

Animation

CS 4620 Lecture 19

What is animation?

- Modeling = specifying shape
 - using all the tools we've seen: hierarchies, meshes, curved surfaces...
- Animation = specifying shape as a function of time
 - just modeling done once per frame?
 - yes, but need smooth, concerted movement

Keyframes in hand-drawn animation

- End goal: a drawing per frame, with nice smooth motion
- “Straight ahead” is drawing frames in order (using a lightbox to see the previous frame or frames)
 - but it is hard to get a character to land at a particular pose at a particular time
- Instead use *key frames* to plan out the action
 - draw important poses first, then fill in the *in-betweens*

Keyframes in computer animation

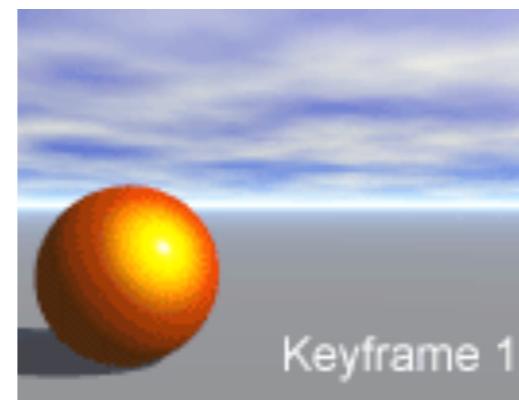
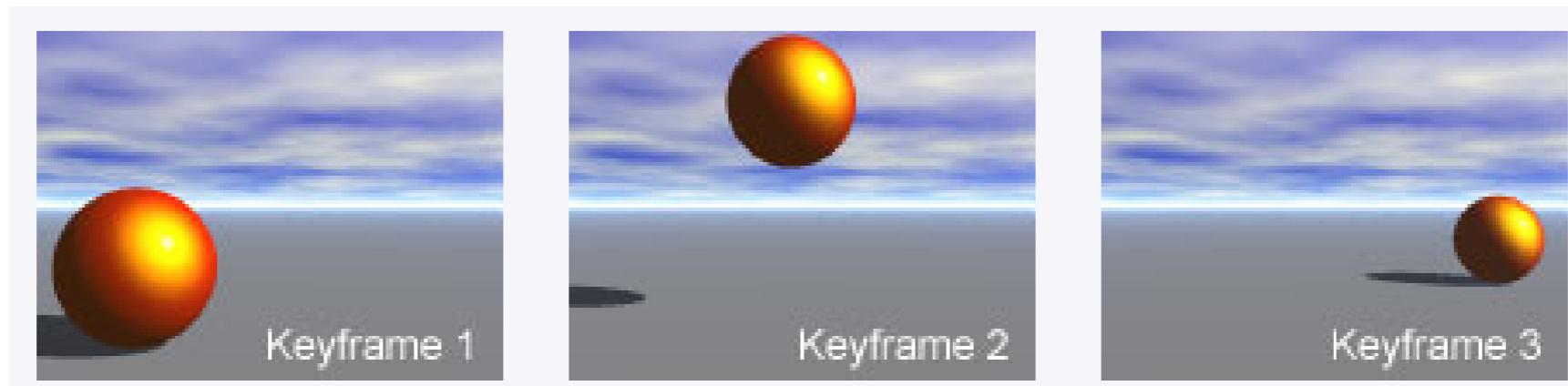
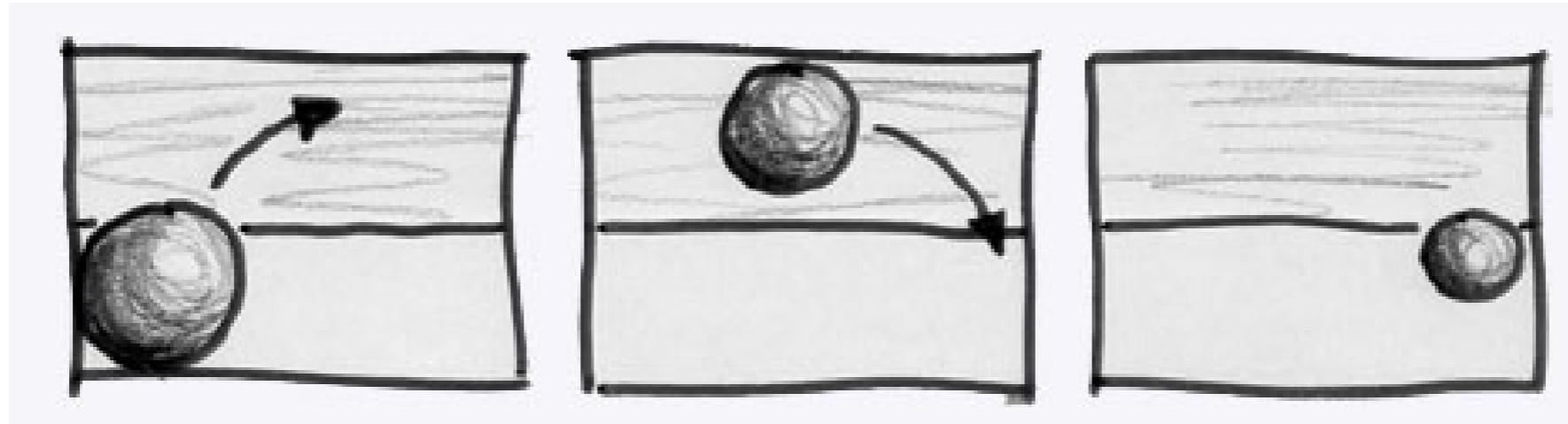
- Just as with hand-drawn animation, adjusting the model from scratch for every frame would be tedious and difficult
- Same solution: animator establishes the keyframes, software fills in the in-betweens
- Two key ideas of computer animation:
 - create *high-level* controls for adjusting geometry
 - *interpolate* these controls over time between keyframes

