User-Guided Variable-Rate Time-Stretching Via Stiffness Control

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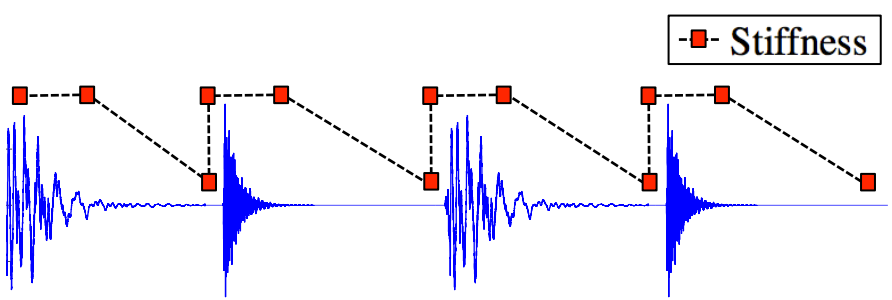
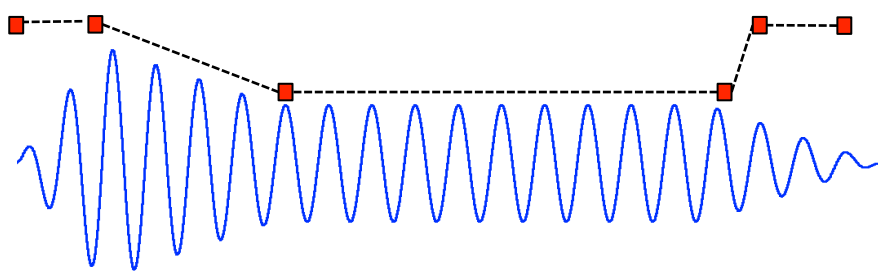
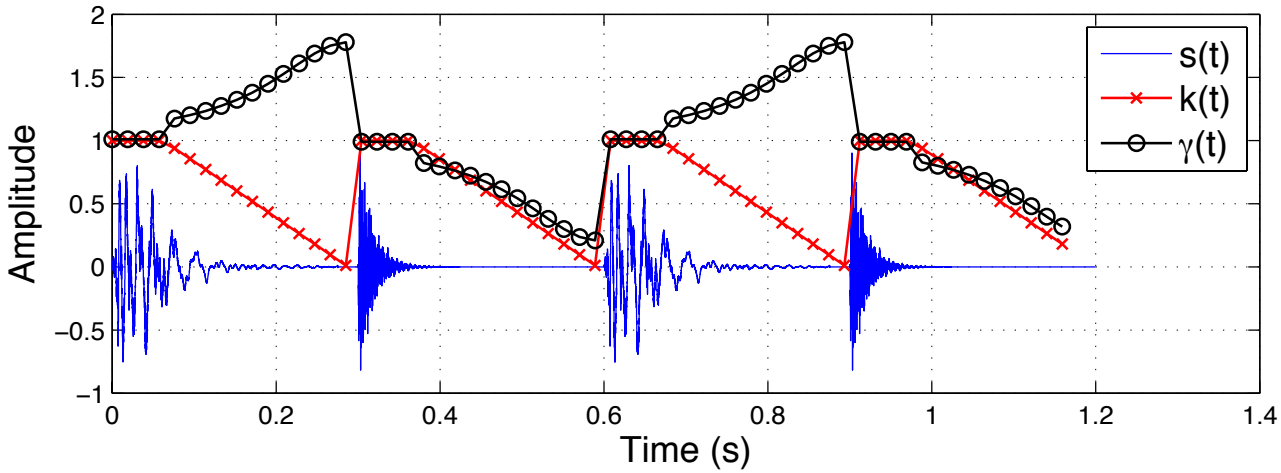
Introduction

