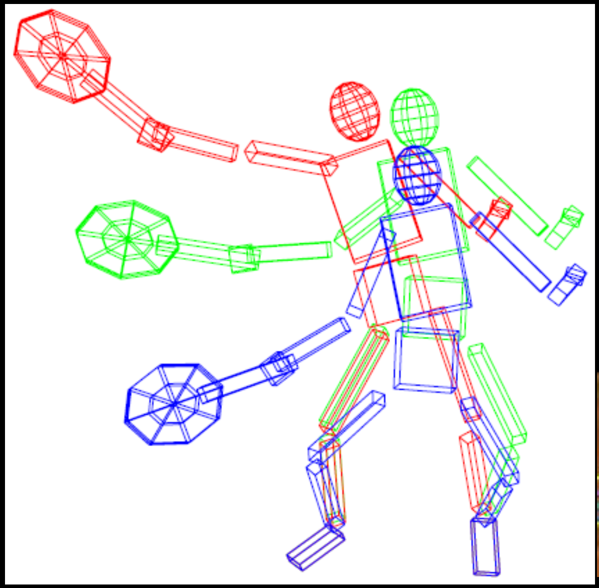
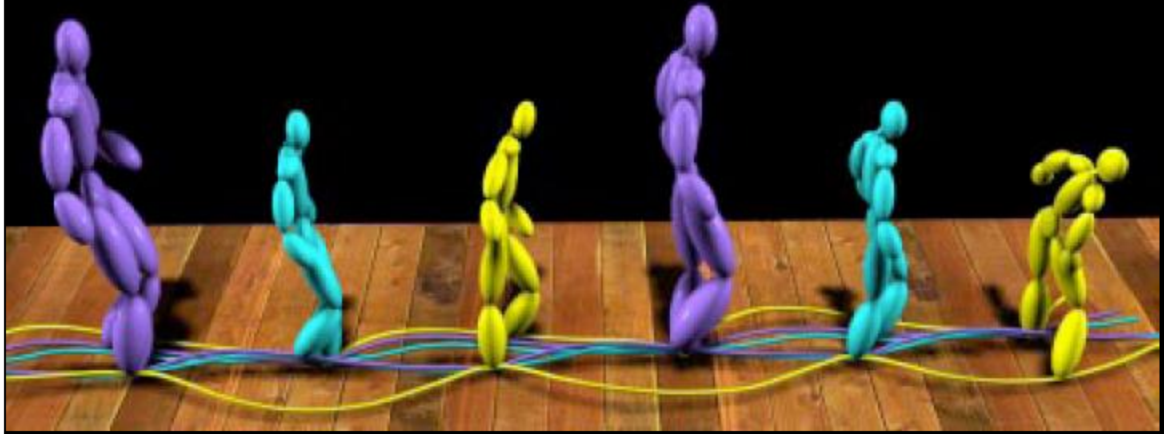
Motion Editing and Synthesis





Motion

- Multidimensional signal (vector-valued signal)
- A function of time $m(t)$: R → R^n
- Not really in R^n
  - 3 DOF in translation
  - 3 DOF in absolute orientation
  - many DOF in relative orientations
- Many different ways to represent a motion
  - ASF/AMC
  - BVH

Motion Editing Problem

- Get a specific motion
  - from capture, keyframes
  - specific character, action, style
- Want something else
- While preserving original
  - which part to preserve is case dependent
  - cannot characterize/distinguish motions well enough

Why motion editing?

- What you get is not what you want
- You get observations of the performance
  - Specific performer (a real human)
  - Specific motion
  - With the noise and “realism” of real sensors
- You want animation
  - A character doing something
  - Or something similar but not the same

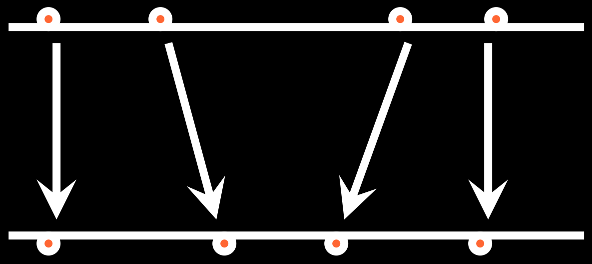
Motion Editing

- Modify temporal relation
  - Time warp / Speed control
  - $m(\mathrm{t}) = m_0(\, f(t)\,)$
  - $f : \mathrm{R} \rightarrow \mathrm{R}$
- Modify motion value
  - $m(t) = f(m_0(t)\,)$
  - $f : \mathrm{R}^n \rightarrow \mathrm{R}^n$

Modifying Temporal Relation

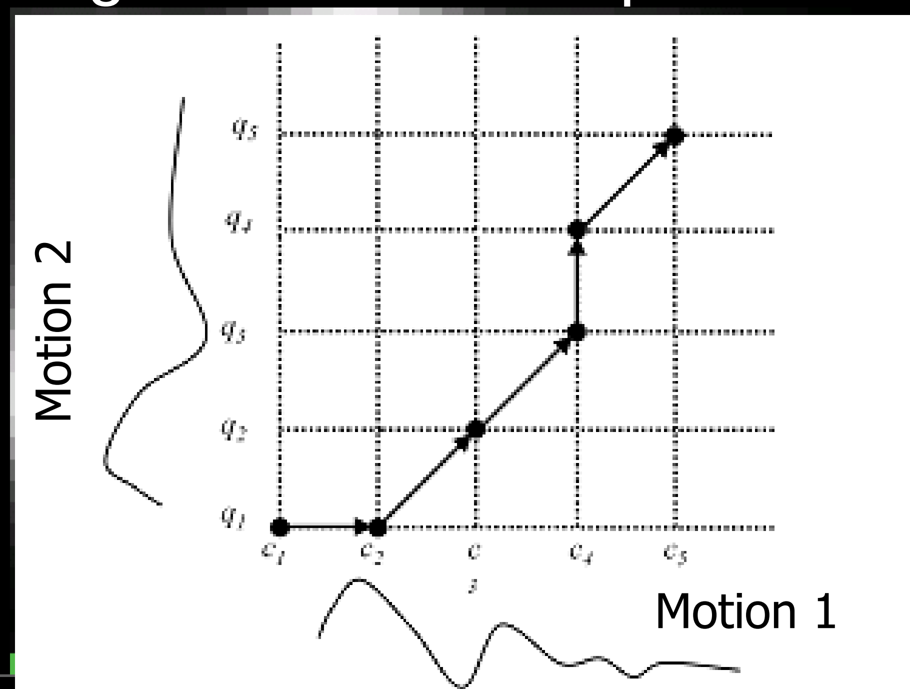
$m(t) = m_0(f(t))$

- Time scaling: $f(t) = k\,t$
- Time shifting: $f(t) = t + k$
- Time warping
  - Interpolate a table
  - Align events
- Speed control
  - Ease in/Ease out



Dynamic Time Warping

- Every frame matches its best correspondence
  - define matching cost between two frames (poses)
  - use dynamic programming to find the best path
- Restrictions
  - Nonnegative slope



Manipulating Values

- Scale
- Shift
- Blending
- Filtering
- Transition between motions
- Cyclification
- Change style
- Constraints on the motion
- Concatenation

Motion Blending

- "Add" two (or more) motions together
  - Really interpolate

    $$m(t) = a\, m_0(t) + (1\text{-}a)\, m_1(t)$$

    This is a per-frame operation

  - We're really interpolating between a series of poses!

    $$m(t) = a(t)\, m_0(t) + (1\text{-}a(t))\, m_1(t)$$

- Only works for interpolating similar poses
- Temporally aligning motions before blending
  - dynamic time warping

