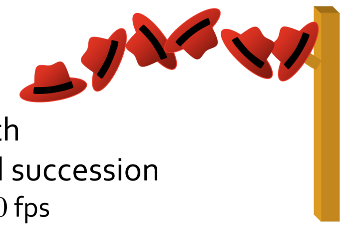
EECS 487: Interactive Computer Graphics

Lecture 33:
- Introduction to animation
- Key-frame character animation
- Inverse kinematics and motion capture

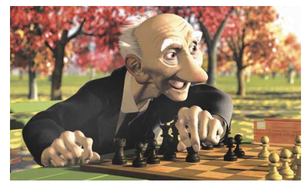
What is Animation?

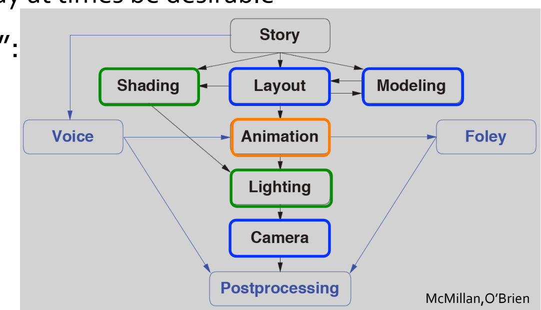


Generate perception of motion with sequence of images shown in rapid succession
- humans "see" smooth motion at 12—70 fps

Must be technically excellent, but more importantly, aesthetically, emotionally compelling
- violation of realism may at times be desirable

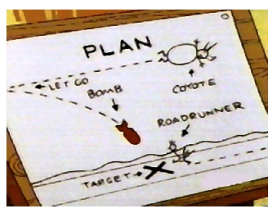
Animation "pipeline":



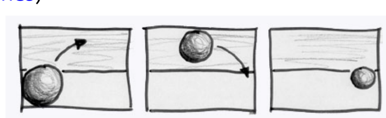


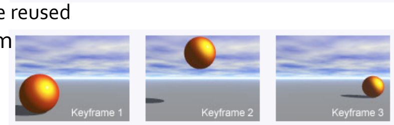
McMillan,O'Brien

Traditional Animation



1. Straight ahead: draw each frame, one frame at a time
   - lead to spontaneity
   - great control
   - tedious: 24 fps, 1,440 frames/minute, 130K frames for a 1.5 hour movie
2. Pose-to-pose (developed by Walt Disney):
   - director plans shots using storyboards
   - senior artists sketch key poses (keyframes)
     - typically when motion changes
   - interns fill in the in-between frames
   - all line drawings are painted on cels
     - composed in layers
     - background changes infrequently, can be reused
   - photograph finished cel-stack onto film





Yu,Marschner,Durand,Hodgins

Computer Animation

2D animation:
- CADrawing and painting are now routine
- but 2D in-betweening (morphing) is hard to get right

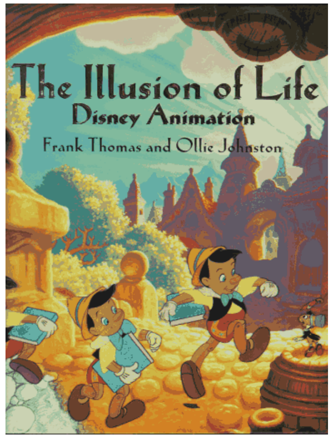
Instead, we assume 3D model of scene
- for each scene, vary parameters to generate desired pose for all objects
- stop-motion: shooting miniature physical models frame by frame

Some Artistic Considerations

Goal: make characters that move in a convincing way to communicate personality and emotion

Animation principles developed by Disney in the 20's—30's, adapted by CG animators, e.g., Lasseter of Pixar (now Disney)

The most important source of traditional animation principles is the book by Thomas and Johnston, *Disney Animation: The Illusion of Life*



Principles of Traditional Animation

Eleven principles of traditional animation compiled by Lasseter:

1. Squash and stretch
2. Slow in, slow out
3. Timing
4. Anticipation
5. Follow through
6. Overlapping action
7. Secondary action
8. Arcs
9. Exaggeration
10. Appeal
11. Staging