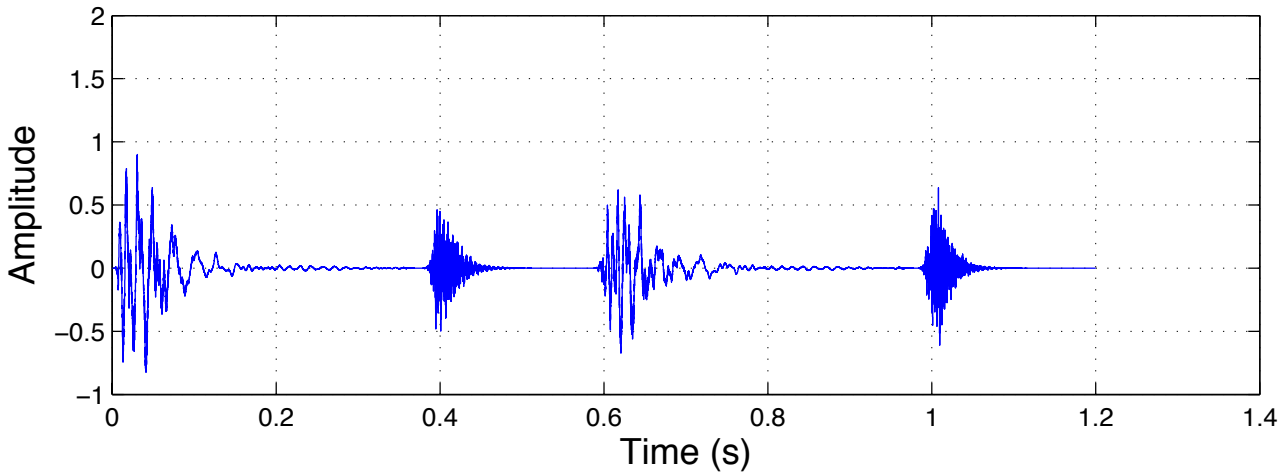
- User control over variable-rate time-stretch processing
- Stretch some regions more than others (e.g. stretchability, stiffness)
- Transient preservation, rhythmic warping, emphasis modification, etc.





Rhythmic Warping Demo





Original

No Stiffness / Stiffness

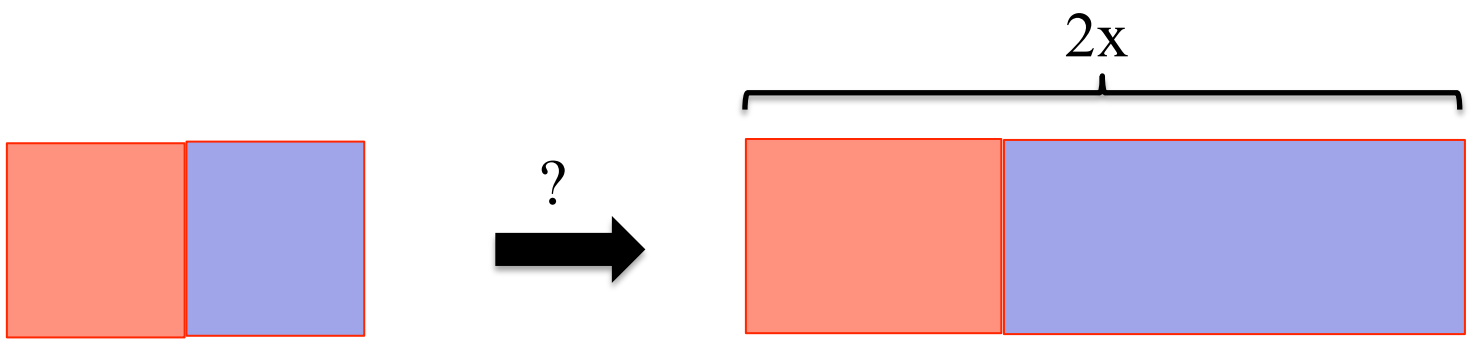
Stretched (2x)

Swung + Stretched (2x)

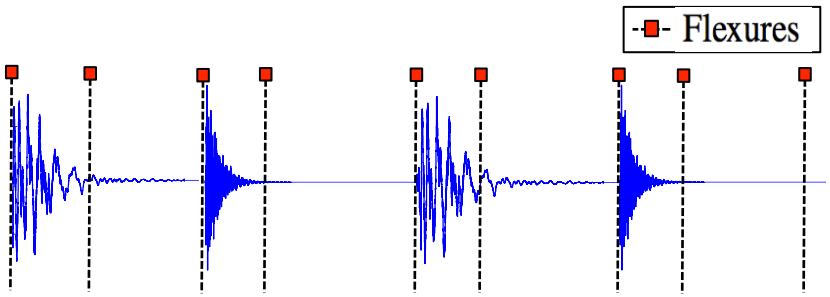
Motivation

- **Automatic** methods have no mechanism for user input

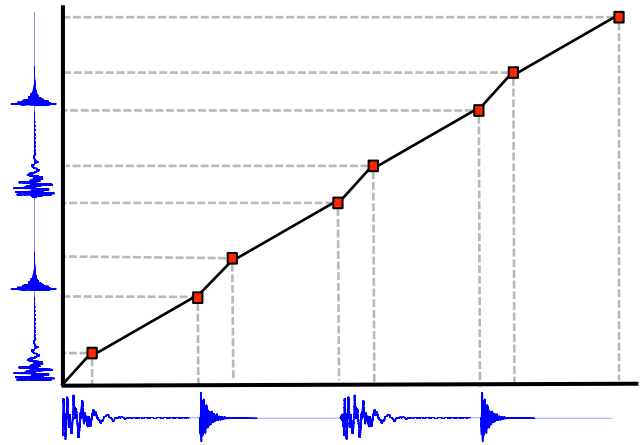
- **Direct** manipulation of the stretch rate is hard!