The most basic animation control

- Affine transformations position things in modeling
- Time-varying affine transformations move things around in animation
- A hierarchy of time-varying transformations is the main workhorse of animation
 - and the basic framework within which all the more sophisticated techniques are built

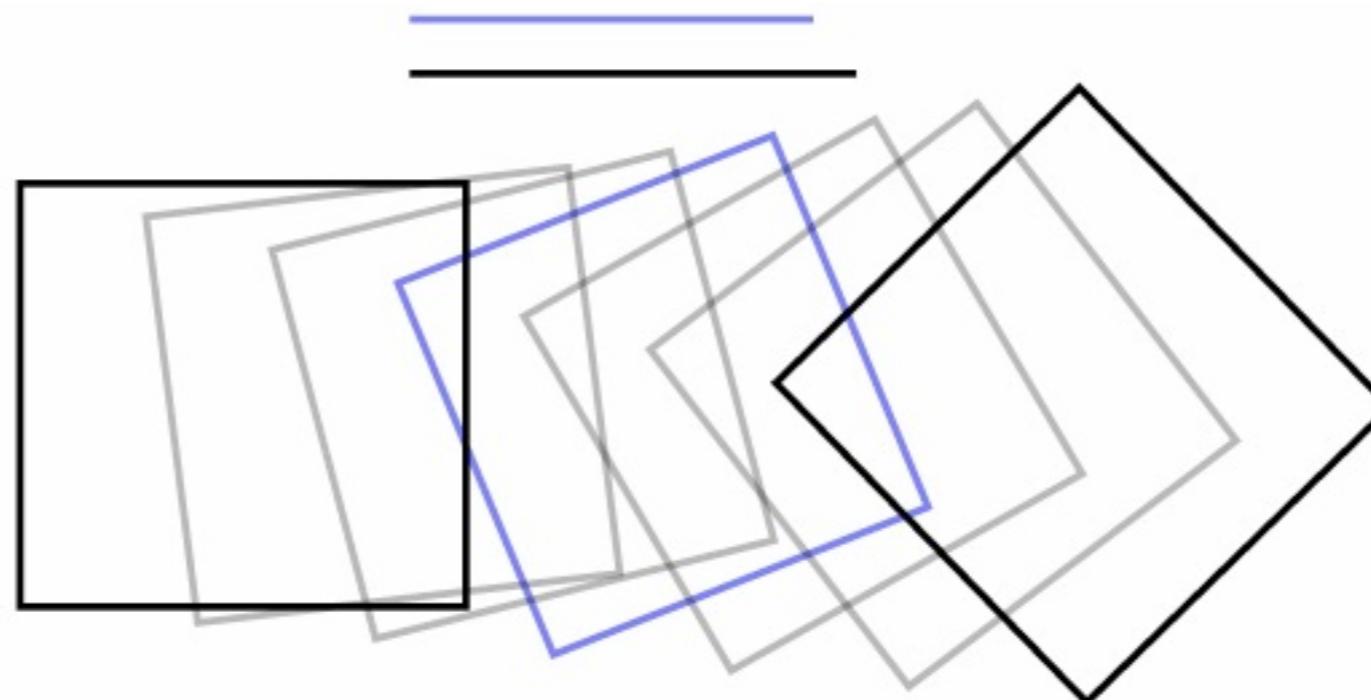
Keyframe animation

[Bryce Tutorial <http://www.cadtutor.net/dd/bryce/anim/anim.html>]



Interpolating transformations

- Move a set of points by applying an affine transformation
- How to animate the transformation over time?
 - Interpolate the matrix entries from keyframe to keyframe?
 - This is fine for translations but bad for rotations



What is a rotation?

- Think of the set of possible orientations of a 3D object
 - you get from one orientation to another by rotating
 - if we agree on some starting orientation, rotations and orientations are pretty much the same thing
- It is a smoothly connected three-dimensional space
 - how can you tell? For any orientation, I can make a small rotation around any axis (pick axis = 2D, pick angle = 1D)
- This set is a subset of linear transformations called $\text{SO}(3)$
 - **O** for orthogonal, **S** for “special” (determinant +1), **3** for 3D

Calculating with rotations

- Representing rotations with numbers requires a function
$$f : \mathbb{R}^n \rightarrow SO(3)$$
- The situation is analogous to representing directions in 3-space
 - there we are dealing with the set S^2 , the two-dimensional sphere (I mean the sphere is a 2D surface)
 - like $SO(3)$ it is very symmetric; no directions are specially distinguished

Warm-up: spherical coordinates

- We can use latitude and longitude to parameterize the 2-sphere (aka. directions in 3D), but with some annoyances