Motion Blending Approaches

- Radial Basis Function (RBF) Interpolation
  - Rose et al., “Verbs and Adverbs,” IEEE CG&A, 1998
  - Rose et al., “Artist-directed IK using radial basis function interpolation,” Eurographics’01 (shown in kinematics lecture)
  - align example motions
  - use B-spline to represent a motion
  - apply RBF to interpolate between B-spline coefficients
  - IK to maintain constraints

Tutorial on RBF Interpolation

- A radial basis function (RBF) is a real-valued function whose value depends only on the distance form the center $d = |x - c|$

- RBF types
  - Gaussian $R(d) = e^{-\beta d^2}$
  - Thin plate spline $R(d) = d^2 \log(d)$
  - Multiquadric $R(d) = \sqrt{d^2 + \beta^2}$

RBF Interpolation

- Approximates a real valued function $f(\mathbf{x})$ by $s(\mathbf{x})$ given the set of values $f = (f_1, \ldots, f_N)$ at distinct points $X = \{\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_N\}$

- $s(\mathbf{x})$ is a weighted sum of translations of a radially symmetric basic function augmented by a polynomial term

real-valued weight

$$s(\mathbf{x}) = A(\mathbf{x}) + \sum_{i=1}^{N} r_i R_i(|\mathbf{x} - \mathbf{x_i}|), \qquad \mathbf{x} \in R^d$$

polynomial of degree at most k

radial basis function

RBF Interpolation (cont.)

- The coefficients in $s(\mathbf{x})$ are obtained by solving a system of linear equations

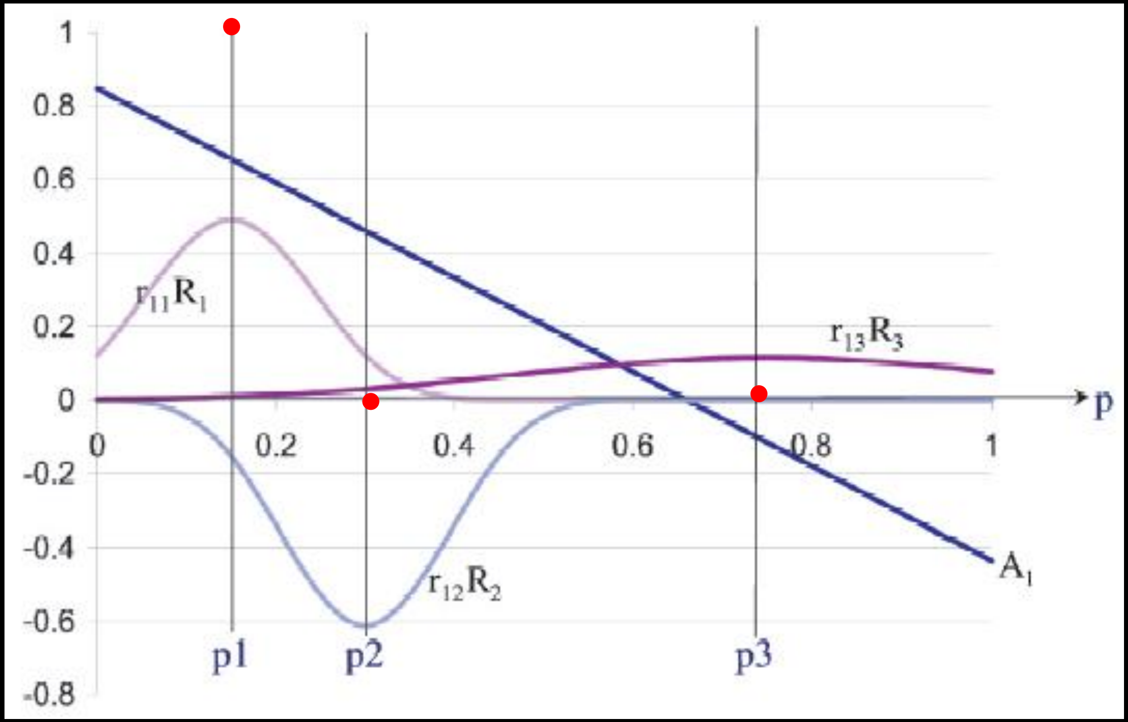
$$s(\mathbf{x}_i) = f_i \qquad\qquad i = 1,\ldots,N$$

- RBFs are popular for interpolating scattered data as the associated system of linear equations is invertible under very mild conditions on the locations of the data points.