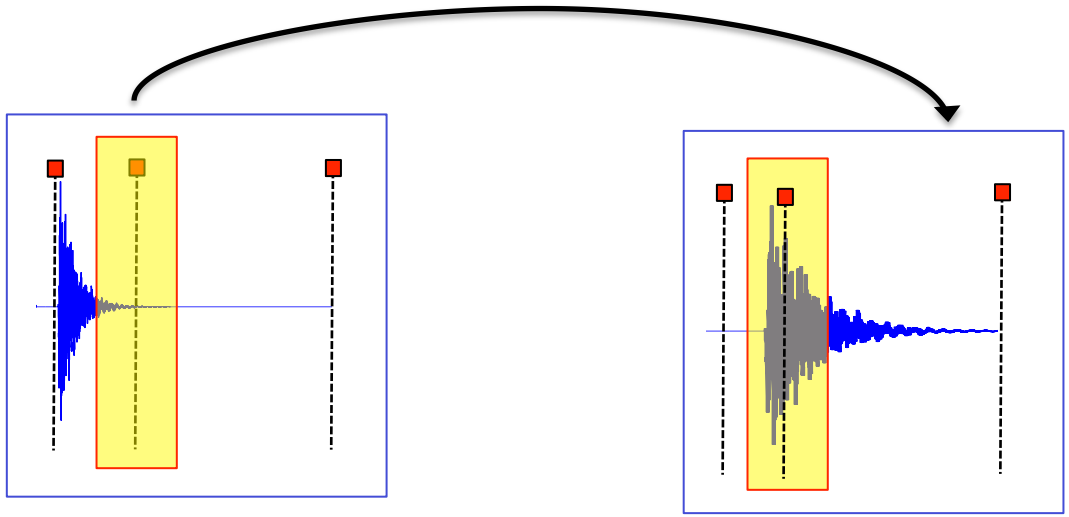
Prior Work



ProTools, Logic Pro, FL Studio, etc.

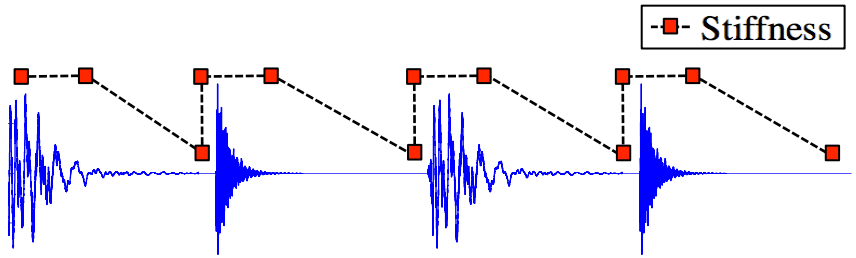


Nielson and Brandorff, 2002



Proposed Method

- User annotates **stiffness** + timing **constraints**



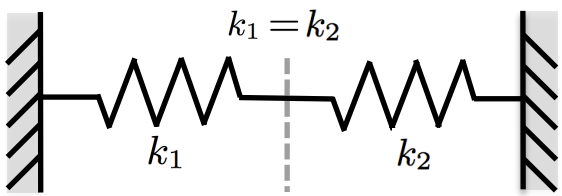
- Solve optimization problem to **convert** stiffness to stretch factor

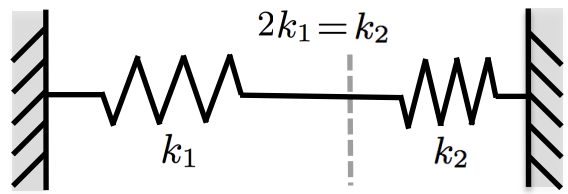
- Use **pre-existing** time-stretch processor to stretch sound

Step I: Spring Chain

- Model audio as **chain of springs**

- Solve for **equilibrium** via Hooke's Law $F_i = -k_i x_i$

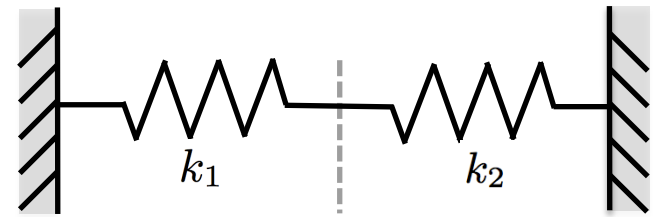




- Spring stiffness an **intuitive** measure (i.e. proportional)