 - the poles are special, and are represented many times
 - if you are at the pole, going East does nothing
 - near the pole you have to change longitude a lot to get anywhere
 - traveling along straight lines in (latitude, longitude) leads to some pretty weird paths on the globe
 - you are standing one mile from the pole, facing towards it; to get to the point 2 miles ahead of you the map tells you to turn right and walk 3.14 miles along a latitude line...
 - Conclusion: use unit vectors instead

Warm-up: unit vectors

- When we want to represent directions we use unit vectors: points that are literally on the unit sphere in \mathbb{R}^3
 - now no points are special
 - every point has a unique representation
 - equal sized changes in coordinates are equal sized changes in direction
- Down side: one too many coordinates
 - have to maintain normalization
 - but normalize() is a simple and easy operation

Warm-up: interpolating directions

- Interpolating in the space of 3D vectors is well behaved
- Simple computation: interpolate linearly and normalize
 - this is what we do all the time, e.g. with normals for fragment shading

$$\hat{\mathbf{v}}(t) = \text{normalize}((1 - t)\mathbf{v}_0 + t\mathbf{v}_1)$$

- but for far-apart endpoints the speed is uneven (faster towards the middle)

- For constant speed: spherical linear interpolation

- build basis $\{\mathbf{v}_0, \mathbf{w}\}$ from \mathbf{v}_0 and \mathbf{v}_1 $\mathbf{w} = \hat{\mathbf{v}}_1 - (\hat{\mathbf{v}}_0 \cdot \hat{\mathbf{v}}_1)\hat{\mathbf{v}}_0$

- interpolate angle from 0 to θ

$$\hat{\mathbf{w}} = \mathbf{w}/\|\mathbf{w}\|$$

$$\theta = \text{acos}(\hat{\mathbf{v}}_0 \cdot \hat{\mathbf{v}}_1)$$

$$\hat{\mathbf{v}}(t) = (\cos t\theta) \hat{\mathbf{v}}_0 + (\sin t\theta) \hat{\mathbf{w}}$$

