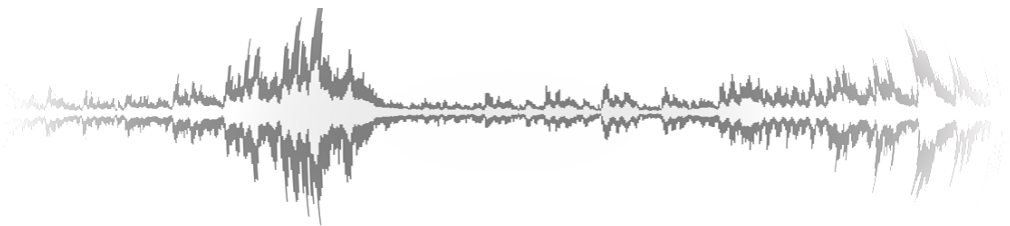
Digital Signal Processing for Music

Part 22: Time-stretching and Pitch-shifting

alexander lerch



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time stretching & pitch shifting

introduction

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- **time stretching**
  change playback speed/tempo without changing pitch
- **pitch shifting**
  change pitch without changing tempo/playback speed
- **terms**
  - time/pitch scaling
  - time expansion/compression

time stretching & pitch shifting

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- **educational software**: pitch and timing visualization

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stretch and pitch factors

$$s = \frac{t_{output}}{t_{input}}$$

$$p = \frac{f_{output}}{f_{input}}$$

examples:

- *half speed*: $s = 2$
- *half pitch*: $p = \frac{1}{2}$
- *semitone up/down*:

$$p_u = 2^{1/12} = 1.059 \quad p_d = 2^{-1/12} = 0.9439$$

- $100\,BPM \rightarrow 75\,BPM$: $s = \frac{4}{3}$

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resampling

- **traditional**: resampling
  - change inter-sample 'distance' by interpolation
  - keep playback sample rate constant
  - audio example
    - original
    - resample

⇒ tempo change results in pitch change (and vice versa)

$$s = \frac{1}{p}$$

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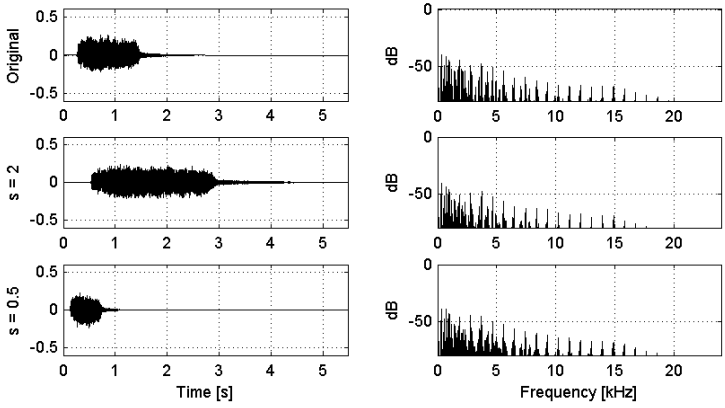
stretching: frequency domain



OLA

introduction

overlap and add approaches for, e.g.,

- granular synthesis
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overlap and add

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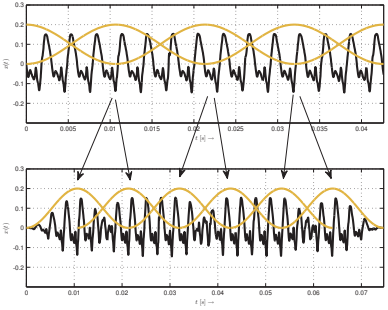

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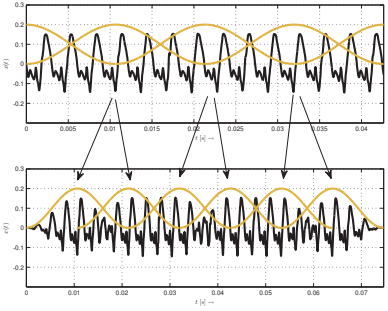