Initial Formulation

$$\begin{aligned} \text{find} \quad & \boldsymbol{x} \\ \text{subject to} \quad & \boldsymbol{f} = \mathbf{0} \\ & \boldsymbol{x}^{\mathrm{T}}\mathbf{1} = L \end{aligned}$$



$\mathbf{x}$ = spring displacement

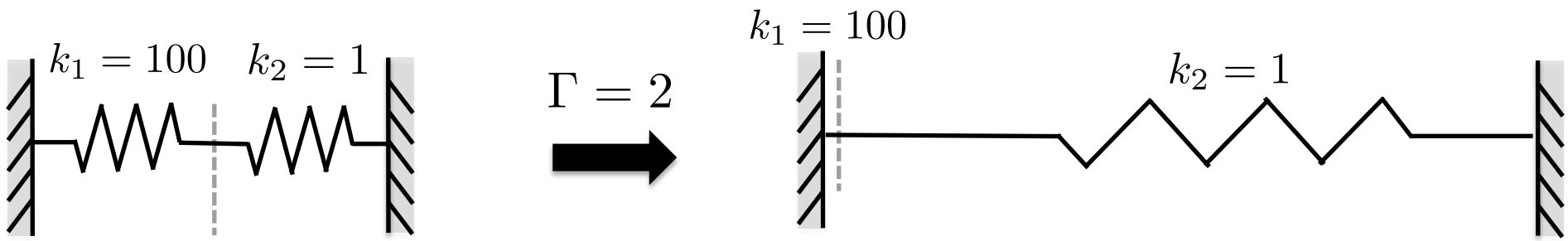
$\mathbf{f}$ = spring forces $\qquad f_i = k_{i+1}x_{i+1} - k_i x_i$

$\mathbf{k}$ = spring stiffness

L = final length

Problem

- Violates intuition: no initial rest length



Reformulation

$$\begin{aligned} \text{find} \quad & \boldsymbol{x} \\ \text{subject to} \quad & \boldsymbol{f} = \mathbf{0} \\ & \boldsymbol{x}^{\mathrm{T}}\mathbf{1} = L \end{aligned}$$

$$\begin{aligned} \text{find} \quad & \boldsymbol{x} \\ \text{subject to} \quad & \boldsymbol{f} = \mathbf{0} \\ & (\boldsymbol{x} + \boldsymbol{x}_0)^{\mathrm{T}}\mathbf{1} = L \\ & \boldsymbol{x} + \boldsymbol{x}_0 \geq \mathbf{0} \end{aligned}$$

$\boldsymbol{x}_0 =$ Initial Rest Length

Reformulation

$$\begin{aligned} \underset{\boldsymbol{x}}{\text{minimize}} \quad & ||\boldsymbol{f}||_2 + \mu||\boldsymbol{x}||_2 \\ \text{subject to} \quad & (\boldsymbol{x} + \boldsymbol{x_0})^{\mathrm{T}}\mathbf{1} = L \\ & \boldsymbol{x} + \boldsymbol{x_0} \geq \mathbf{0} \end{aligned}$$