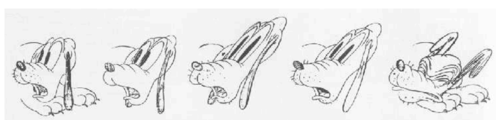
Many of these principles follow indirectly from physics, e.g., anticipation, follow-through, and many other effects can be produced by simply minimizing physical energy, but exaggerated

Marschner

Squash and Stretch and Slow In/Out

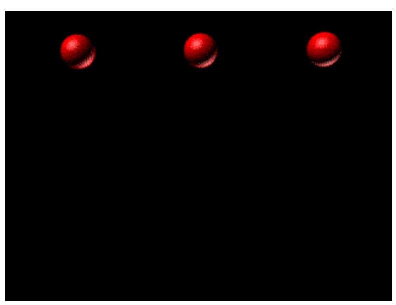
Squash and stretch

- rigidity/softness via distortion during motion
- pseudo-physics: carrying momentum
- increase the sense of speed
- try to keep the volume constant



Slow in and out

- an extreme pose can be emphasized by slowing down as you get to it (and as you leave it)
- in practice, many things do not move abruptly but start and stop gradually
- pseudo-physics: overcoming inertia



no fx | squash/stretch +slow in/out | squash/stretch only

Owen

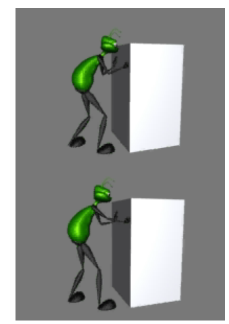
Timing of Motion

Timing can completely change the interpretation of motion

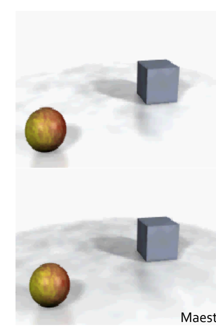
Time spent on action affects perception

- timing indicates weight
- speed determines emotion

Since timing is so critical, animators usually draw a time scale next to keyframes to indicate how to generate the in-between frames



Comet



Maestri

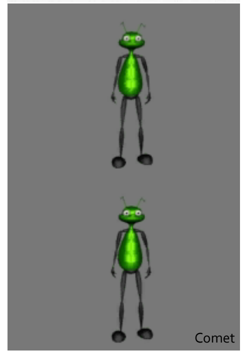
Anticipation

An action can be divided into three:
- anticipation
- action
- reaction

Anatomical motivation: a muscle must extend before it can contract

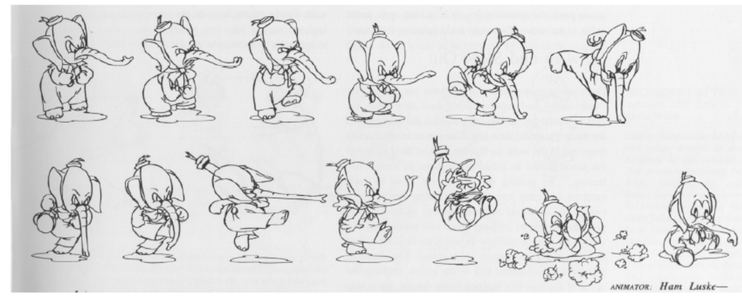
Prepares audience for an action
- don't surprise the audience
- direct their attention to what's important

Amount of anticipation can affect perception of speed and weight



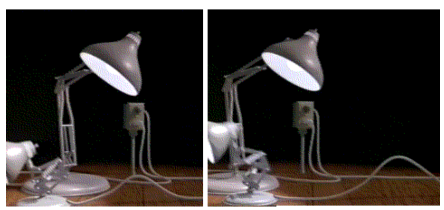
Follow Through and Overlapping Action

Actions do not end abruptly
- hand continues to move after throwing a ball: inertia
- audience likes to see resolution of action
- discontinuities are unsettling
- the termination of an action anticipates the next
- overlaps indicate intentions

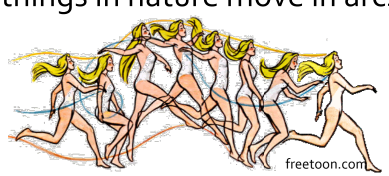


Secondary Actions and Arcs

Use secondary actions to increase complexity of scene, but it should not interfere with the primary action