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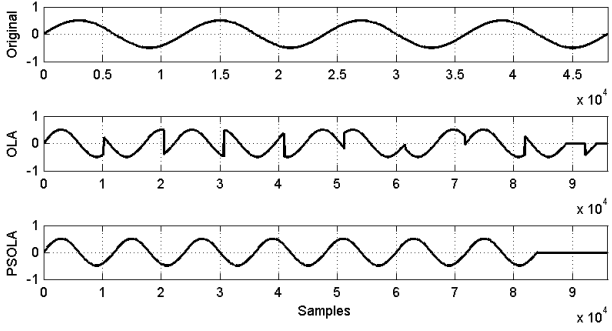
PSOLA

time stretching

pitch synchronous overlap and add

- use the OLA principle, but
- **adapt block length** to fundamental period length



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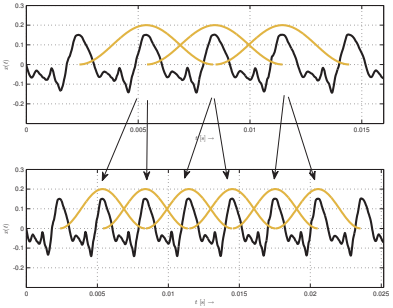

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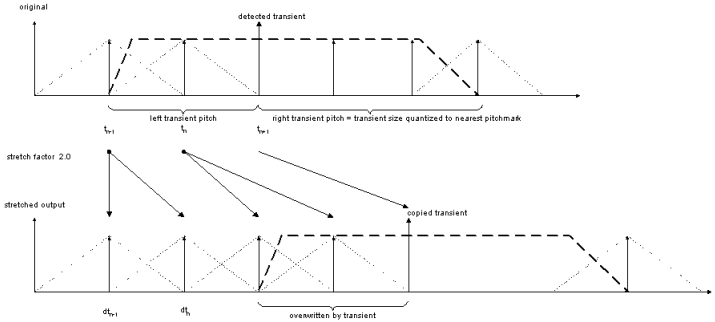
PSOLA

transient copying



PSOLA

time stretching summary

- **processing steps**
  1. detect *fundamental frequency*/period length
  2. set *pitch marks*
  3. intelligently *select blocks* to be repeated/discarded
- **advantages**
  - *high granularity* — modify audio on period length resolution
  - *high quality*
- **problems**
  - quality depends on *pitch tracking* reliability
  - quality and timbre depends on *pitch mark positioning*
  - works only for *monophonic* input signals
    - polyphonic and noisy segments
    - reverberation and overlapping tones
  - *noise*, *plosives* require special consideration
  - *copying* artifacts (double transients, timing deviations)
- **typical applications**
  - **standard approach for vocal editing tools**

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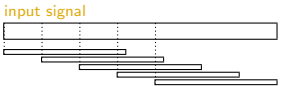
time stretching

phase vocoder

1. **split input** signal into overlapping blocks
2. compute **magnitude and phase spectrum** of each block
3. **change overlap ratio** between blocks depending on stretch factor
4. keep the magnitude, **adapt the phase per bin** to the block's new time stamp



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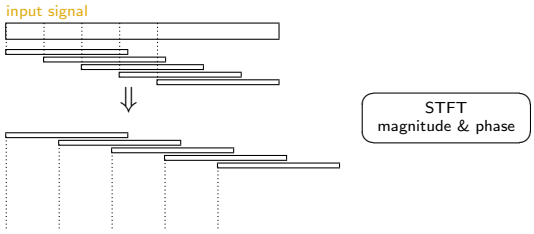

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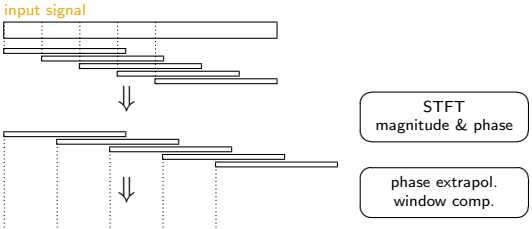