$\boldsymbol{x}_0 =$ Initial Rest Length

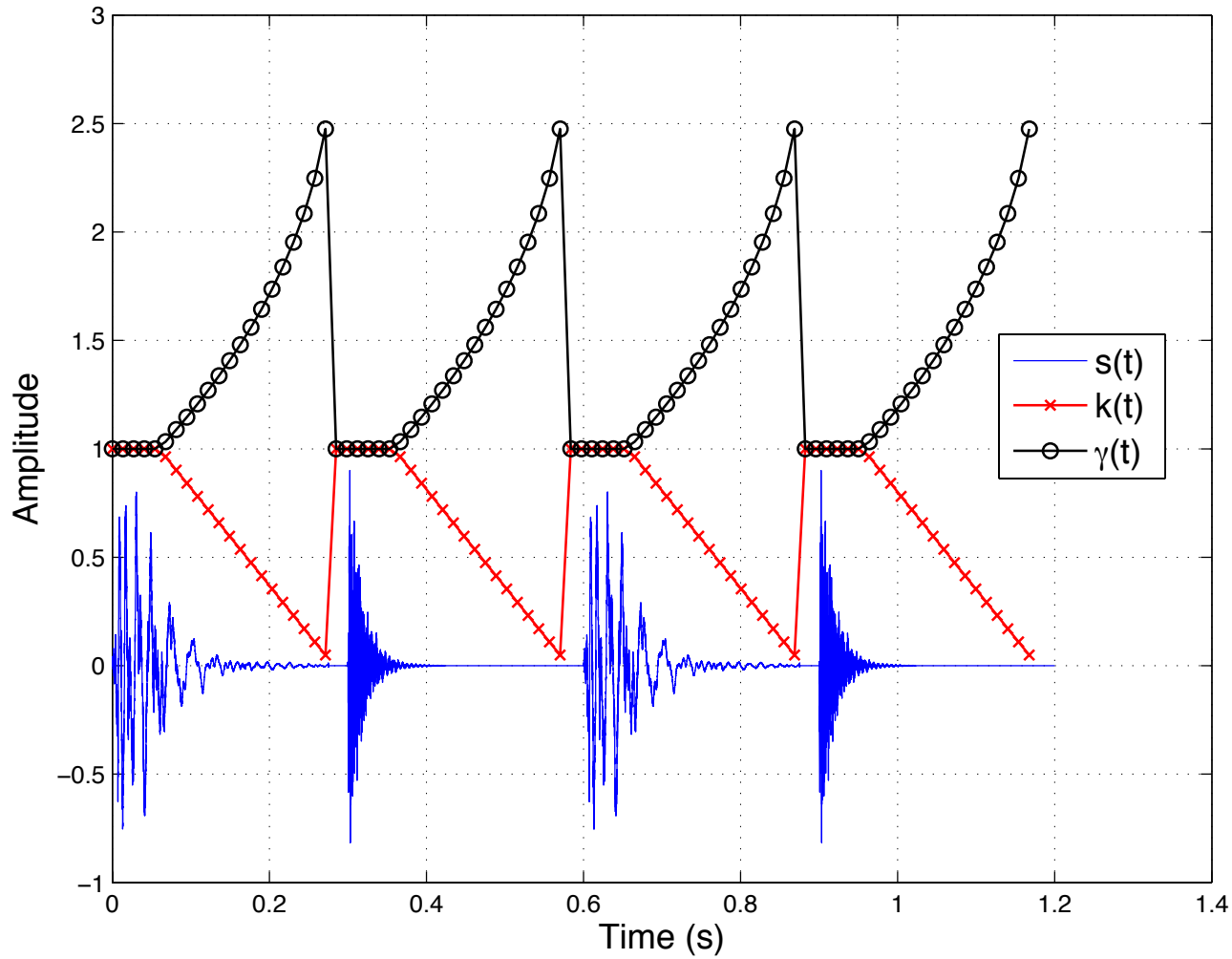
$\mu =$ Penalty Weight

- Minimize the force disturbance from equilibrium (smoothly)

Step II: Stiffness to Stretch Factor

- Given input and output lengths, compute stretch factor as simple ratio

$$\gamma = \frac{x + x_0}{x_0}$$



Step III: Time-Stretching

- Given optimal variable-rate stretch factor, process sound
- Phase Vocoder (PV)
- Pitch Synchronous overlap add (PSOLA)

Extensions

- Rhythmic warping, smoothing of user input, max stretching limits
- Example: Straight-to-Swing

$$\underset{\boldsymbol{x}}{\text{minimize}} \quad ||\boldsymbol{f}||_2 + \mu||\boldsymbol{x}||_2$$

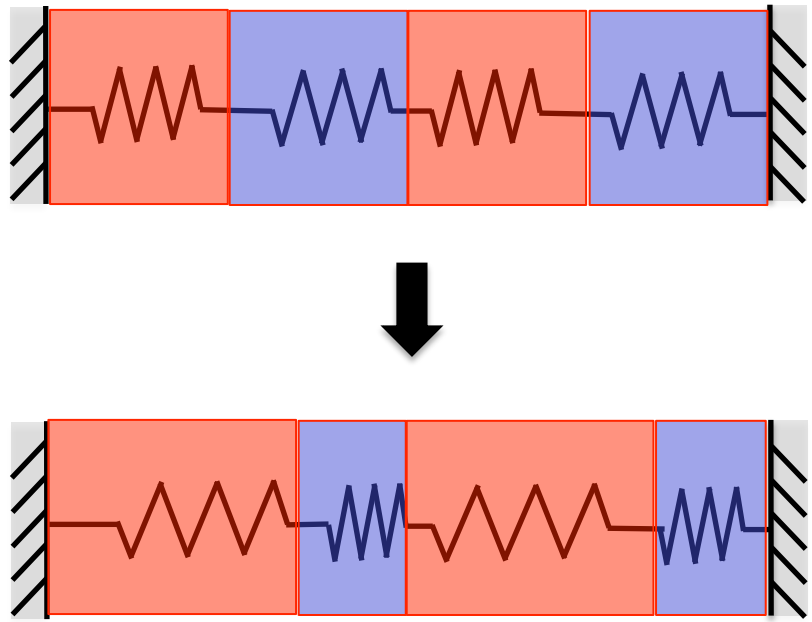
$$\text{subject to} \quad (\boldsymbol{x} + \boldsymbol{x_0})^{\mathrm{T}}\mathbf{1} = L$$

$$\boldsymbol{x} + \boldsymbol{x_0} \geq \mathbf{0}$$

$$(\boldsymbol{x^1} + \boldsymbol{x_0^1})^{\mathrm{T}}\mathbf{1} = \tfrac{2}{3}L/2$$

