Animation, Motion Capture, & Inverse Kinematics
Spacetime Swing - Siggraph 1998

HW2 Velocity Interpolation Debugging

```plaintext
grid 6 4 1
cell_dimensions 1 1 1
timestep 0.01
flow compressible
xy_boundary free_slip
yz_boundary free_slip
zz_boundary free_slip
viscosity 0.1
gravity 0
initial_particles everywhere random
density 64
initial_velocity zero
u 1 2 0 10
```
Last Time?

- Tetrahedral Meshing
- Haptics
- Anisotropic Materials
- Fracture

Today: How do we Animate?

- **Readings for Today**
  - How do we Animate?
    - Keyframing
    - Procedural Animation
    - Physically-Based Animation
    - Motion Capture
    - Skeletal Animation
    - Forward and Inverse Kinematics
  - Research Paper: Simple Artist Sketch + Motion Capture + Inverse Kinematics
- Figure Skating Lesson
- Readings for Next Time
Reading for Today

• “Real-Time Hand-Tracking with a Color Glove”
  SIGGRAPH 2009, Wang & Popović

Capturing and Animating Occluded Cloth,
White, Crane, & Forsyth, SIGGRAPH 2007
• Rapid prototyping of realistic character motion from rough low-quality animations
• Obey the laws of physics & stay within space of naturally-occurring movements

Reading for Today

“Synthesis of Complex Dynamic Character Motion from Simple Animation”, Liu & Popović, 2002

“Artist-Directed Dynamics for 2D Animation”, Bai, Kaufman, Liu, & Popović, SIGGRAPH 2016

Figure 6: Keyframes used in the articulated character walk example. The artist only specifies keyframes for a subset of handles (handles at hands and feet) which are shown as blue dots. Nine keyframes are used to create a walking cycle. Their timing is visualized by the black lines at the bottom. The artworks are adapted from Angry animator.com (http://www.angryanimator.com/)
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Keyframing

- Use spline curves to automate the in betweening
  - Good control
  - Less tedious than drawing every frame
- Creating a good animation still requires considerable skill and talent and learning from observing the real world

ACM © 1987 “Principles of traditional animation applied to 3D computer animation”
Disney’s 12 Principles of Animation

“The Illusion of Life: Disney Animation”, Ollie Johnston & Frank Thomas, 1981

Squash & Stretch

Slow In & Slow Out

Procedural Animation

• Describes the motion algorithmically, as a function of small number of parameters

• Example: a clock with second, minute and hour hands
  – express the clock motions in terms of a “seconds” variable
  – the clock is animated by varying the seconds parameter

• Example: A bouncing ball
  – $\text{Abs}(\sin(\omega t + \theta_0))e^{-kt}$
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Physically-Based Animation

- Assign physical properties to objects (masses, forces, inertial properties)
- Simulate physics by solving equations
- Realistic, but difficult to control
- Used for secondary motions (hair, cloth, scattering, splashes, breaking, smoke, etc.) that respond to primary user controlled animation

“Interactive Manipulation of Rigid Body Simulations” SIGGRAPH 2000, Popović, Seitz, Erdmann, Popović & Witkin
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Motion Capture

• Optical markers, high-speed cameras, triangulation → 3D position
• Captures style, subtle nuances and realism at high-resolution
• You must observe someone do something
• Difficult (or impossible?) to edit mo-cap data

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Articulated Models

• Articulated models:
  – rigid parts
  – connected by joints
• They can be animated by specifying the joint angles as functions of time.

Skeleton Hierarchy

• Each bone transformation described relative to the parent in the hierarchy:
Skeletal Animation Challenges

- **Skinning**
  - Complex deformable skin, muscle, skin motion
- **Hierarchical controls**
  - Smile control, eye blinking, etc.
  - Keyframes for these higher-level controls
- A huge amount of time is spent building the 3D models, its skeleton, and its controls


Forward Kinematics

- Given skeleton parameters $p$, and the position of the effector in local coordinates $V_l$, what is the position of the effector in the world coordinates $V_w$?

$$V_w = T(x_h, y_h, z_h)R(q_h, f_h, s_h)T_hR(q_t, f_t, s_t)T_tR(q_c)T_cR(q_f, f_f)V_l$$

$$V_w = S(p)V_l$$

*S(p) is “just” a 4x4 affine transformation matrix!*
Inverse Kinematics (IK)

- Given the position of the effector in local coordinates $V_l$ and the desired position $V_w$ in world coordinates, what are the skeleton parameters $p$?
- Much harder requires solving the inverse of the non-linear function:

  \[ \text{find } p \text{ such that } S(p)V_l = V_w \]

Why is this hard? Why is it non-linear?