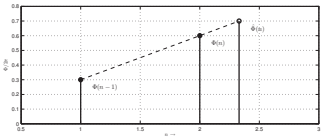

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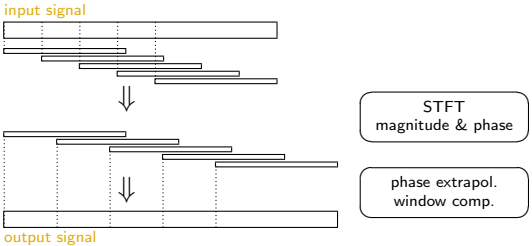
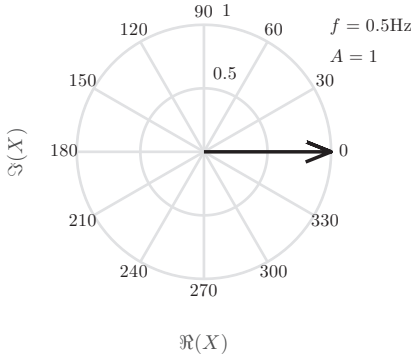


- original
- pv $s = 4/3$

time stretching

frequency reassignment: relation of phase and frequency 1/2

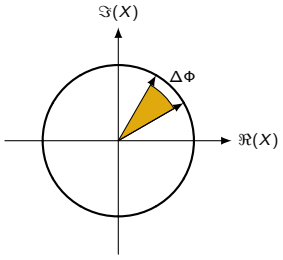


- phasor representation:
  1. sine value is defined by magnitude and phase
  2. decreasing the amplitude $\Rightarrow$ shorter vector
  3. increasing the frequency $\Rightarrow$ increasing speed

matlab source: matlab/animatePhasor.m

time stretching

frequency reassignment: relation of phase and frequency 2/2



- frequency and phase change closely related:
  - time for full rotation is period length T with

$$f = \frac{1}{T}$$

  - time for fractional rotation $\Delta\Phi$ is corresponding fraction of period length

$$f = \frac{\Delta\Phi}{\Delta t}$$

  - in other words:

$$\begin{aligned} \Phi(t) &= \omega \cdot t \\ \Rightarrow \frac{d\Phi(t)}{dt} &= \omega = 2\pi f \end{aligned}$$

time stretching

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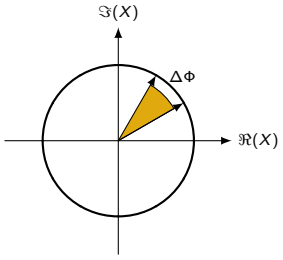

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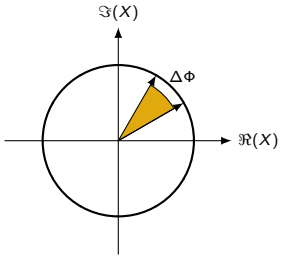

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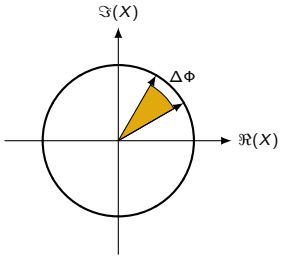

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frequency reassignment: principles

frequency domain:

- instead of using the bin frequency

$$f(k) = k * \frac{f_S}{\mathcal{K}}$$

- we use the phase of each bin $\Phi(k, n)$
- to compute the frequency from the phase difference of neighboring blocks

$$\omega_I(k, n) \propto \Phi(k, n) - \Phi(k, n-1)$$

- $\omega_I(k, n)$ is called **instantaneous frequency** per block per bin

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frequency reassignment: scaling factor

- instantaneous frequency calculation has to take into account
  - hop size $\mathcal{H}$
  - sample rate f_S

$$\omega_\mathrm{I}(k,n) = \frac{\Delta\Phi_\mathrm{u}(k,n)}{\mathcal{H}} \cdot f_\mathrm{S}$$

- problem: phase ambiguity

$$\Phi(k,n) = \Phi(k,n) + j \cdot 2\pi$$

$\Rightarrow$ *phase unwrapping*

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frequency reassignment: phase unwrapping

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1. compute unwrapped phase $\Phi_{\mathrm{u}}(k,n)$
   - estimate unwrapped bin phase

$$\hat{\Phi}(k,n) = \Phi(k,n-1) + \underbrace{2\pi k \cdot \frac{\mathcal{H}}{\mathcal{K}}}_{=\omega_k \cdot \frac{\mathcal{H}}{f_{\mathrm{S}}}}$$