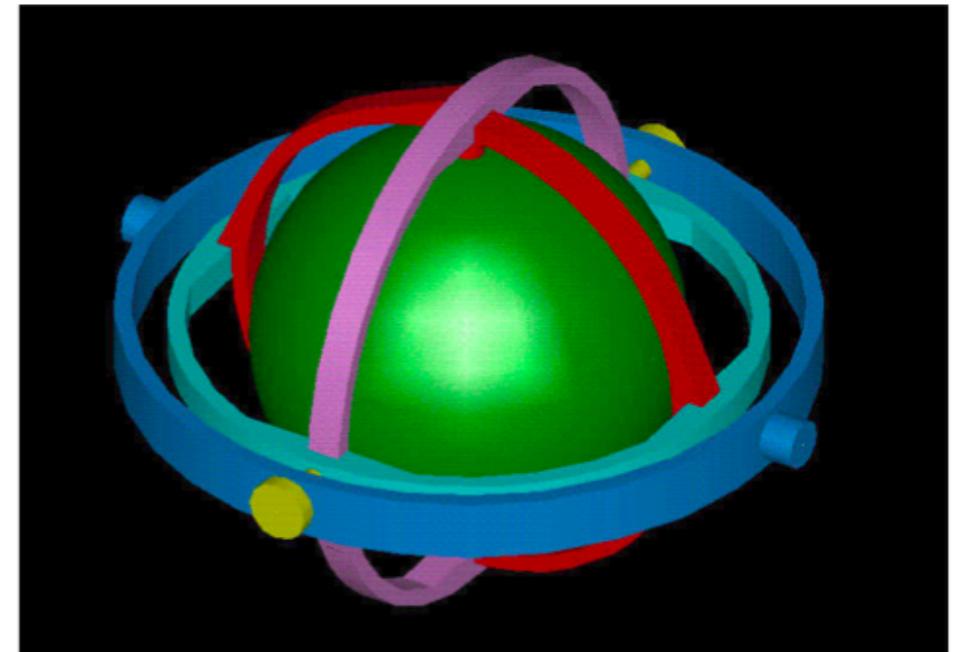
Warm-up: rays vs. lines

- The set of directions (unit vectors) describes the set of rays leaving a point
- The set of lines through a point is a bit different
 - no notion of “forward” vs. “backward”
- Would probably still represent using unit vectors
 - but every line has exactly two representations, \mathbf{v} and $-\mathbf{v}$

Parameterizing rotations

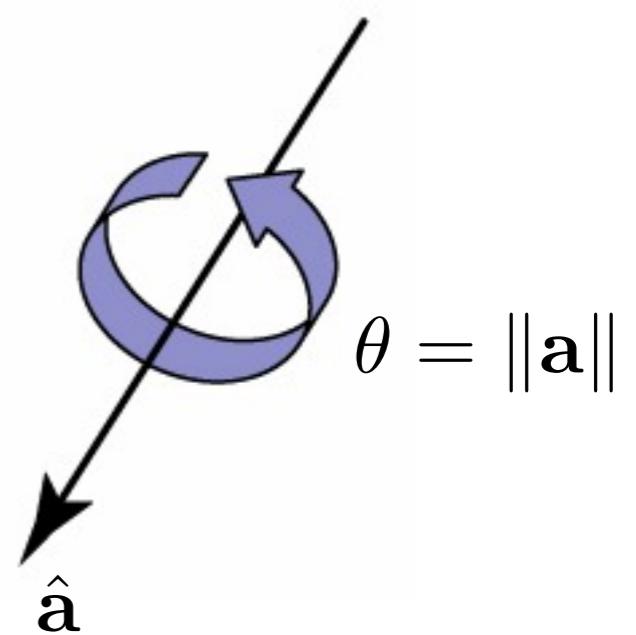
- Euler angles
 - rotate around x, then y, then z
 - nice and simple

$$f(\alpha, \beta, \gamma) = R_z(\gamma)R_y(\beta)R_x(\alpha)$$



- Axis/angle
 - specify axis to rotate around, then angle by which to rotate
 - multiply axis and angle to get a more compact form

$$f(\mathbf{a}) = R_{\hat{\mathbf{a}}}(\|\mathbf{a}\|)$$



Problems

- Euler angles
 - gimbal lock (saw this before)
 - some rotations have many representations
- Axis/angle
 - with separate rotation angle, multiple representations for identity rotation
 - even with combined rotation angle, making small changes near 180 degree rotations requires larger changes to parameters
- These resemble the problems with polar coordinates on the sphere
 - as with choosing poles, choosing the reference orientation for an object changes how the representation works