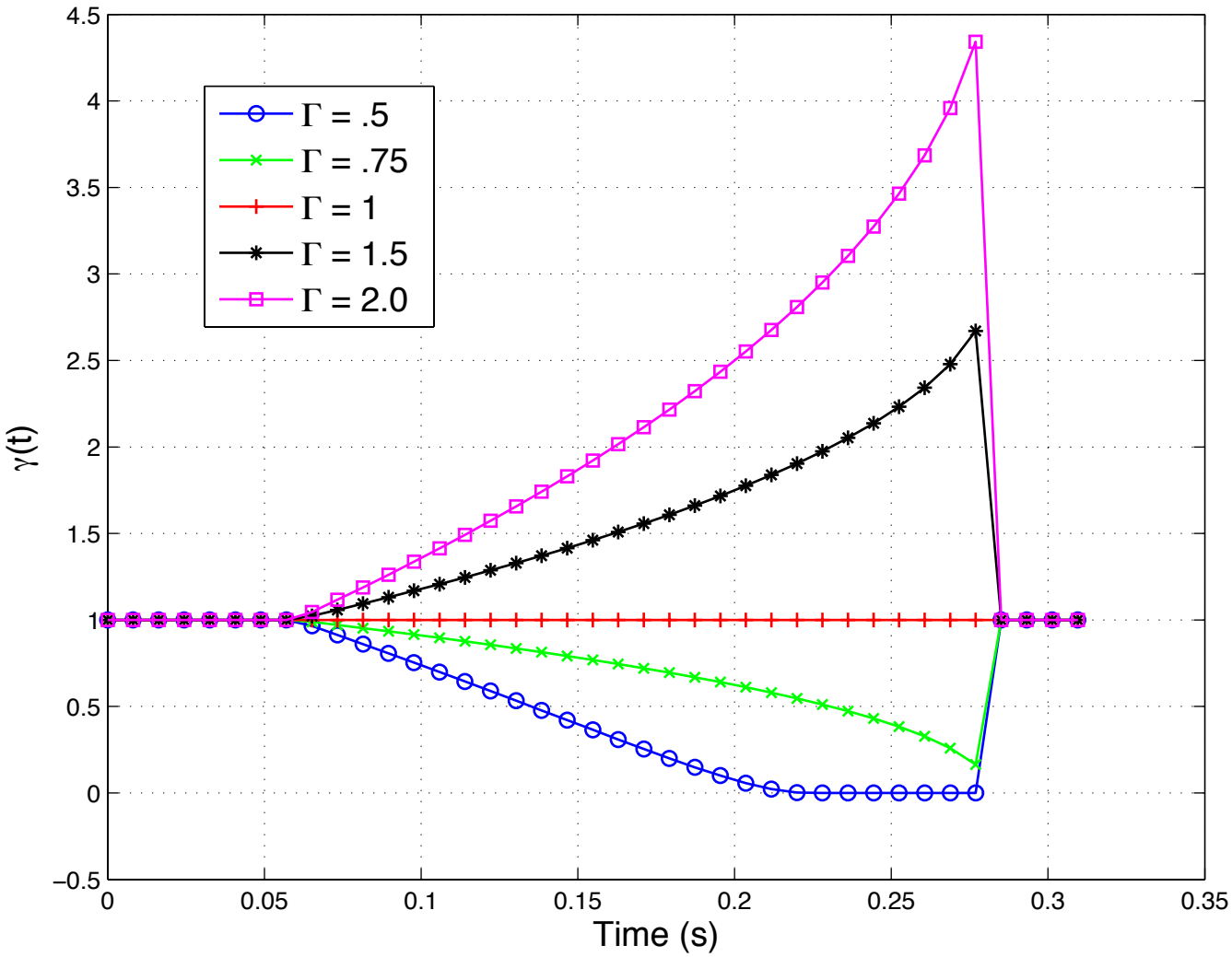
$$(\boldsymbol{x^2} + \boldsymbol{x_0^2})^{\mathrm{T}}\mathbf{1} = \tfrac{1}{3}L/2$$

$$(\boldsymbol{x^3} + \boldsymbol{x_0^3})^{\mathrm{T}}\mathbf{1} = \tfrac{2}{3}L/2$$



Results

Varying Stretch Length



$$\underset{\boldsymbol{x}}{\text{minimize}} \quad ||\boldsymbol{f}||_2 + \mu||\boldsymbol{x}||_2$$