   - unwrap phase by shifting current phase to estimate's range

$$\Phi_{\mathrm{u}}(k,n) = \hat{\Phi}(k,n) + \mathrm{princarg}\left[\Phi(k,n) - \hat{\Phi}(k,n)\right]$$

2. compute unwrapped phase difference

$$\begin{aligned}\Delta\Phi_{\mathrm{u}}(k,n) &= \Phi_{\mathrm{u}}(k,n) - \Phi(k,n-1)\\ &= \hat{\Phi}(k,n) + \mathrm{princarg}\left[\Phi(k,n) - \hat{\Phi}(k,n)\right] - \Phi(k,n-1)\\ &= \frac{2\pi k}{\mathcal{K}}\mathcal{H} + \mathrm{princarg}\left[\Phi(k,n) - \Phi(k,n-1) - \frac{2\pi k}{\mathcal{K}}\mathcal{H}\right]\end{aligned}$$

time stretching

frequency reassignment: phase unwrapping

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frequency reassignment: problems

- **overlapping spectral components**
  - sinusoidal components often overlap (spectral leakage, several instruments playing the same pitch, ...)
    - $\Rightarrow$ incorrect phase estimate
      - spectrum should be as sparse as possible, increase STFT length
- **inaccurate phase unwrapping**
  - unwrapping algorithm is based on assumption of similarity between predicted and measured phase
    - decrease hop size

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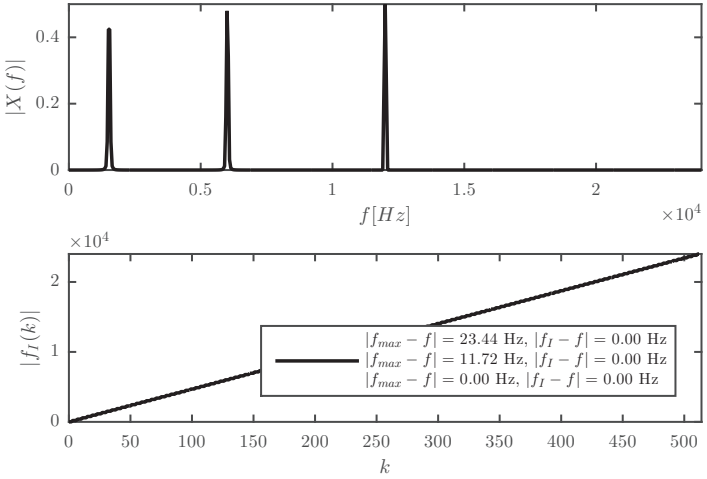
time stretching

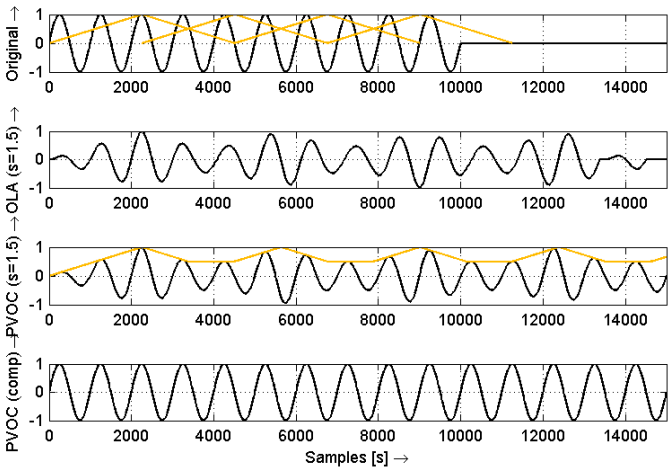
frequency reassignment: example



matlab source: matlab/displnstantaneousFreq.m

time stretching

phase vocoder window compensation



time stretching

phase vocoder — properties & artifacts

- **advantages**:
  - allows *polyphonic input* (assumption: no overlapping harmonics)
  - absolute *timing stability* (i.e., sample resolution)

- **disadvantages**:
  - *low granularity* — FFT block size
  - artifacts:
    1. phasing
    2. transient smearing/doubling