Quaternions for Rotation

- A quaternion is an extension of complex numbers

$$q = (s, v) = (s, v_1, v_2, v_3)$$

- Review of complex numbers

$$z = a + bi$$

$$z' = a - bi$$

$$||z|| = \sqrt{z.z'} = \sqrt{a^2 + b^2}$$

Complex numbers to quaternions

- Rather than one imaginary unit i , there are three such symbols i, j , and k , with the properties

$$i^2 + j^2 + k^2 = ijk = -1$$

- Multiplication of these units acts like the cross product

$$ij = k \quad ji = -k$$

$$jk = i \quad kj = -i$$

$$ki = j \quad ik = -j$$

- Combining multiples of i, j, k with a scalar gives the general form of a quaternion:

$$\mathbf{H} = \{a + bi + cj + dk \mid (a, b, c, d) \in \mathbb{R}^4\}$$

Complex numbers to quaternions

- Like complex numbers, quaternions have conjugates and magnitudes

$$q = a + bi + cj + dk$$

$$\bar{q} = a - bi - cj - dk$$

$$|q| = (q\bar{q})^{\frac{1}{2}} = \sqrt{a^2 + b^2 + c^2 + d^2} = \|(a, b, c, d)\|$$

- Also like complex numbers, quaternions have reciprocals of the form

$$q^{-1} = \frac{1}{q} = \frac{\bar{q}}{|q|}$$

Quaternion Properties

- **Associative**

$$q_1(q_2q_3) = q_1q_2q_3 = (q_1q_2)q_3$$

- **Not commutative**

$$q_1q_2 \not\equiv q_2q_1$$

- **Magnitudes multiply**

$$|q_1q_2| = |q_1| |q_2|$$

- **For unit quaternions:**

$$|q| = 1$$

$$q^{-1} = \bar{q}$$

Unit quaternions

- The set of unit-magnitude quaternions is called the “unit quaternions”

$$S^3 = \{q \in \mathbf{H} \mid |q| = 1\}$$

- as a subset of 4D space, it is the unit 3-sphere
- multiplying unit quaternions produces more unit quaternions

$$|q_1| = |q_2| = 1 \implies |q_1 q_2| = 1$$

$$q_1, q_2 \in S^3 \implies q_1 q_2 \in S^3$$

Quaternion as scalar plus vector

- Write q as a pair of a scalar $s \in \mathbf{R}$ and vector $\mathbf{v} \in \mathbf{R}^3$

$$q = a + bi + cj + dk$$

$$q = (s, \mathbf{v}) \text{ where } s = a \text{ and } \mathbf{v} = (b, c, d)$$

- Multiplication

$$(s_1, \mathbf{v}_1)(s_2, \mathbf{v}_2) = (s_1s_2 - \mathbf{v}_1 \cdot \mathbf{v}_2, s_1\mathbf{v}_2 + s_2\mathbf{v}_1 + \mathbf{v}_1 \times \mathbf{v}_2)$$

- For a unit quaternion, $|s|^2 + \|\mathbf{v}\|^2 = 1$

- so think of these as the sine and cosine of an angle ψ :

$$q = (\cos \psi, \hat{\mathbf{v}} \sin \psi) \text{ or } \cos \psi + \hat{\mathbf{v}} \sin \psi$$