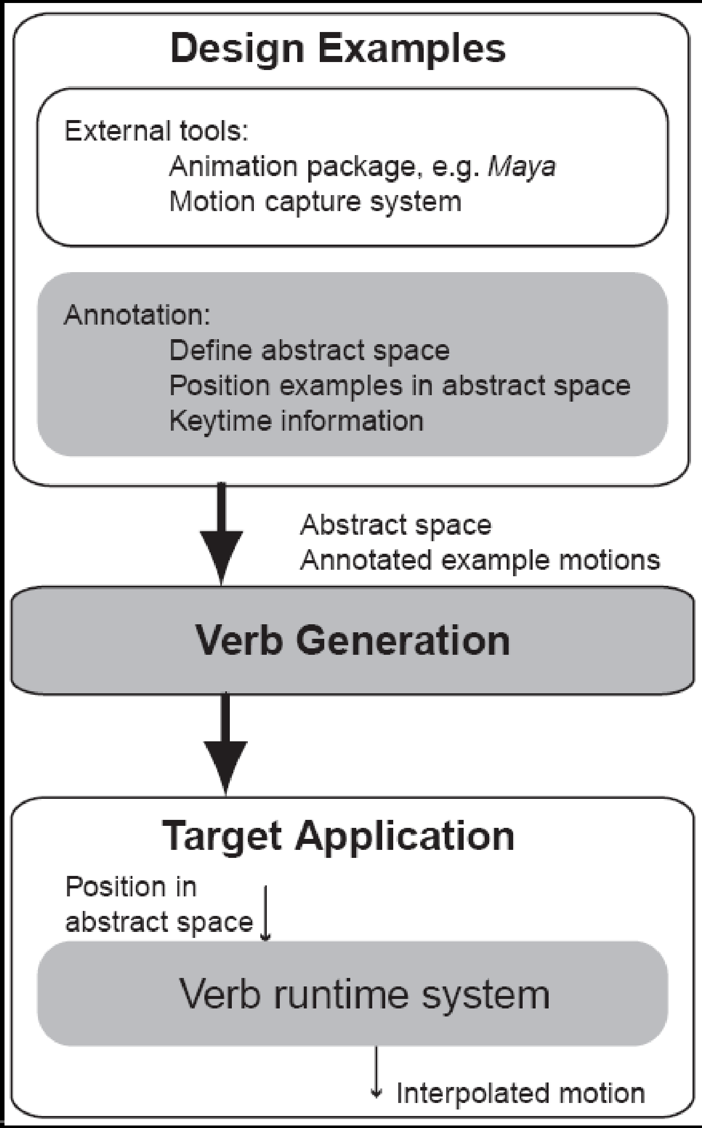
Example: 1D RDF Interpolation

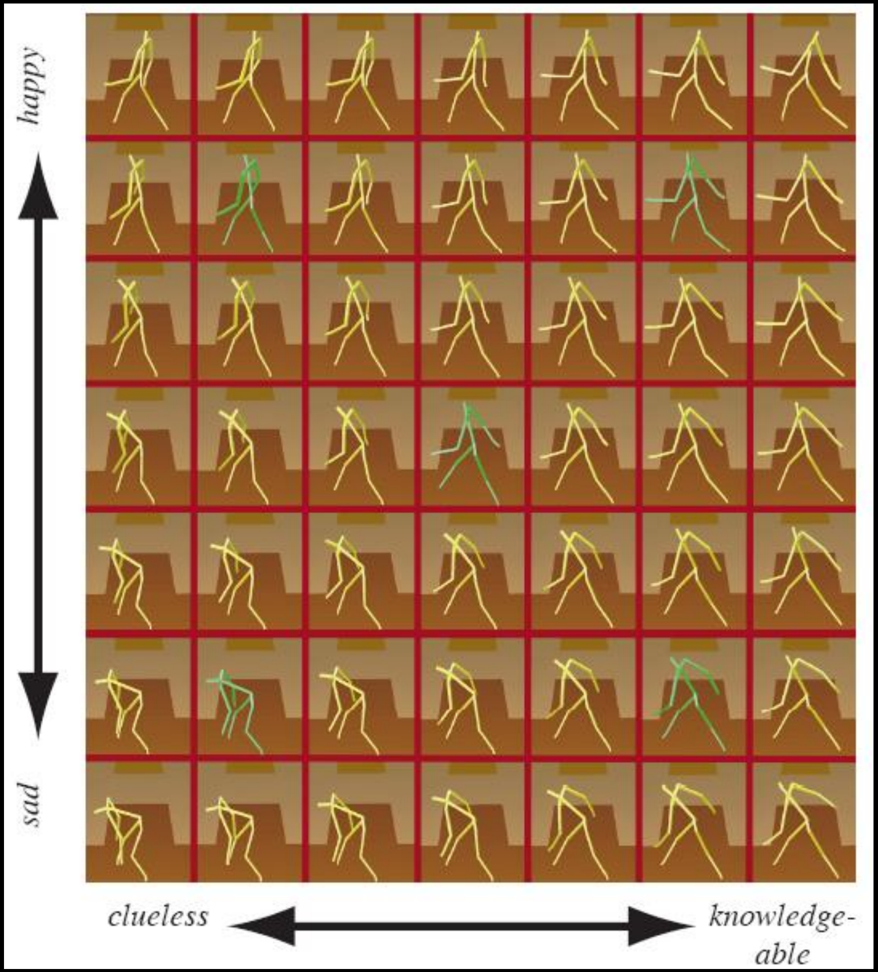
- Fit data (x, y) = {(0.15, 1), (0.3, 0), (0.75, 0)}

$$s(x) = A(x) + \sum_{i=1}^{3} r_i R_i(|x - x_i|)$$



Verbs and Adverbs



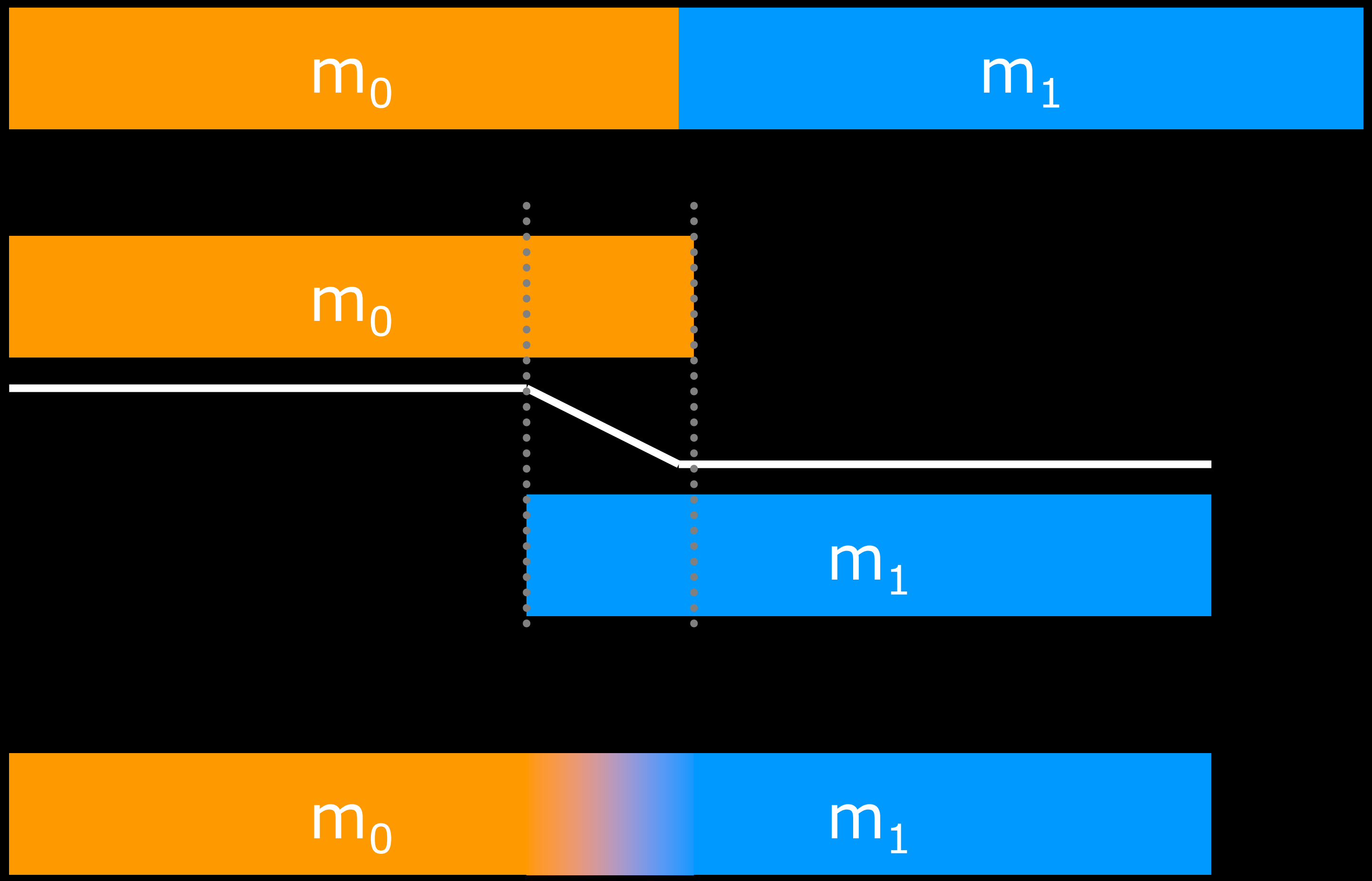


Green: example motions

Yellow: interpolated motions

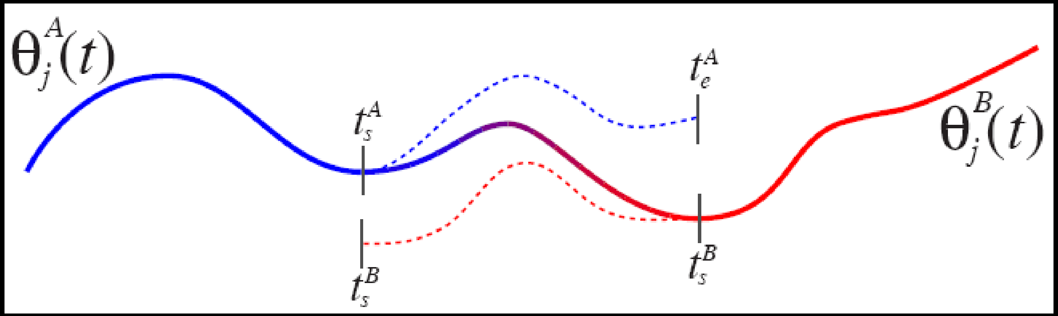
Verbs and Adverbs Video

Motion Transition



Motion Transition

- Often get small pieces of motion
- Need to connect them
- Very useful
  - motion graph (next lecture)
  - games: concatenate short motions
- Easy if motions are similar