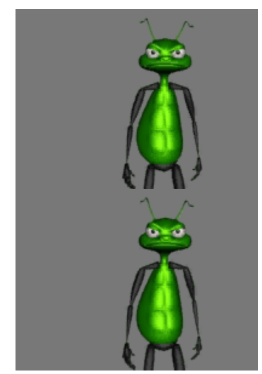
Avoid straight lines since most things in nature move in arcs



Exaggeration and Appeal

Exaggeration
- get to the heart of the idea and emphasize it so the audience can see it
- choose which properties to exaggerate

Appeal
- the character must interest the audience
- it doesn't have to be cute and cuddly
- design, simplicity, behavior all affect appeal
- avoid perfect symmetries
- example: Luxo, Jr. was made to appear childlike

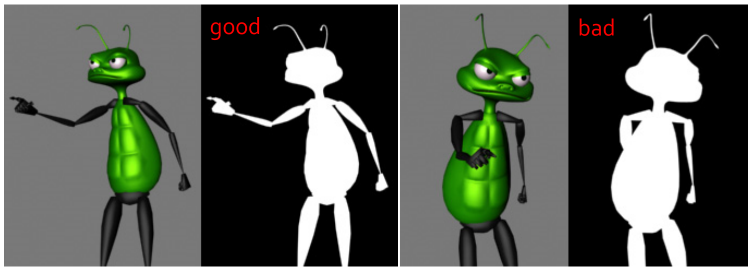


Comet

Staging

Present the idea so that it is unmistakably clear

- audience can only focus on one thing at a time: main object should be contrasted
- stage action in silhouette
- in dialogue, characters should face ¾ towards the camera, not right at each other



comet-cartoons.com/3ddocs/charanim/

What is Animation?

Make objects change over time

Key technical problems are how to specify, generate, and manipulate motion

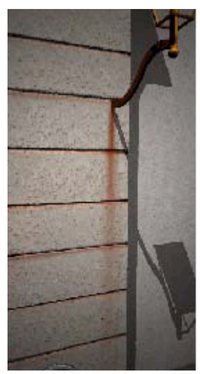
Four alternatives:

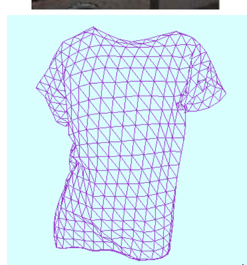
1. brute force: model each frame
2. key-frame animation:
   - key poses specified by hand
   - or poses recorded by motion capture
   - interpolate in-between frames

Durand

What is Animation?

3. procedural/behavioral: describe motion algorithmically
   - local rules, global emergent behavior: boids, brain-spring
   - procedural texture: crack propagation in glass or concrete, metallic patina, stone aging, water flow and rust
4. physical simulation: motion according to physical laws
   - particle systems for fire, smoke
   - mass-spring damper arrays for fluttering cloth
   - fluid simulation





Durand

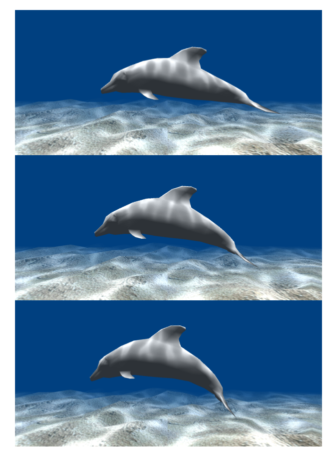
Key-frame Character Animation

Two approaches:

1. blend shapes or morph targets
2. rigged characters or articulated models

Blend shapes:

- a very simple surface control scheme
- no skeleton
- based on interpolating (tweening) among several key poses
  - given a number of base meshes, combine them with time-dependent coefficients



Marschner

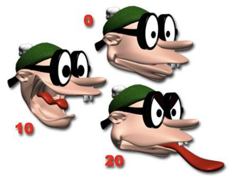
Blend Shapes

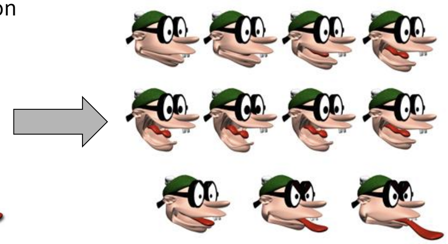
Setup:

