as a windowed analysis frame with the amplitude normalization

$$y_m(r) = \frac{w(r)\ x_m(r)}{\sum_{n \in \mathbb{Z}} w\ (r - nH_S)}$$

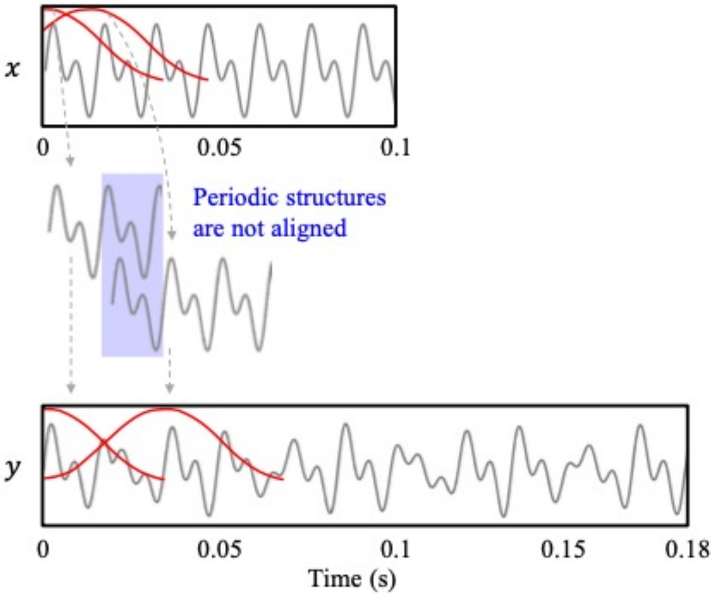
OverLap-and-Add (OLA)



Overlap and Add TSM [Driedger and Müller, 2016]

OverLap-and-Add (OLA)

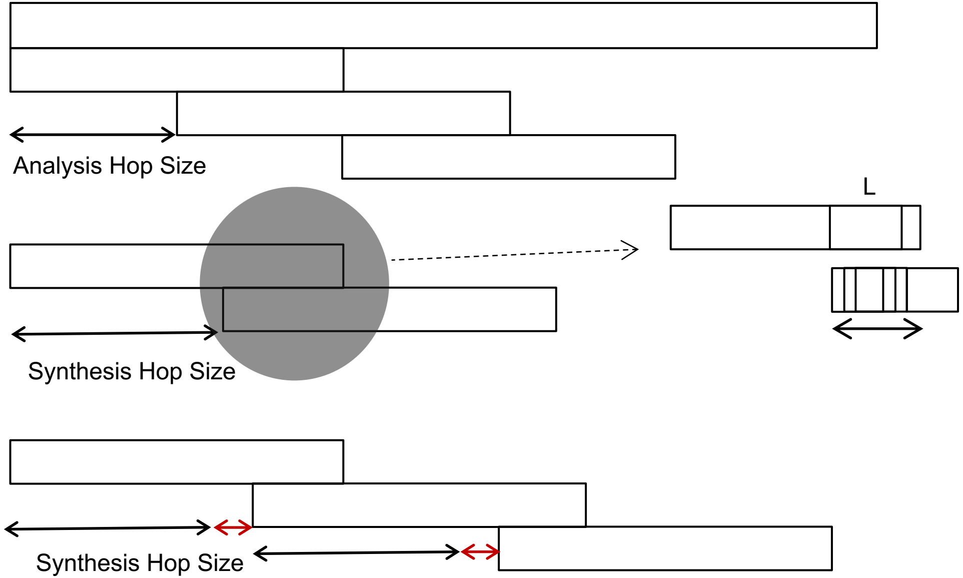
- However, OLA has a problem for periodic signals
  - They are called **phase jump artifacts**



Overlap and Add TSM [Driedger and Müller, 2016]

Synchronized OverLap-and-Add (SOLA)

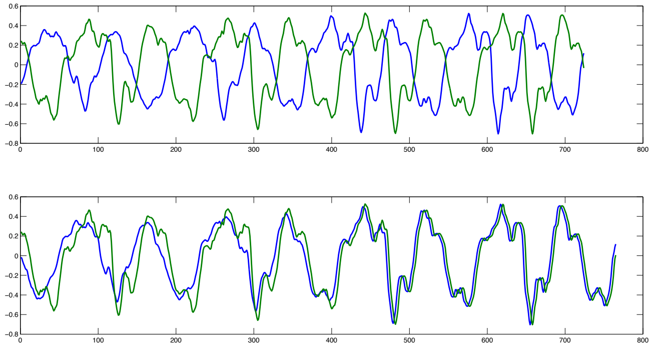
- Reduce artifacts in OLA by shifting the overlapped region such that the two adjacent frames are maximally correlated