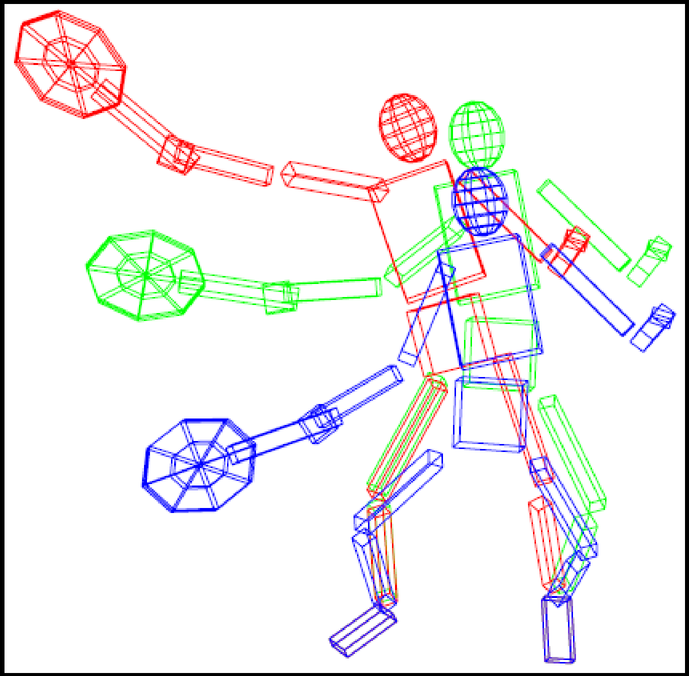
- Hard if motions are not similar

Cyclification

- Transition from the end of a motion to the beginning of the same motion
- Find good transition points

Motion Warping

- Witkin and Popovic, “Motion Warping,” SIGGRAPH’95
- Keyframes (θ_i, t_i) as constraints in smooth deformation
- Keyframe placing the ball on the racket at impact



$$\theta'(t) = a(t)\theta(t) + b(t) \longrightarrow \theta_i'(t_i) = a(t_i)\theta(t_i) + b(t_i)$$

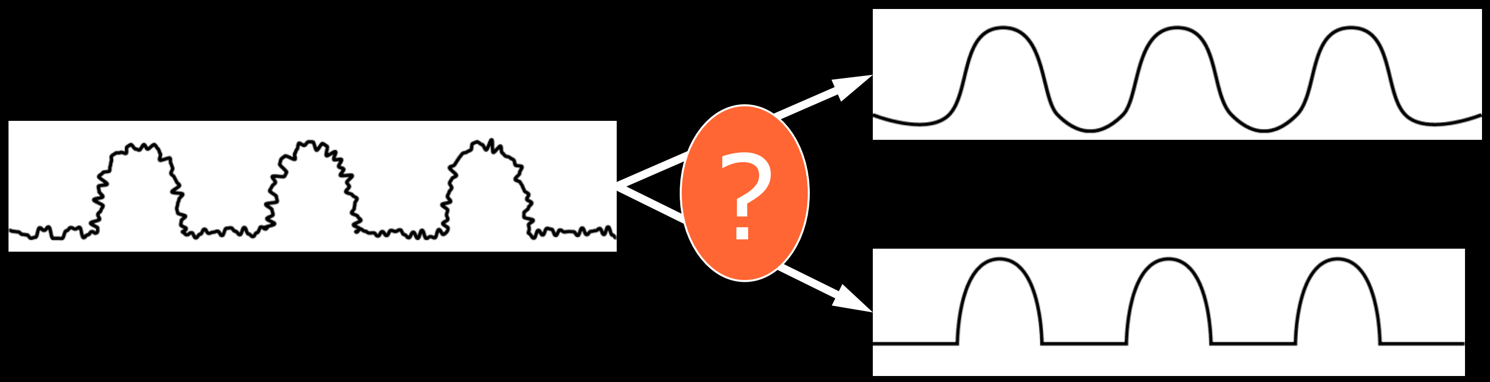
Motion Warping Results

- Tennis forehand
- Walk over obstacles

Motion Signal Processing—Filtering

- Treat motion as a multi-dimensional signal
- Low pass filtering
  - noise removal
- High pass filtering
  - style change
- High frequency component can be motion details, not just noise
- Modify a motion through filtering is not easy
  - Physical constraints (joint limit, ground contact)?
  - Naturalness?

High Frequency Noise?



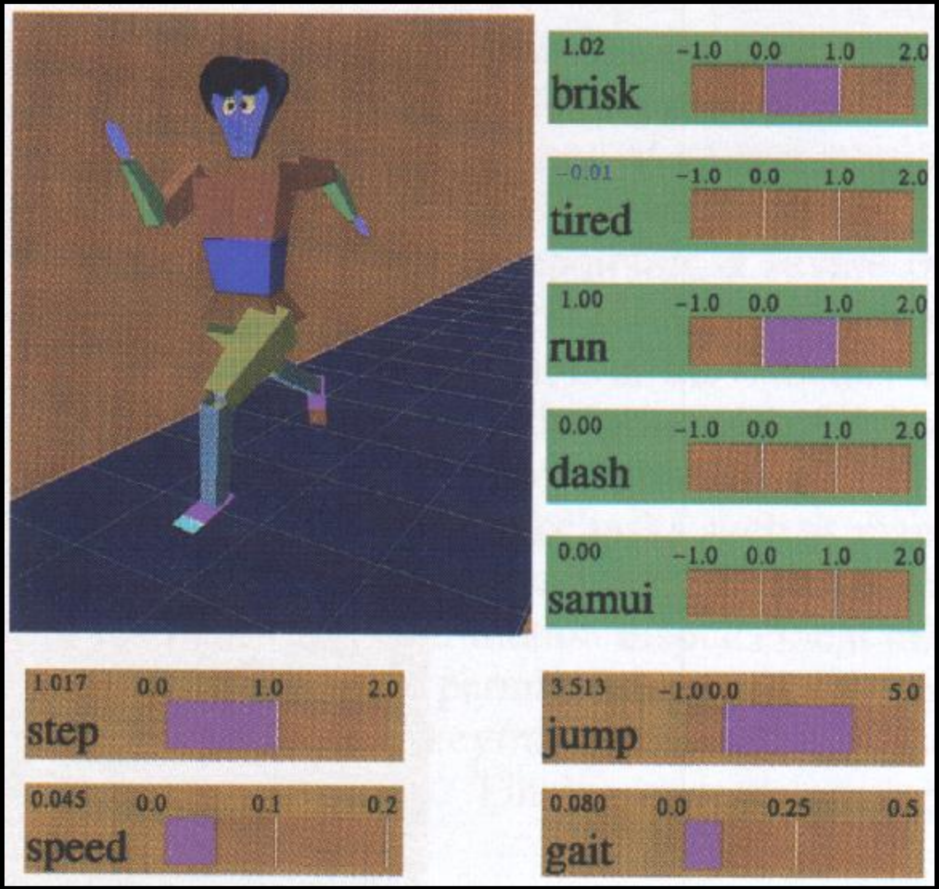
- PROBLEM: High frequencies can be important!
  - Getting rid of them makes motion look soggy
- ANSWER: Do not over-apply LPF
  - Small amounts of Low-Pass Filtering
  - Noise modeling
  - Non-linear filters

High frequencies are important!

- Don't occur often
- Always significant
  - Impact
  - Rapid, sudden movement
  - Emphasis
- Sensitivity of perception
  - Eye is sensitive to high frequencies

Frequency-domain Processing

- Unuma, Anjyo, Takeuchi, "Fourier Principles for Emotion-based Animation," SIGGRAPH'95



Frequency-domain Processing (cont.)