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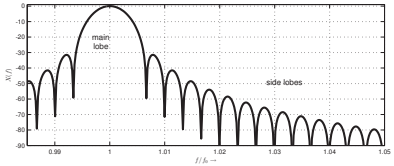
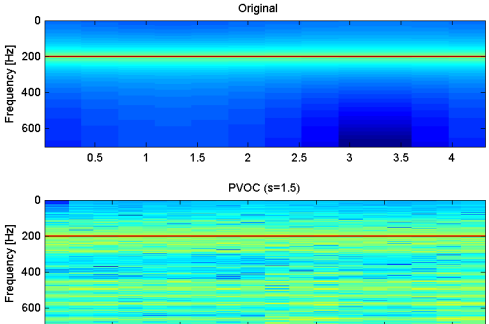
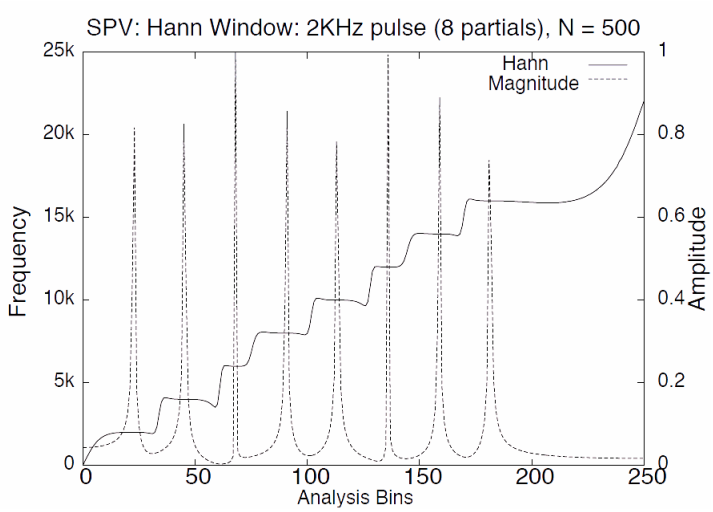




time stretching

phase vocoder artifacts: phasing — spectral leakage 2/3



time stretching

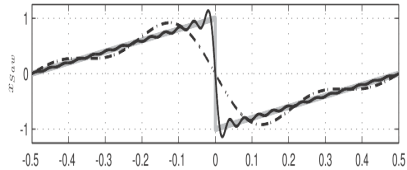
phase vocoder artifacts: phasing — spectral leakage 3/3

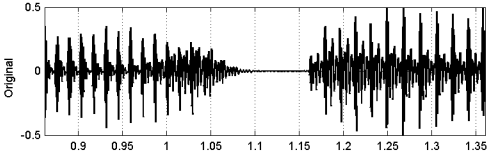
⇒ use *frequency reassignment* for grouping and phase sync

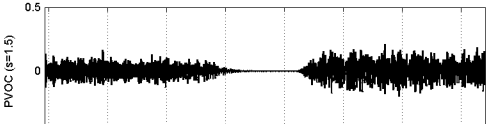
- original
- pv $s = 4/3$
- grouped phase

time stretching

phase vocoder artifacts: phasing — unsynced harmonics







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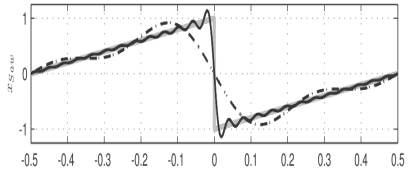

⇒ use *harmonic analysis* for grouping and phase sync

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phase vocoder artifacts: interchannel phasing

- phase estimation between channels slightly off due to
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  - overlapping frequency components

$\Rightarrow$ change in spatial image

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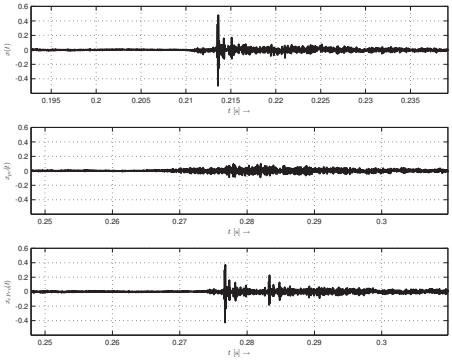