- user provides key shapes with a position ($\mathbf{p}_{ij}$) for every control point i in shape j
- for each frame k user provides a weight $w_{j,k}$ for each key shape ($\sum_j w_{j,k} = 1$), i.e., how much each key shape affects frame k
- the shape for frame k can be computed from the control points: $\mathbf{p}_{ik} = \sum_j w_{j,k} \mathbf{p}_{ij}$

Works well for relatively small motions

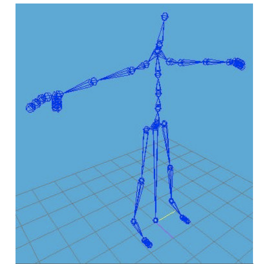
- runs in real time, e.g., as vertex shader
- often used for facial animation
- popular for games

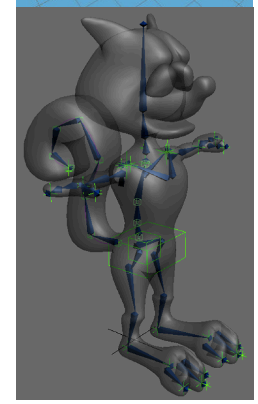




Marschner

Rigged Character





To support more complex character animation, models are often based on jointed skeletons (articulated models)

Kinematics: the study of movement of articulated models

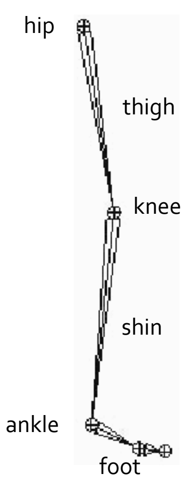
- began in the mechanical engineering of robots

The skeleton can be fleshed out in any way, e.g., with mesh skinning

- skin deforms following bone movements

Marschner, Gillies

Articulated Model



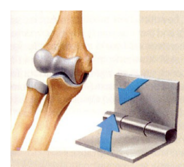
Setup:

- rigid parts: each link (bone) in the articulated chain (skeleton) is rigid
  - not physically accurate, but rigid skeleton constrains movement
- connected by joints: movement is constrained by the degree of freedom at each joint

Can be animated by specifying the joint angles as functions of time

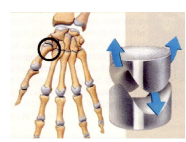
Gillies

Degrees of Freedom (DoFs)



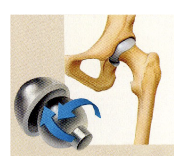
Hinge/pin joint: 1 DoF

- knee or elbow joint



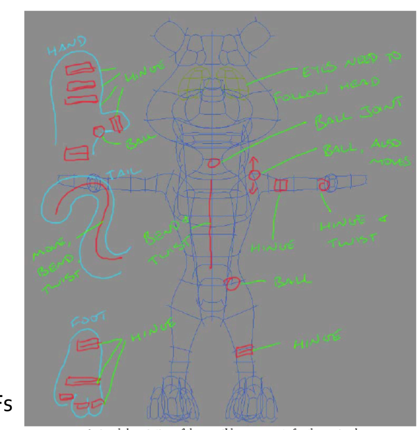
Saddle: 2 DoFs

- wrist/hand joints



Ball/socket joint: 3 DoFs

- hip, shoulder, neck



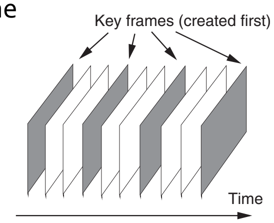
A visual description of the possible movements for the squirrel

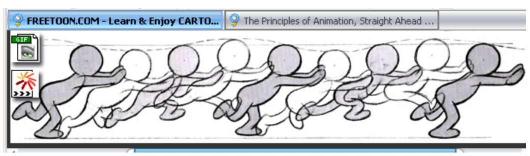
Marschner, Gillies

Key-frame Animation

With the character rigged, next specify key poses at specific time steps:

- each pose controlled by a set of variables: joint angles, positions, etc.
- each variable changes as a function of time
- for each variable, specify its key value at "important" or key frames
  - in-between frames will be created by interpolating these key values
  - more generally, each variable may have a different set of key frames