- Represent motion in Fourier serires

$$\theta(t) = A_0 + \sum_n A_n \sin(nt + \phi_n)$$

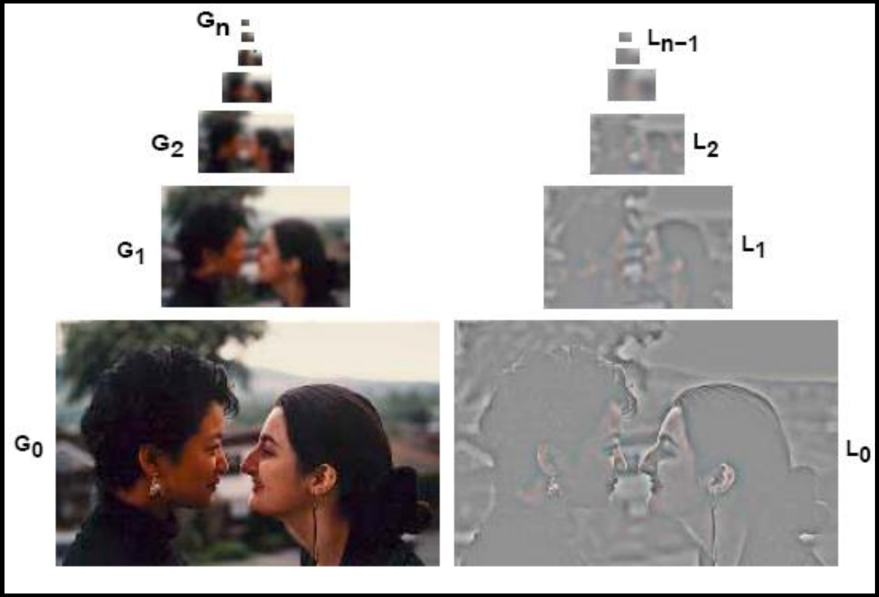
- Interpolation

$$\alpha(s,t) = (1-s)A_0 + sB_0 + \sum_n ((1-s)A_n + sB_n)\sin(nt + (1-s)\phi_n + s\psi_n)$$

Multiresolution Filtering

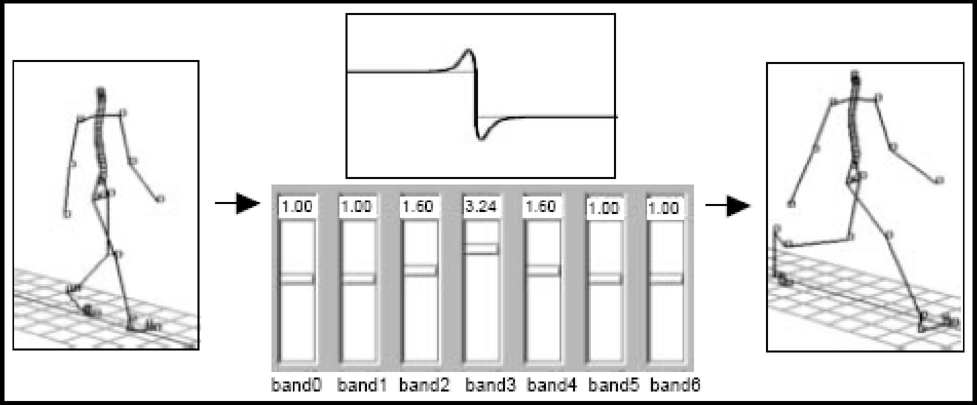
- Bruderlin and Williams, "Motion Signal Processing," SIGGRAPH'95
- Decompose a motion into multi freq. bands

$$G_0 = L_0 + L_1 + \cdots + L_{n-1} + G_n$$

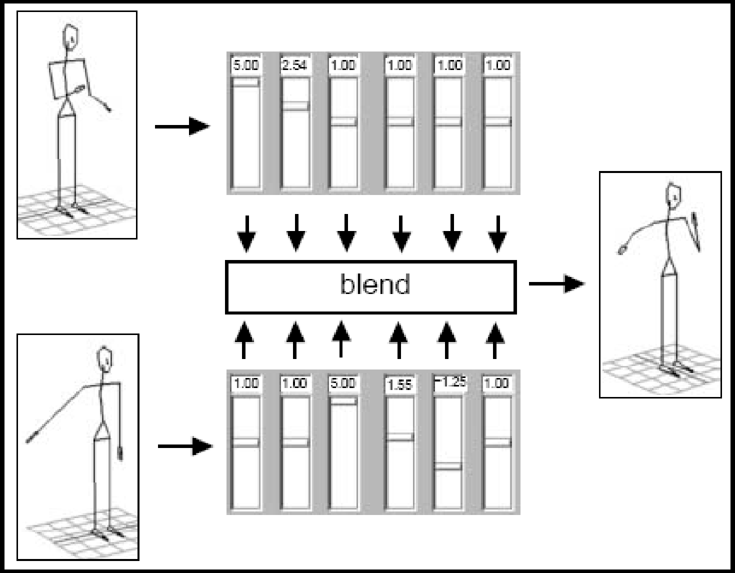


Multiresolution Filtering (cont.)

- "Motion equalizer"