Under-/Over- Constrained IK

- Application: Robot Motion Planning

“No solutions”

“One solution”

“Two solutions (2D)”

“Many solutions”

“The good-looking textured light-sourced bouncy fun smart and stretchy page”

Hugo Elias, [http://freespace.virgin.net/hugo.elias/models/m_ik.htm](http://freespace.virgin.net/hugo.elias/models/m_ik.htm)
Searching Configuration Space

- Use *gradient descent* to walk from starting configuration to target
- Angle restrictions & collisions can introduce local minima

“The good-looking textured light-sourced bouncy fun smart and stretchy page” Hugo Elias, [http://freespace.virgin.net/hugo.elias/models/m_ik2.htm](http://freespace.virgin.net/hugo.elias/models/m_ik2.htm)

IK Challenge

- Find a “natural” skeleton configuration for a given collection of pose constraints
- A *vector constraint function* $C(p) = 0$ collects all pose constraints
- A *scalar objective function* $g(p)$ measures the quality of a pose, $g(p)$ is minimum for most natural poses.

Example $g(p)$:
- deviation from natural pose
- joint stiffness
- power consumption

Force: $\text{Newton (N)} = \text{kg} \times \text{m} / \text{s}^2$
Work: $\text{Joule (J)} = \text{N} \times \text{m} = \text{kg} \times \text{m}^2 / \text{s}^2$
Power: $\text{Watt (W)} = \text{J}/\text{s} = \text{kg} \times \text{m}^2 / \text{s}^3$
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Rapid prototyping of realistic character motion from rough low-quality animations
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What’s a Natural Pose?

Training database of ~50 “natural poses”
For each, compute center of mass of:
– Upper body
– Arms
– Lower body
The relative COM of each generated pose is matched to most similar database example
**Linear and Angular Momentum**

- In unconstrained animation (no contacts), both linear & angular momentum should be conserved.
- The center of mass should follow a parabolic trajectory according to gravity.
- The joints should move such that the angular momentum of the whole body remains constant.

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**During Constrained Motion**

- During *constrained* motion (when in contact with the ground), the angular momentum follows a spline curve modeled after biomechanics data.

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Liu & Popović
System Features

- Automatically detect point/line/plane constraints
- Divide animation into constrained portions (e.g., feet in contact with ground) and unconstrained portions (e.g., free flight)
- Linear and angular momentum constraints without having to compute muscle forces
- Minimize:
  - Mass displacement
  - Velocity of the degrees of freedom (DOF)
  - “Unbalance” (distance the COM is outside of ground constraints)

“Synthesis of Complex Dynamic Character Motion from Simple Animation”, Liu & Popović, 2002
“Synthesis of Complex Dynamic Character Motion from Simple Animation”, Liu & Popović, 2002

Coach Mary Figure Skating

https://www.youtube.com/channel/UCUqodbdTE3hIjfloPDn6amw
https://www.youtube.com/watch?v=eVP8r-ubbp8
Coach Mary Figure Skating

https://www.youtube.com/channel/UCUqodbdTE3hljfloPDn6amw
https://www.youtube.com/watch?v=eVP8r-ubbp8

Figure Skating Motion Capture, Richards Biomechanics Lab, University of Delaware, 2017

https://www.udel.edu/udaily/2017/december/figure-skating-biomechanics-olympics/
**Figure 8:** A five-link eel swims in a 2D fluid environment. In contrast to the simulation in 3D, an eel swimming in 2D fluid sheds only one single vortex street. Red traces show the counter-clockwise vortices while blue traces show the clockwise vortices.

http://www.cc.gatech.edu/~jtan34/project/articulatedSwimmingCreatures.html
“Flexible Muscle-Based Locomotion for Bipedal Creatures”, Geijtenbeek, van de Panne, van der Stappen, SIGGRAPH Asia 2013

Figure 1: Physics-based simulation of locomotion for a variety of creatures driven by 3D muscle-based control. The synthesized controllers can locomote in real time at a range of speeds, be steered to a target heading, and can traverse variable terrain.

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