Durand,O'Brien

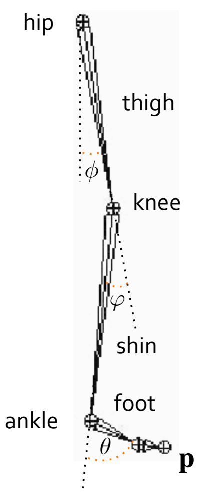
Key-frame Animation

Steps:

1. character modeling: design the geometry
2. character rigging: set up a bunch of parameters
   - joint angles, positions, etc.
3. set up key-framing
   - specify key values of parameters at specific times
     - by forward kinematics
     - by inverse kinematics
       - incl. motion capture
   - specify an interpolation for the in-between values

Yu

Forward Kinematics



Calculate the position and orientation of a limb's end point (end effector) as a function of the angles of all joints:

$\mathbf{p} = f(\Theta)$

where:

$\mathbf{p}$: position of end effector

Θ: angles, positions, … of joints

For example: $\begin{bmatrix} p_x \\ p_y \end{bmatrix} = \begin{bmatrix} g(\phi,\varphi,\theta) \\ h(\phi,\varphi,\theta) \end{bmatrix}$

Yu

Hierarchical Modeling

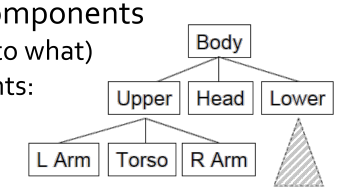
Could animate by moving every control point (joint) at every key frame: tedious, hard to get smooth, consistent motion

Animation need to be controlled at a higher level:

- "bend elbow" instead of
- "move left forearm one square inch"

Model objects as a hierarchy of components

- encodes topology (what's connected to what)
- specifies geometric relations from joints: tree structure
  - each component defined relative to parent
- independent of display geometry



Marschner,Gillies,Yu, Hodgins,Durand

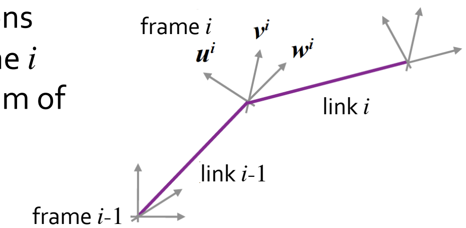
Moving Components

Define a coordinate system at the top of the hierarchy and at each joint

Each joint is thus a separate frame of reference, with its own local coordinate system

Each local coordinate system is defined in the coordinate system of the previous frame

We can express positions and directions for frame i in the coordinate system of frame $i-1$ by a matrix transformation



Gillies

Embedding Transformations

To draw an object, traverse its hierarchical model

Two types of nodes:

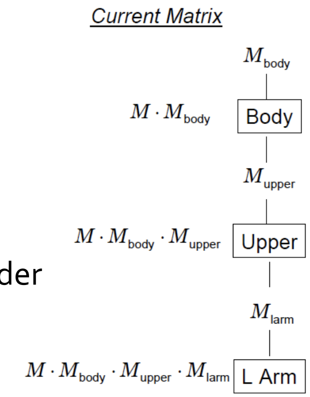
- object nodes: draw them (may include attributes)
- transform nodes:
  - multiply into Current Matrix on the way down
  - remove from Current Matrix on the way up
  - ⇒ constantly changing local coordinate system

Allows changes at different scales

- apply rotation above "Upper Body"
- vs. rotation above "L Arm"

Be careful about transformation order

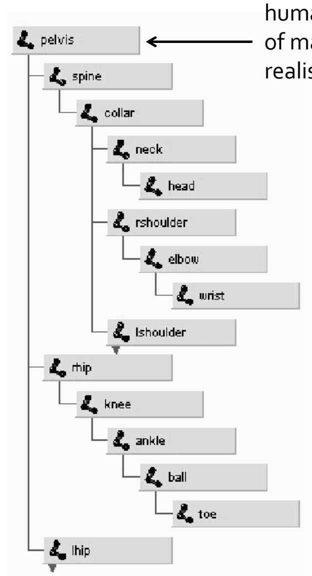
- (usually) scale before rotate
- (usually) rotate before translate



Yu

Use OpenGL Matrix Stack

```
human()
{
  pelvis();
  glPushMatrix();
    glTranslate( ... );
    glRotate( ... );
    lhip();
    . . .
  glPopMatrix();
  glPushMatrix();
    glTranslate( ... );
    glRotate( ... );
    rhip();
    glPushMatrix();
      glTranslate( ... );
      glRotate( ... );
      knee();
      . . .
    glPopMatrix();
  glPopMatrix();
  . . .
}
```