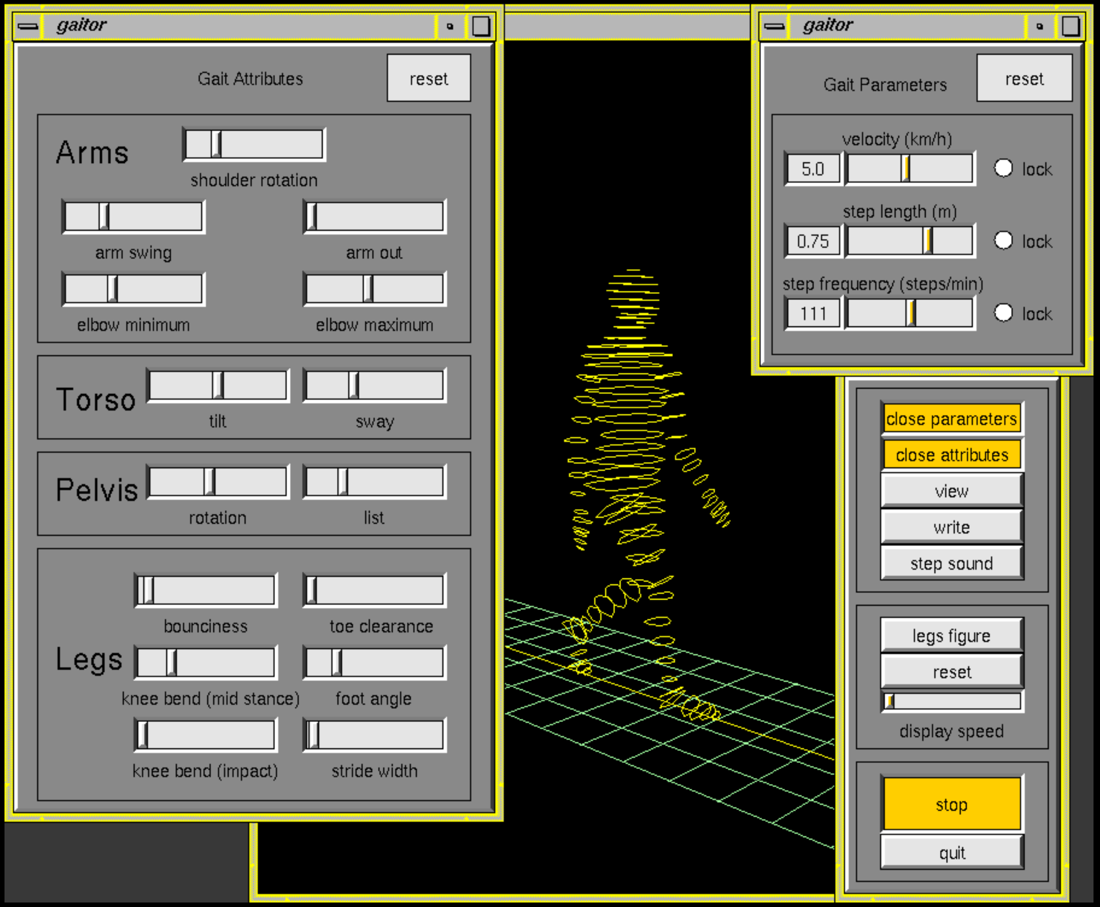


- Blending



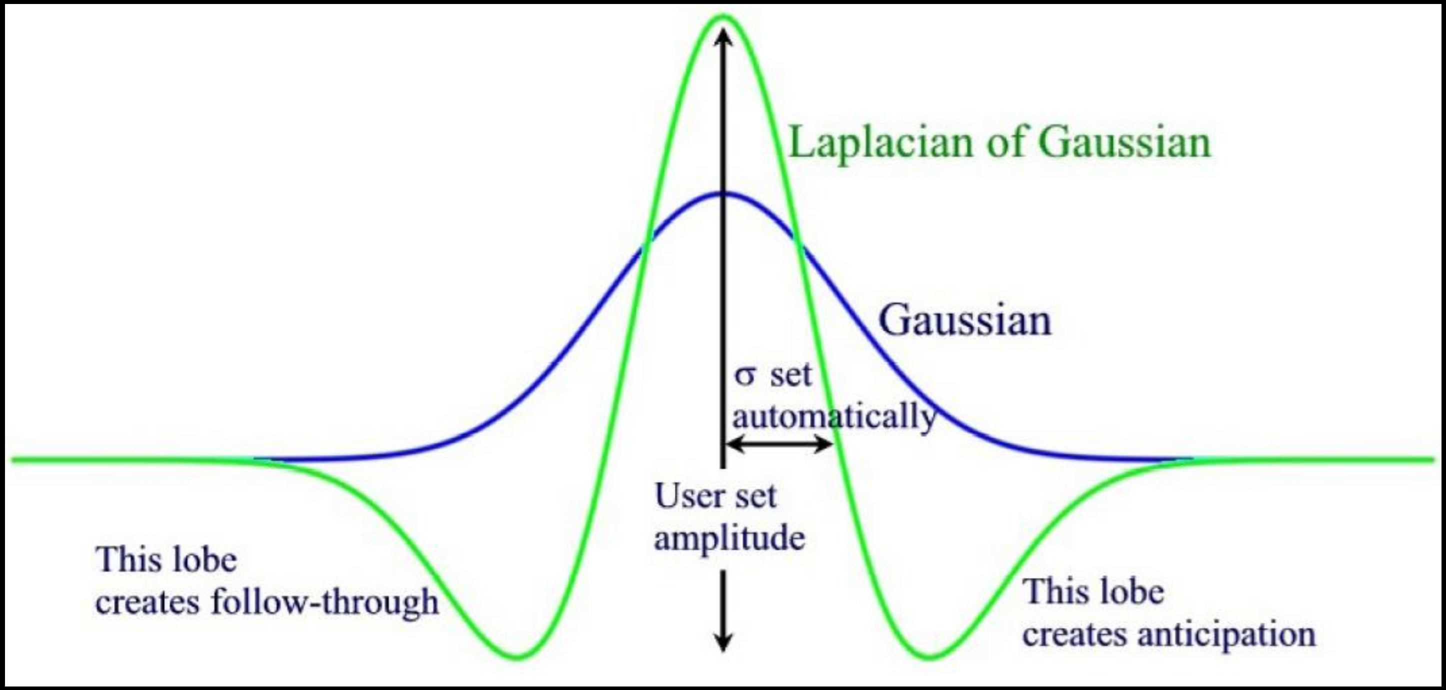
Interactive Real-time Animation of Human Walking and Running

- Bruderlin and Williams
- High-level control
  - velocity
  - step length
  - frequency
  - arm/torso/pelvis angle



Cartoon Animation Filter

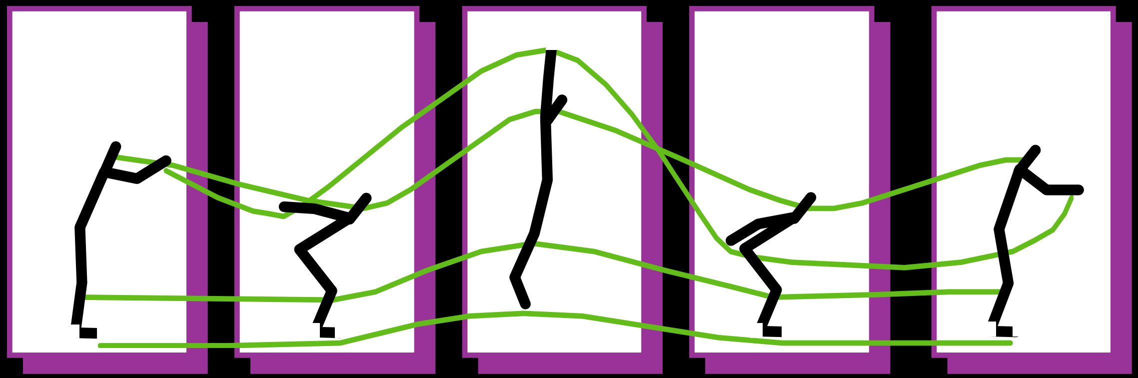
- Wang et al., "The Cartoon Animation Filter," SIGGRAPH'06
- Laplacian of Gaussian filter



Motion Editing with Constraints

- How to handle interactions with environment?
  - ground contact (avoid foot sliding, penetration)
  - hand shake
  - reach an object
  - path following (based on footprints specified)
- IK provides a solution for one frame
  - motion continuity is not guaranteed
  - may not be physically (dynamically) correct

Spacetime Constraints

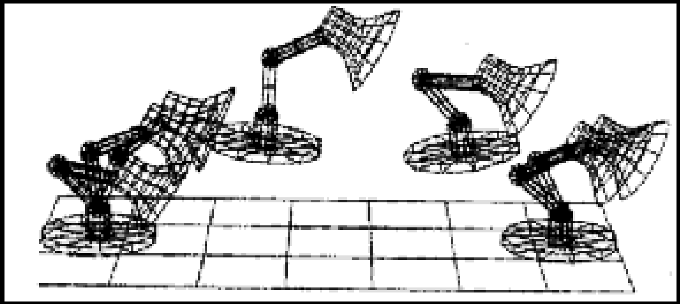


- A method for synthesizing physically correct motions (Witkin and Kass, SIGGRAPH’88)
- Consider all constraints simultaneously
  – NOT a frame at a time
- Solve for motions
  – “best” motion that meets constraints
- Physics is just a constraint

Spacetime Constraints (cont.)

- Solve for the forces required to reach constraints
- Animator specifies:
  - What the character has to do (constraints)
    - initial, intermediate, final positions, velocities, etc.
  - How the motion should be performed (metric)
    - jump this high, this much force at impact
  - The character’s physical structure
    - mass, joints, etc.
  - What the physical resources are
    - constraints on the muscles

Spacetime Constraints (cont.)