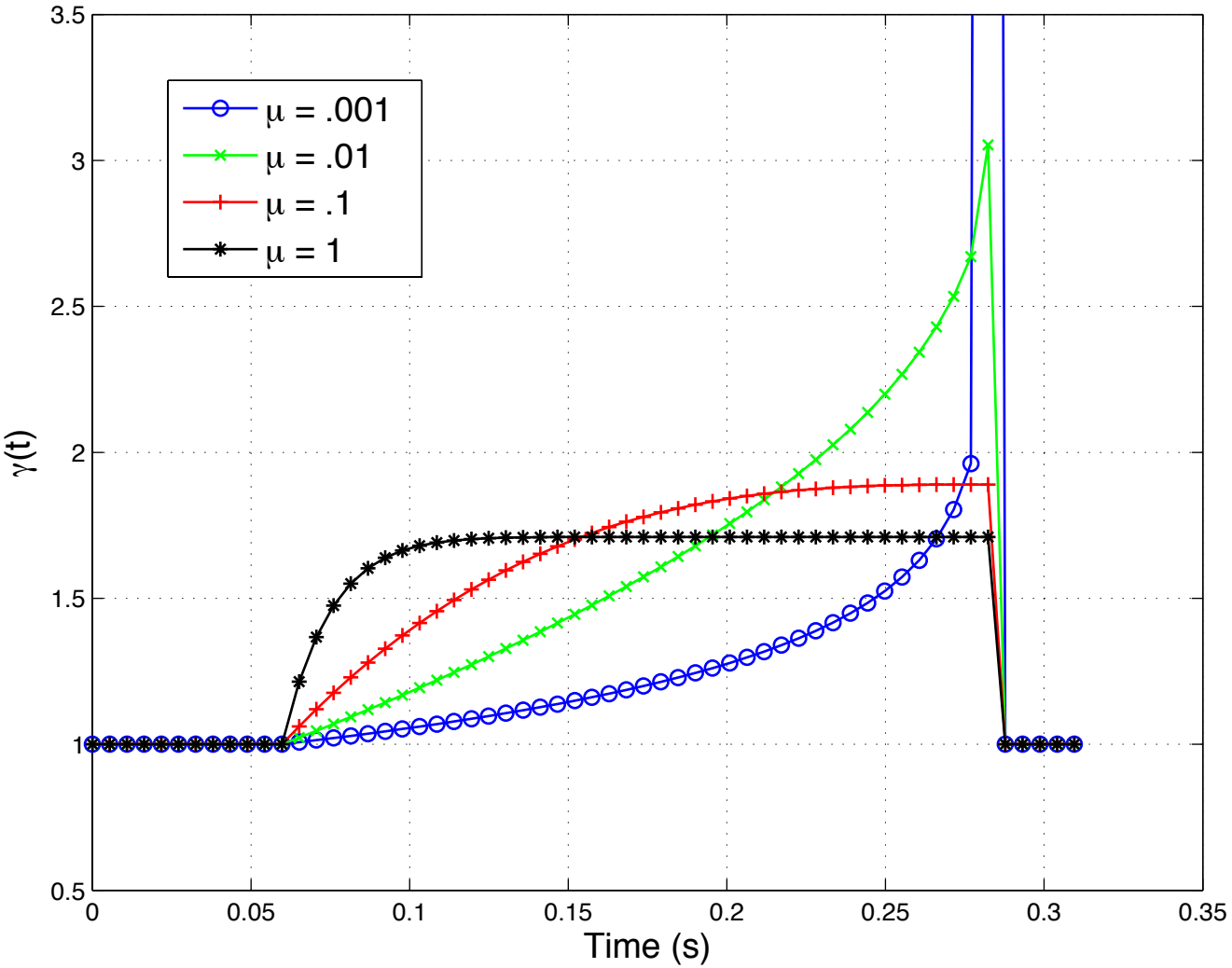
$$\text{subject to} \quad (\boldsymbol{x} + \boldsymbol{x_0})^{\mathrm{T}}\mathbf{1} = L$$

$$\boldsymbol{x} + \boldsymbol{x_0} \geq \mathbf{0}$$

- $\Gamma = .5$
- $\Gamma = .75$
- $\Gamma = 1.0$
- $\Gamma = 1.5$
- $\Gamma = 2.0$

- Varying the overall stretch factor gives smooth, intuitive stretch factors

Regularization



$$\underset{\boldsymbol{x}}{\text{minimize}} \quad ||\boldsymbol{f}||_2 + \mu||\boldsymbol{x}||_2$$