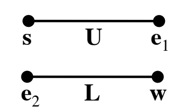


human's center of mass, more realistic motion

Hodgins

Example

Out of two bones:

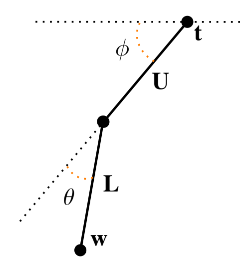


We want to model an arm as a hierarchy:

where:

U: upper arm

L: lower arm (forearm)



User controlled parameters:

ϕ: shoulder joint angle

θ: elbow joint angle

t: where shoulder meets torso

w: wrist joint location

Yu

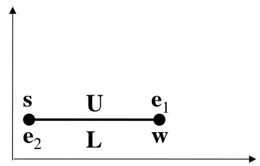
Positioning the Forearm

Initially, segments in same position

s: shoulder joint location

$\mathbf{e}_1$, $\mathbf{e}_2$: elbow joint locations

w: wrist joint location

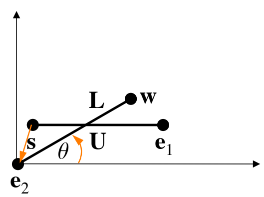


First, perform elbow rotation

- translate elbow joint to origin
- rotate by given angle (θ)

(1) translate($-\mathbf{e}_2$)

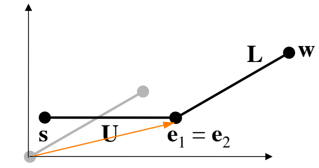
(2) rotate(θ)



Attaching Forearm to Upper Arm

Second, align corresponding elbow

(3) translate($\mathbf{e}_1$)

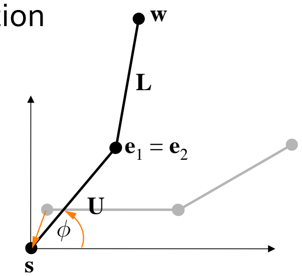


Third, perform shoulder rotation

- operate on whole arm

(4) translate($-\mathbf{s}$)

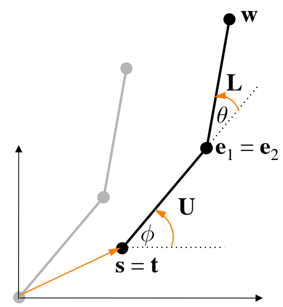
(5) rotate(ϕ)



Placing the Shoulder

Fourth, put shoulder in place

(6) translate(**t**)



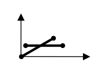
Important things to notice

- limited control knobs (just the angles)
- automatically handle interconnection (elbow joint)

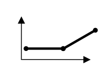
Converting to Hierarchy

(1) translate($-\mathbf{e}_2$)

(2) rotate(θ)

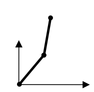


(3) translate($\mathbf{e}_1$)

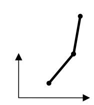


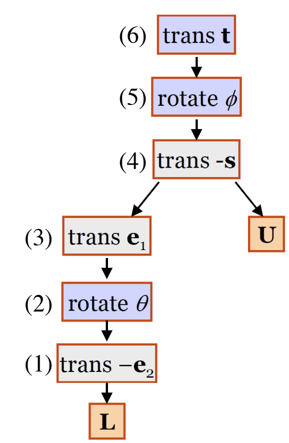
(4) translate($-\mathbf{s}$)

(5) rotate(ϕ)



(6) translate(**t**)

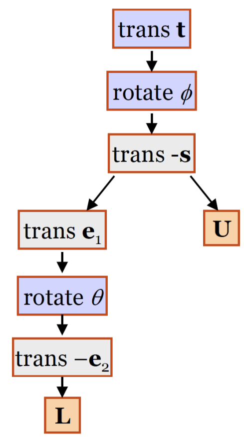




Properties of Hierarchy

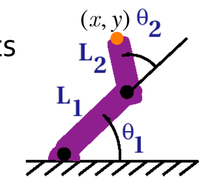
Geometry is always at the leaves
- internal nodes are transform nodes