- Given the constraints
  - Animator specified constraints
  - Muscle and joint constraints
  - Physical laws
- And the metric (objective function) to optimize
  - How to perform the action
- Solve the constrained optimization for the force curves over the entire time of the motion

Pros and Cons of Spacetime Constraints

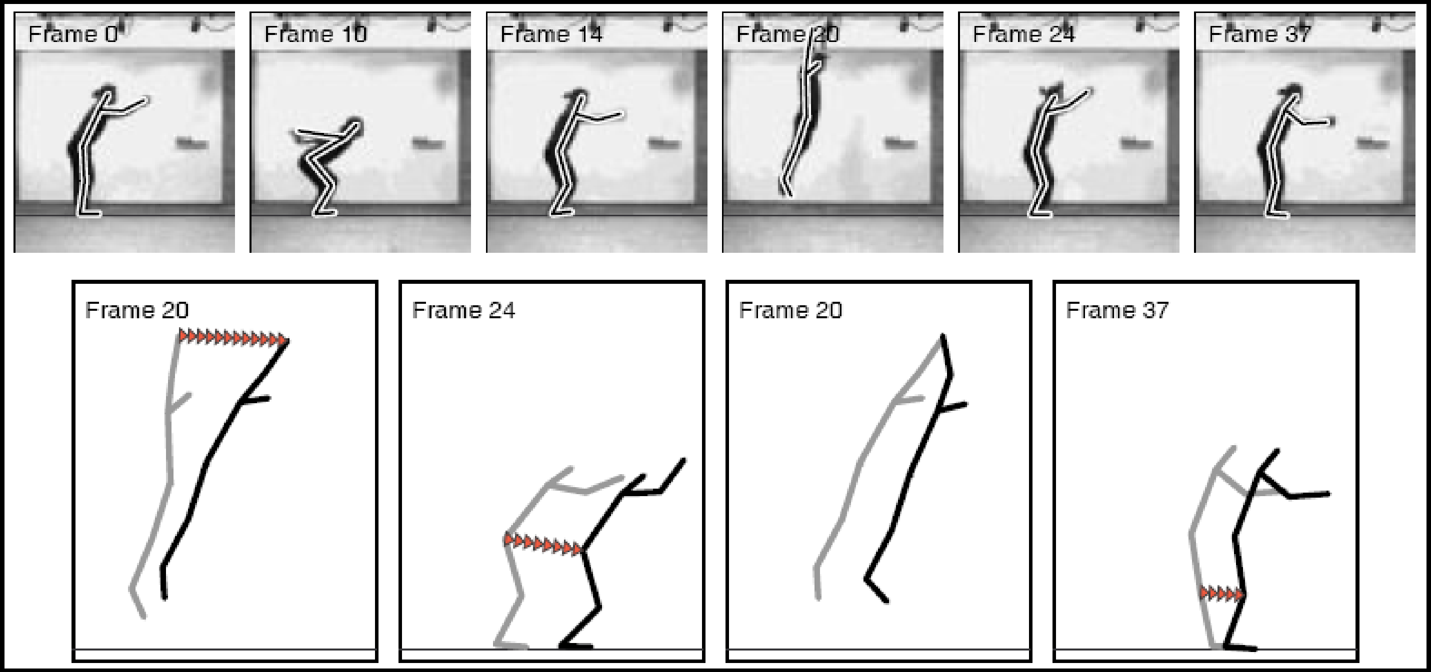
- Pros
  - Temporal properties are considered
  - Physical correctness can be enforced
- Cons
  - may not converge for complex model (large DOF)
    - Simplified model
    - Good initial condition
  - objective function may not be easily defined
    - Difficult to define low energy motions in physics
    - How to represent styles as an objective function?

Motion Editing with Spacetime Constraints

- Define geometric constraints on frames of the motion
  - properties to preserve
  - new goals to establish
- Find new motions that:
  - satisfy constraints (physics, naturalness, style, …)
  - match original motion
- Spacetime constraints consider entire motion simultaneously

Motion Editing with Spacetime Constraints

- Gleicher, Symposium on Interactive 3D graphics 1997



Motion Editing with Spacetime Constraints

- Interactively add constraints
- Minimize change in motion while maintaining constraints
- Allow user to interactively refine
  - Represent new motion as $m(t,x) = m_0(t) + d(t,x)$
  - Minimize $g(x)$ subject to $f(x) = c$

Physically Based Motion Transformation

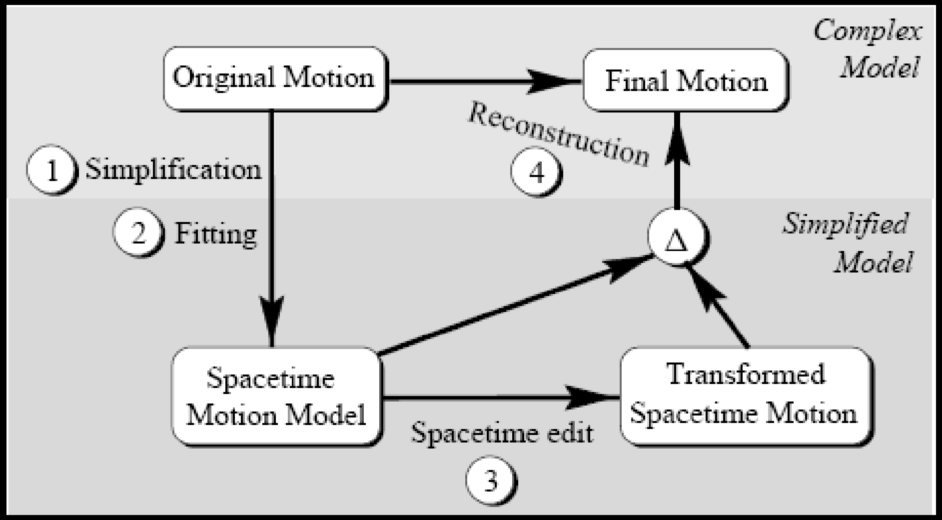
- Popovic & Witkin, SIGGRAPH'99
- Spacetime optimization in simplified motion space

Original motion

Final Motion

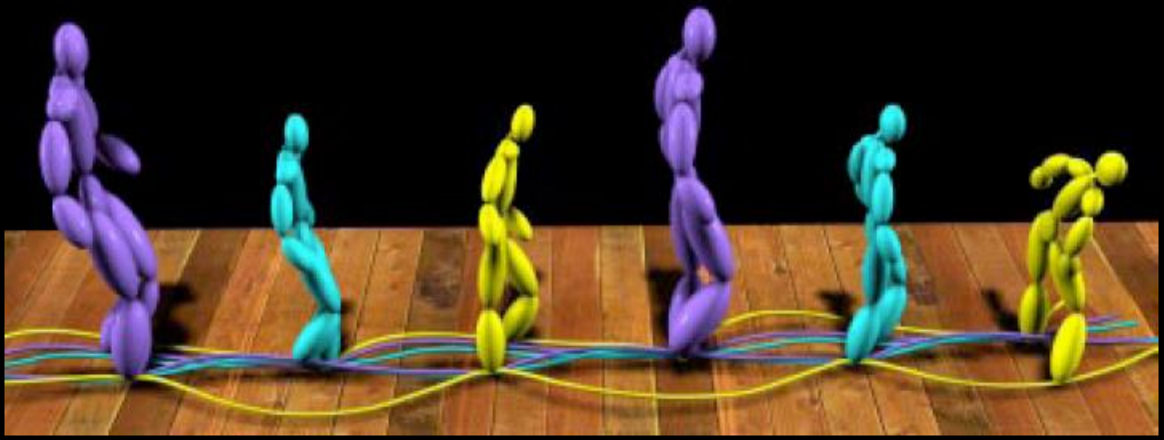
Simplified motion

Edited simplified



Motion Retargetting

- Gleicher, "Retargetting motion to new characters," SIGGRAPH'98
- Adapting an animated motion from one character to another
  - characters with different sizes



Motion Retargetting (cont.)

- Define constraints

- Apply to a new character

Motion Retargetting (cont.)