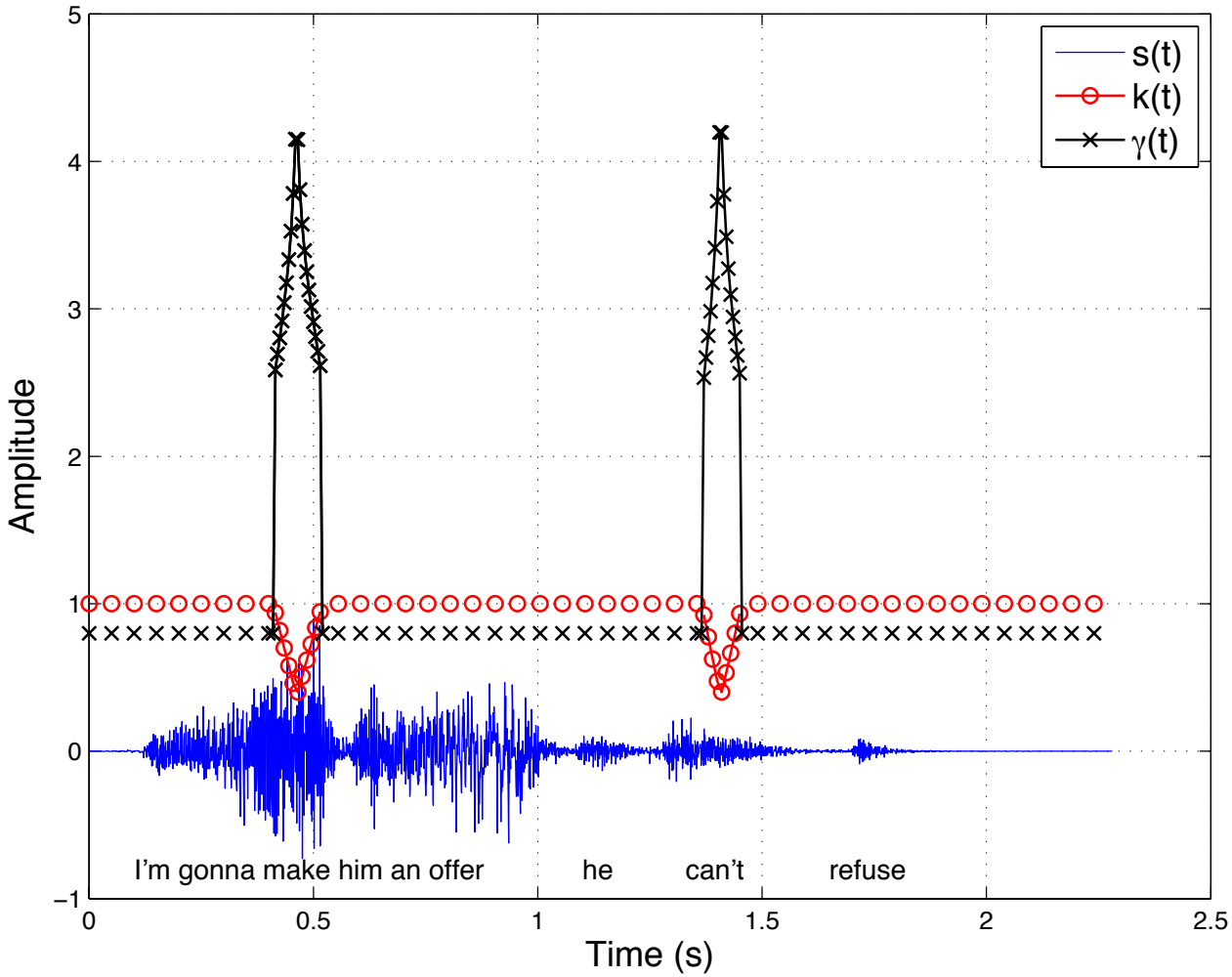
$$\text{subject to} \quad (\boldsymbol{x} + \boldsymbol{x_0})^{\mathrm{T}}\mathbf{1} = L$$

$$\boldsymbol{x} + \boldsymbol{x_0} \geq \mathbf{0}$$

- $\mu = .001$
- $\mu = .01$
- $\mu = .1$
- $\mu = 1$

- Regularization penalty smooths the time-varying stretch factor

Rhythmic Emphasis Modification



original

warped

warped + stretched (slowed by 1.3x)

I'm gonna make him an offer he can't refuse

I'm gonna maaake him an offer he caaaan't refuse

Conclusions

- Method of **user control** over variable-rate time-stretching
- **Decouples** stiffness control + timing constraints to user
- Converts user control into **optimal** time-dependent stretch rate
- **Agnostic** to time modification algorithms

Acknowledgments & Thanks

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- School of Humanities and Sciences, Stanford University

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