There are two types of transforms
- structural
  - fixed at design time
  - keeps things together
- control knobs
  - variable parameters
  - controlled by user



Inverse Kinematics

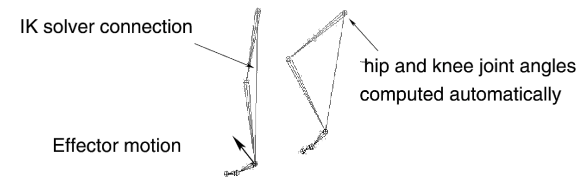
Forward kinematics: the angle of all joints are explicitly specified by the animator



$$x = L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2)$$
$$y = L_1 \sin\theta_1 + L_2 \sin(\theta_1 + \theta_2)$$

This gets tedious … even with hierarchical modeling

Inverse kinematics: the animator drags the hands and feet into place and inverse kinematics solves for the angles to achieve the final position

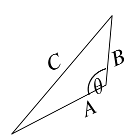


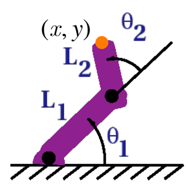
Inverse Kinematics Example

Determine joint angles from position of end effector ●

First compute θ_2: by cosine rule,

$$|C|^2 = |A|^2 + |B|^2 - 2|A||B|\cos\theta$$
$$x^2 + y^2 = L_1^2 + L_2^2 - 2L_1L_2\cos(180 - \theta_2)$$
$$\theta_2 = \cos^{-1}\left(\frac{x^2 + y^2 - L_1^2 - L_2^2}{2L_1L_2}\right)$$





Then solve for θ_1 by expanding x and y (from prev slide) using: $\cos(\varphi + \psi) = \cos\varphi\cos\psi - \sin\varphi\sin\psi$

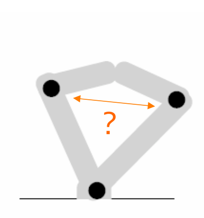
$\sin(\varphi + \psi) = \sin\varphi\cos\psi + \sin\psi\cos\varphi$

$$\theta_1 = \tan^{-1}\left(\frac{-(L_2\sin\theta_2)x + (L_1 + L_2\cos\theta_2)y}{(L_2\sin\theta_2)y + (L_1 + L_2\cos\theta_2)x}\right)$$

Inverse Kinematics

Unfortunately, real models are much more complex:
- a human has around 200 degrees of freedom

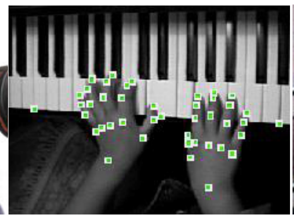
Suppose we specify locations of end effectors
- the mapping of parameters to effector positions is non-linear
  - inverting this function is not possible
- we need to calculate the relative positions of all intermediate links to achieve the pose
  - this is an ill-posed problem (there may be infinitely many solutions for some chains)
    - need to find a constrained solution, minimizing for example, the joint movements, maintain balance, …
  - similarly, there may not be any parameter settings that work
    - need to pick one that is "close enough"
- both involve some kind of optimization algorithm that rely on numerical methods, e.g., the Jacobian

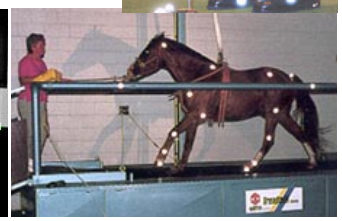


Motion Capture

Instead of specifying end effector positions manually, measure it from the real world

Captures style, subtle nuances and realism





Motion Capture Technologies

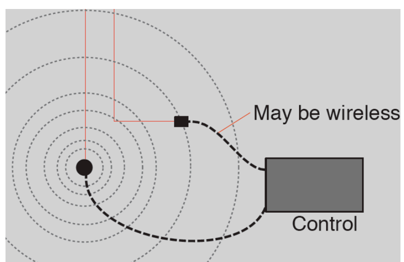
Mechanical
- measure joint angles directly
- works in any environment
- restricts motion

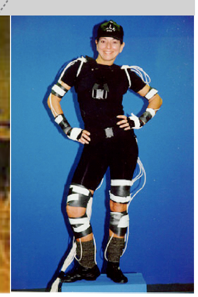
Popovic,O'Brien

Motion Capture Technologies

Magnetic
- tethered or wireless
- transmitter emits field
- trackers sense field
- trackers report position and orientation