- this is a lot like writing a complex number as $\cos \theta + i \sin \theta$

Quaternions and rotations

There is a natural association between the unit quaternion

$$\cos \psi + \hat{\mathbf{v}} \sin \psi \in S^3 \subset \mathbf{H}$$

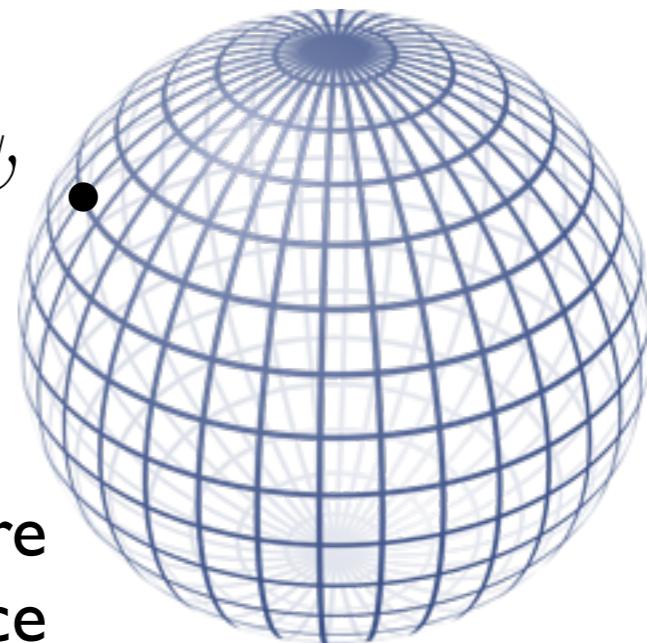
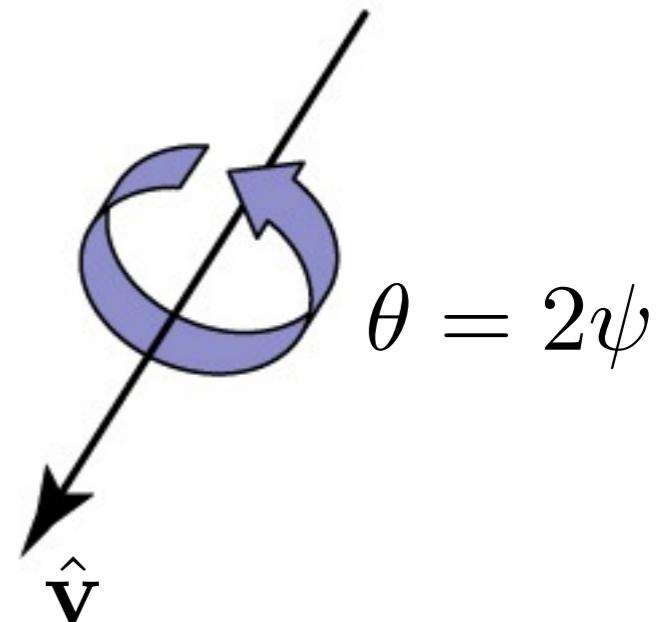
and the 3D axis-angle rotation

$$R_{\hat{\mathbf{v}}}(\theta) \in SO(3)$$

where $\theta = 2\psi$.

$$\cos \psi + \hat{\mathbf{v}} \sin \psi$$

unit 3-sphere
in 4D space



Rotation and quaternion multiplication

- Represent a point in space by a pure-imaginary quaternion

$$\mathbf{x} = (x, y, z) \in \mathbb{R}^3 \leftrightarrow X = xi + yj + zk \in \mathbb{H}$$

- Can compute rotations using quaternion multiplication

$$X_{\text{rotated}} = qX\bar{q}$$

- note that q and $-q$ correspond to the same rotation
- you can verify this is a rotation by multiplying out...
- Multiplication of quaternions corresponds to composition of rotations

$$q_1(q_2X\bar{q}_2)\bar{q}_1 = (q_1q_2)X(\bar{q}_2\bar{q}_1) = q_1q_2 X \overline{q_1q_2}$$

- the quaternion q_1q_2 corresponds to “rotate by q_2 , then rotate by q_1 ”

Rotation and quaternion multiplication

If we write a unit quaternion in the form

$$q = \cos \psi + \hat{\mathbf{v}} \sin \psi$$

then the operation

$$X_{\text{rotated}} = qX\bar{q} = (\cos \psi + \hat{\mathbf{v}} \sin \psi)X(\cos \psi - \hat{\mathbf{v}} \sin \psi)$$

is a rotation by 2ψ around the axis \mathbf{v} .

So an alternative explanation is, “All this algebraic mumbo-jumbo aside, a quaternion is just a slightly different way to encode an axis and an angle in four numbers: rather than the number θ and the unit vector \mathbf{v} , we store the number $\cos(\theta/2)$ and the vector $\sin(\theta/2)\mathbf{v}$.“

Unit quaternions and axis/angle

- With this in hand, we can write down a parameterization of 3D rotations using unit quaternions (points on the 3-sphere)

$$f : S^3 \subset \mathbf{H} \rightarrow SO(3)$$

$$: \cos \psi + \hat{\mathbf{v}} \sin \psi \mapsto R_{\hat{\mathbf{v}}} (2\psi)$$

$$: (w, x, y, z) \mapsto \begin{bmatrix} w^2 + x^2 - y^2 - z^2 & 2(xy - wz) & 2(xz + wy) \\ 2(xy + wz) & w^2 - x^2 + y^2 - z^2 & 2(yz - wx) \\ 2(xz - wy) & 2(yz + wx) & w^2 - x^2 - y^2 + z^2 \end{bmatrix}$$