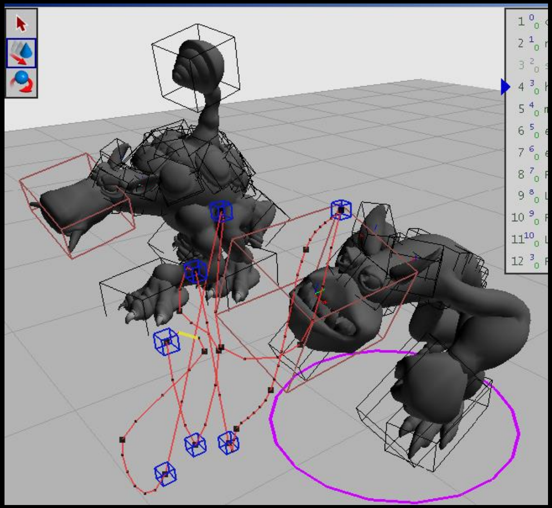
- Add Translational Offset
  (approximated answer)

- Solve for constraints
  (Nonlinear constrained optimization)

Motion Retargeting Video

Real-time Motion Retargetting

- Hecker et al., "Real-time Motion Retargeting to Highly Varied User-Created Morphologies," SIGGRAPH'08
- Retargetting to unknown skeletons



- Used in game "Spore"
  - Allow players to author their own characters with different skeletons

Deep Motion Retargeting & Style Transfer

- Skeleton-Aware Networks for Deep Motion Retargeting, SIGGRAPH’20
- Unpaired Motion Style Transfer from Video to Animation, SIGGRAPH’20

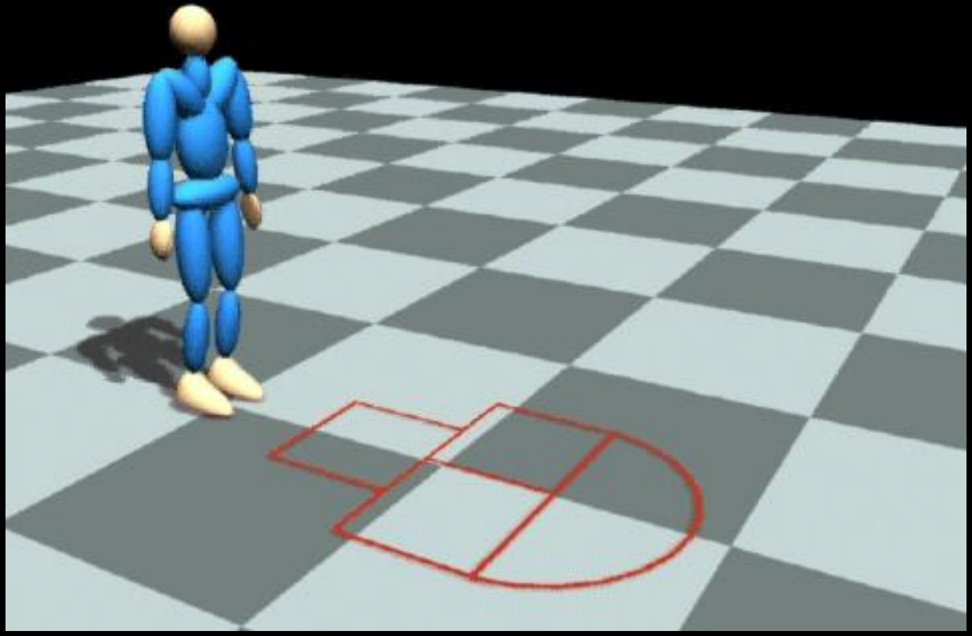
Motion Synthesis using Spacetime Constraints

- Simplified physics—momentum patterns enforced
  - Liu & Popovic, “Synthesis of Complex Dynamic Character Motion from Simple Animations,” SIGGRAPH’02

Top: input
Bottom: synthesized motion

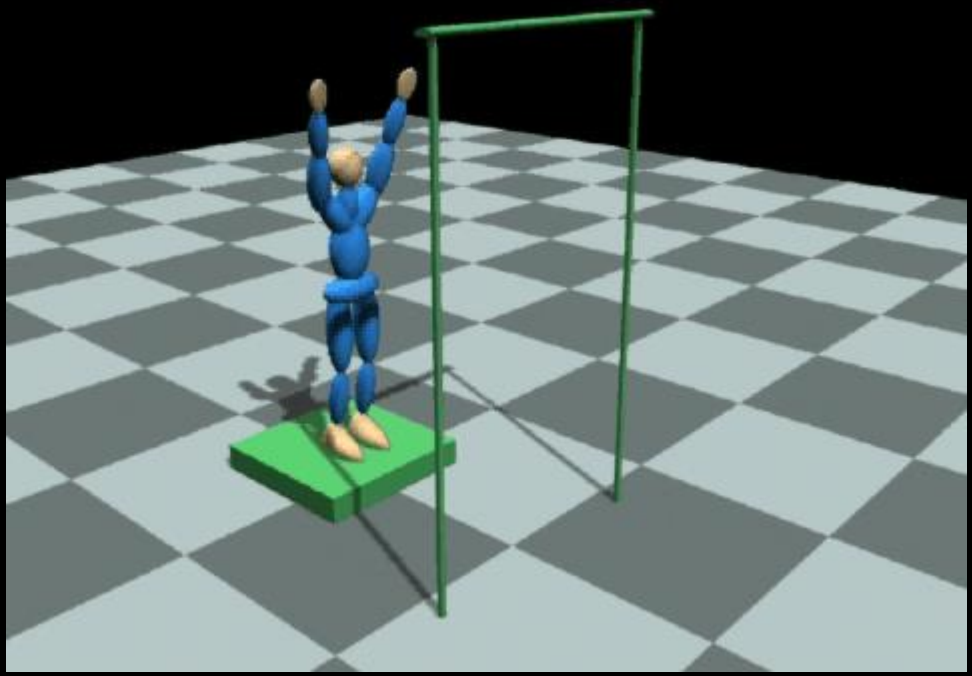
Motion Synthesis Results

- Video



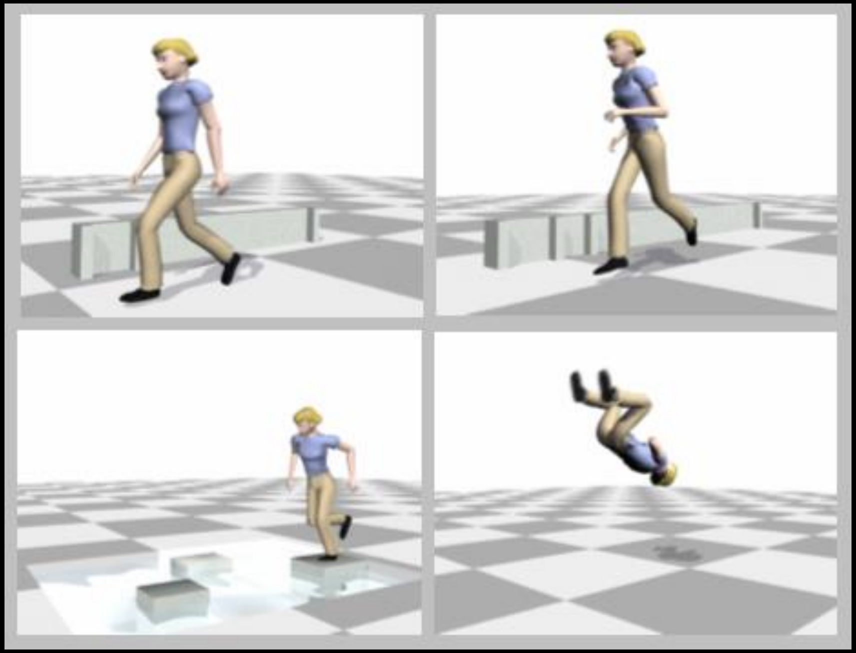
Motion Synthesis Results

- Video



Spacetime Constraints in PCA space

- Safonova et al., "Synthesizing physically realistic human motion in low-dimensional, behavior-specific spaces," SIGGRAPH'04



Human Motion Generation: A Survey
TPAMI 2024