Shift the next frame by the lag

Synchronization by cross-correlation

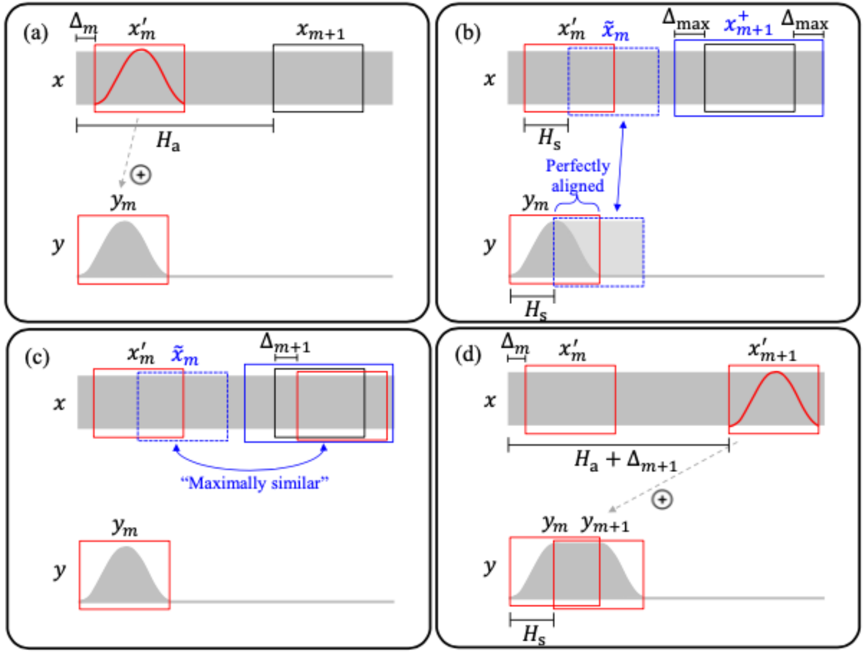
$$X_{corr}(l) = \sum_{n=0}^{n=L-1} x_1(n)x_2(n+l)$$



Find the lag (*l*) where the cross correlation is maximum

Waveform Similarity OverLap-and-Add (WSOLA)

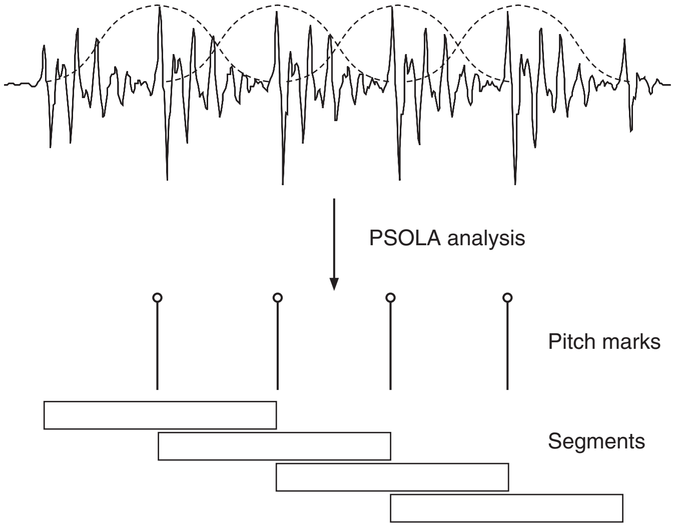
- A variant of SOLA that adjusts the analysis hop size



WSOLA TSM [Driedger and Müller, 2016]

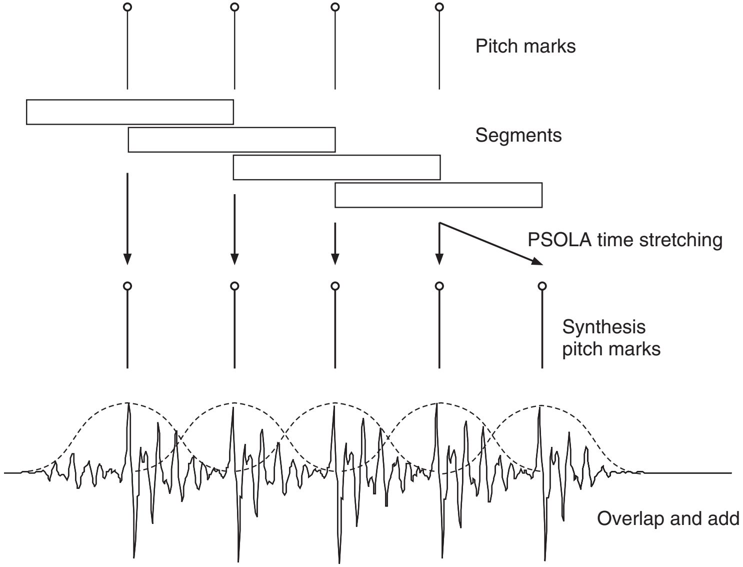
Pitch-Synchronous OLA (PSOLA)