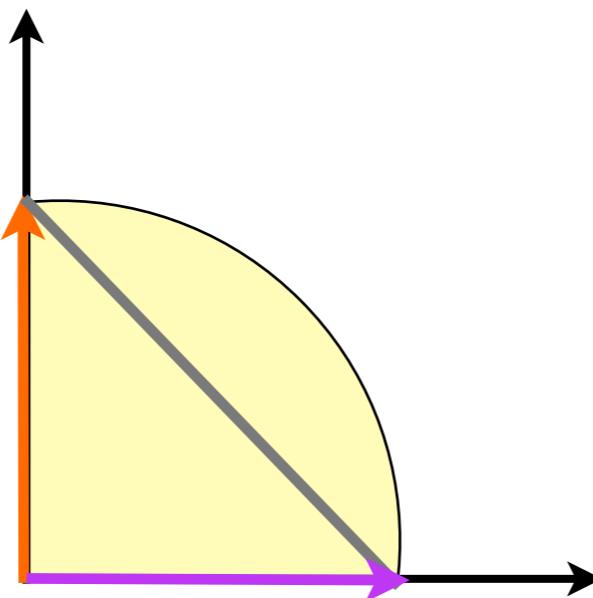
- This mapping is wonderfully uniform:
 - is exactly 2-to-1 everywhere
 - has constant speed in all directions
 - has constant Jacobian (does not distort “volume”)
 - maps shortest paths to shortest paths
 - and... it comes with a nice multiplication operation!

Why Quaternions?

- Fast, few operations, not redundant
- Numerically stable for incremental changes
- Composes rotations nicely
- Convert to matrices at the end
- Biggest reason: spherical interpolation

Interpolating between quaternions

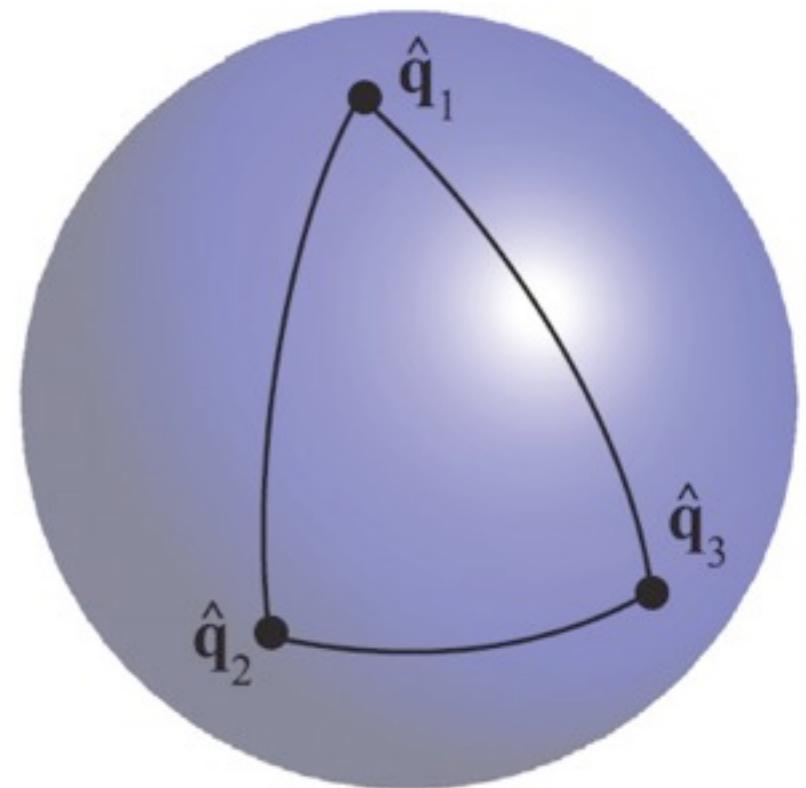
- Why not linear interpolation?
 - Need to be normalized
 - Does not have constant rate of rotation