Disadvantages:
- nearby metal objects cause distortions
- limited range
- limited number of trackers
- low frequency (60 Hz)





Popovic,O'Brien

Motion Capture Technologies

Optical Passive
- strap a bunch of passive markers on subject (body, face)
- location of markers tracked by 8 or more cameras
- triangulate to get marker's 3D position
- convert this to joint angles and map to articulated model
- high frequency (240 Hz)
- restricted volume: studio size, lighting, number of cameras
- occlusions are troublesome

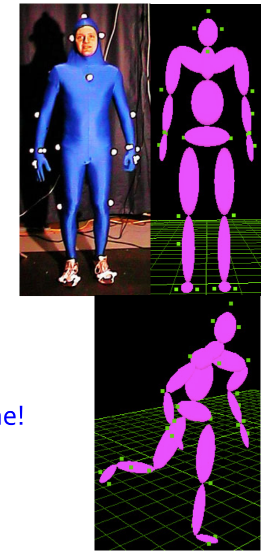

retroreflective markers


camera with IR illuminators

Popovic,O'Brien

Optical Motion Capture Process

1. Start with standard rest pose
2. Calibrate: match skeleton, find offsets to markers
3. Identify and uniquely label markers
4. Motion trial: use a short sequence that exercises all DOFs of the subject
5. Track forward through time (but watch for markers dropping out due to occlusion!)
6. Compute joint angles: explain data using skeleton DOFs
   ⇒ an inverse kinematics problem per frame!

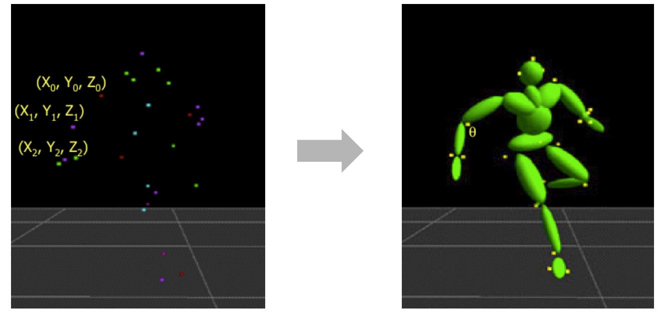


Popovic

Marker Data to Motion

Motion capture gives inconvenient raw data

- passive optical gives "least information"
- accurate position, but correspondence difficult
  - which marker is which?
  - where are the markers relative to the skeleton?

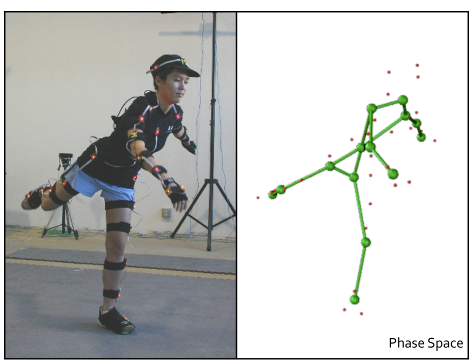


Popovic

Motion Capture Technologies

Active Optical

- uses LEDs instead of passive markers
- LEDs blink IDs → correspondence automatic
- number of markers trades off with frame rate



O'Brien

Pros and Cons of Motion Capture

Mocap data is very realistic

- timing matches performance exactly
- dimensions are exact

But it is not enough for good character animation

- noise, errors from non-rigid marker mounting
- contains no exaggeration
- limited in the complexity of the scenes they can capture

Popovic,Yu

Pros and Cons of Motion Capture

To increase versatility of mocap:

- break scenes into smaller pieces and re-construct later
- gather lots of snippets of motion capture
  - e.g.: several ways to dunk, dribble, pass
- arrange them so that they can be pieced together smoothly
- at run time, figure out which pieces to play for desired motion

Automated stop motion?

Problem: once the data is captured, it's hard to modify for a different purpose

Performance Capture

Mocap is no panacea for assigning key values to parameters ⇒ mocap data is generally a starting point for skilled animators to create the final product

Many studios regard motion capture as low quality, cheap motion

- no directive/creative control

Performance capture is different

- use mocap device as an expressive input device
- e.g., James Cameron's *Avatar*