- The analysis and synthesis hop size is synchronized to estimated pitch
- Analysis
  - Perform block-based pitch detection and find pitch marks t_i
    - Pitch period: $P(t) = t_{i+1} - t_i$
  - Extract a segment centered at every pitch mark t_i using a Hanning window with length $L_i = 2P(t_i)$ to ensure fade-in and fade-out



Pitch-Synchronous OLA (PSOLA)

- Synthesis for time-stretching
  - For every synthesis pitch mark $\tilde{t}_k$, search the corresponding t_i that minimizes $|\alpha t_i - \tilde{t}_k|$
  - Overlap and add the selected segment
    - If $\alpha > 1$, some segments will be repeated
    - If $\alpha < 1$, some segments will be discarded
  - The next synthesis pitch mark $\tilde{t}_k$ is determined to preserve local pitch
    - $\tilde{t}_{k+1} = \tilde{t}_k + \tilde{P}(\tilde{t}_k) = \tilde{t}_k + P(t_i)$



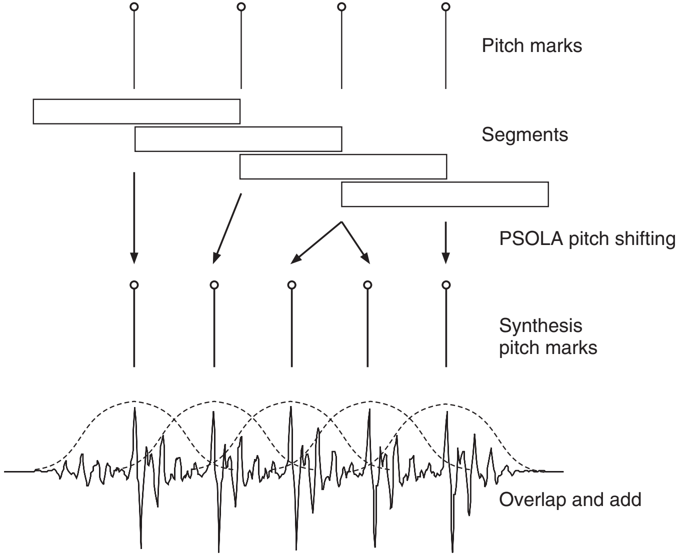
Pitch-Shifting

- TSM followed by Resampling
  - First, perform time-stretching with a ratio of α
  - Second, resampling the output with the same ratio of α

- Problem
  - Timbre (i.e. formant) changes by the resampling
  - This is quite audible for human voice (e.g. speech or singing)

Pitch-Shifting

- PSOLA can be used for pitch-shifting
    - For every synthesis pitch mark $\tilde{t}_k$, search the corresponding t_i that minimizes $|t_i - \tilde{t}_k|$
    - Overlap and add the selected segment
        - If $\beta > 1$, some segments will be repeated
        - If $\beta < 1$, some segments will be discarded
    - The next synthesis pitch mark $\tilde{t}_k$ is determined to preserve local pitch
        - $\tilde{t}_{k+1}$= $\tilde{t}_k + \tilde{P}(\tilde{t}_k)$=$\tilde{t}_k + P(t_i)/\beta$
    - It is possible to combine the time-stretching (with the term $|\alpha t_i - \tilde{t}_k|$) and pitch-shifting
    - This preserves the formant of the input sound!



Ambient Sound Design Using Paul’s Extreme Sound Stretch

- Extreme time scale modification (e.g. α = 50) with spectral smoothing can transform any sound/music into a texture or ambient sound
  - http://hypermammut.sourceforge.net/paulstretch/
  - https://cdm.link/2018/02/free-plug-brings-extreme-paulstretch-stretching-daw/

Resources

- Rubberband
  - https://breakfastquay.com/rubberband/

- PyTSMod
  - https://github.com/KAIST-MACLab/PyTSMod