⇒ detect transients and *reset phase* per bin

- original
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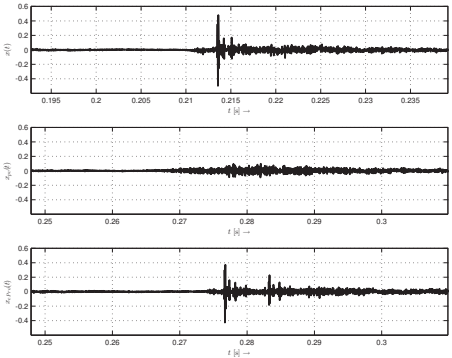
- phase reset

- original
- pv $s = 3/2$

time stretching

phase vocoder artifacts: transient smearing



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inherent problems

- stretching the audio data can lead to **“non-natural” results**

- **examples**
  - tempo dependent *timing variations*
  - other performance related aspects may get inappropriate lengths and speed: *vibrato, tremolo, glissando*

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pitch shifting

standard approach

- **definition**:
  change pitch without changing tempo
- **method**:
  combine stretching and *sample rate conversion* (interpolation)
  1. change length with stretching
  2. resample to compensate for length difference
- **implementation**: differentiate "external" and "internal" parameters
  - *extern*: stretch s_e and pitch p_e
  - *intern*: stretch s_i and resample r_i
- **example**: pitch shift factor $p = 4/3$
  1. *time stretch* (increase length/decrease tempo) $s = 4/3$
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  - audio:
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standard approach: stretch, pitch, resample factor examples

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  intern: $s_i = 4$ $r_i = \frac{1}{2}$

pitch shifting

frequency domain approach

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2. magnitude and phase
3. magnitude and instantaneous frequency
4. resample both magnitude and frequency spectrum acc. to pitch factor
5. magnitude and phase
6. complex spectrum
7. IFFT and OLA

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- **idea**
  - signal is pulse train filtered by transfer function
    - pulse train determines fundamental frequency
    - transfer function determines formant shape/timbre characteristics
- **approach**
  - change grain/pulse distance
  - grain "content" not modified
    $\rightarrow$ freq domain not modified

$\Rightarrow$ **"same" spectrum, different pitch**

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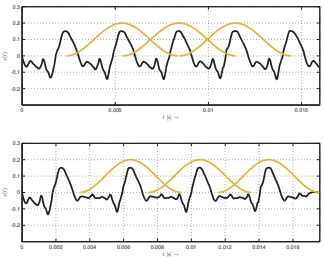

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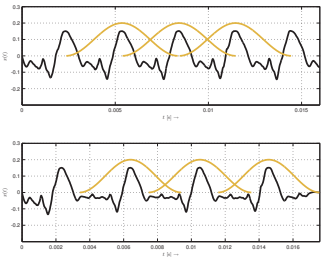

pitch shifting

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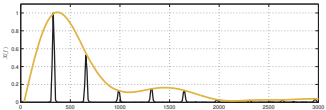

pitch shifting

spectral envelope estimate

- **approaches**
  - LPC coefficients
  - spectral maxima

- **potential issues**
  - *polyphonic input* audio: 'superposition' of envelopes
  - *very high/low pitch factors*: high frequency boost/cut
  - *estimate resolution*
    - too coarse → loss of timbre characteristics
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pitch shifting

audio examples

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	OLA	PSOLA	PVOC
orig			
resample $p = 4/3$			
formant $p = 4/3$			

summary

time stretching and pitch shifting

- pitch stretching and pitch shifting are largely equivalent algorithms
  - same artifacts
  - same workload
- monophonic time-stretching with PSOLA-based approaches is
  - easier to solve
  - has very bad artifacts is pitch tracker is off
- polyphonic time-stretching with PV-based approaches is
  - complicated due to tradeoffs (e.g., frequency vs time resolution)
- general challenges:
  - noisy and transient signals
  - resulting timbre changes
  - perceived naturalness of result
  - time resolution/accuracy due to blocked processing