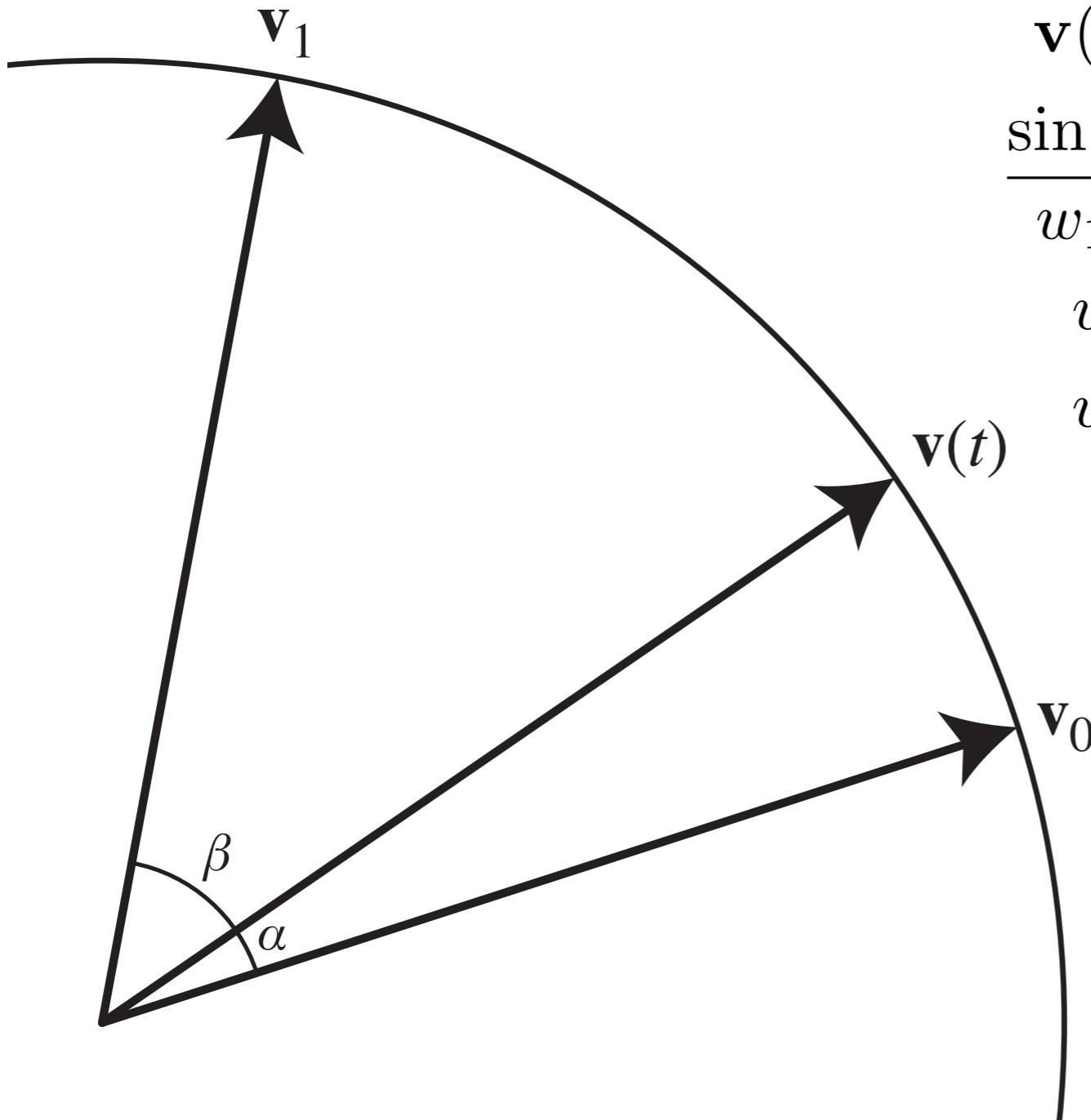
$$\frac{(1 - \alpha)x + \alpha y}{\|(1 - \alpha)x + \alpha y\|}$$

Spherical Linear Interpolation

- Intuitive interpolation between different orientations
 - Nicely represented through quaternions
 - Useful for animation
 - Given two quaternions, interpolate between them
- Shortest path between two points on sphere
 - Geodesic, on Great Circle



Spherical linear interpolation (“slerp”)



$$\alpha + \beta = \psi$$

$$\mathbf{v}(t) = w_0 \mathbf{v}_0 + w_1 \mathbf{v}_1$$

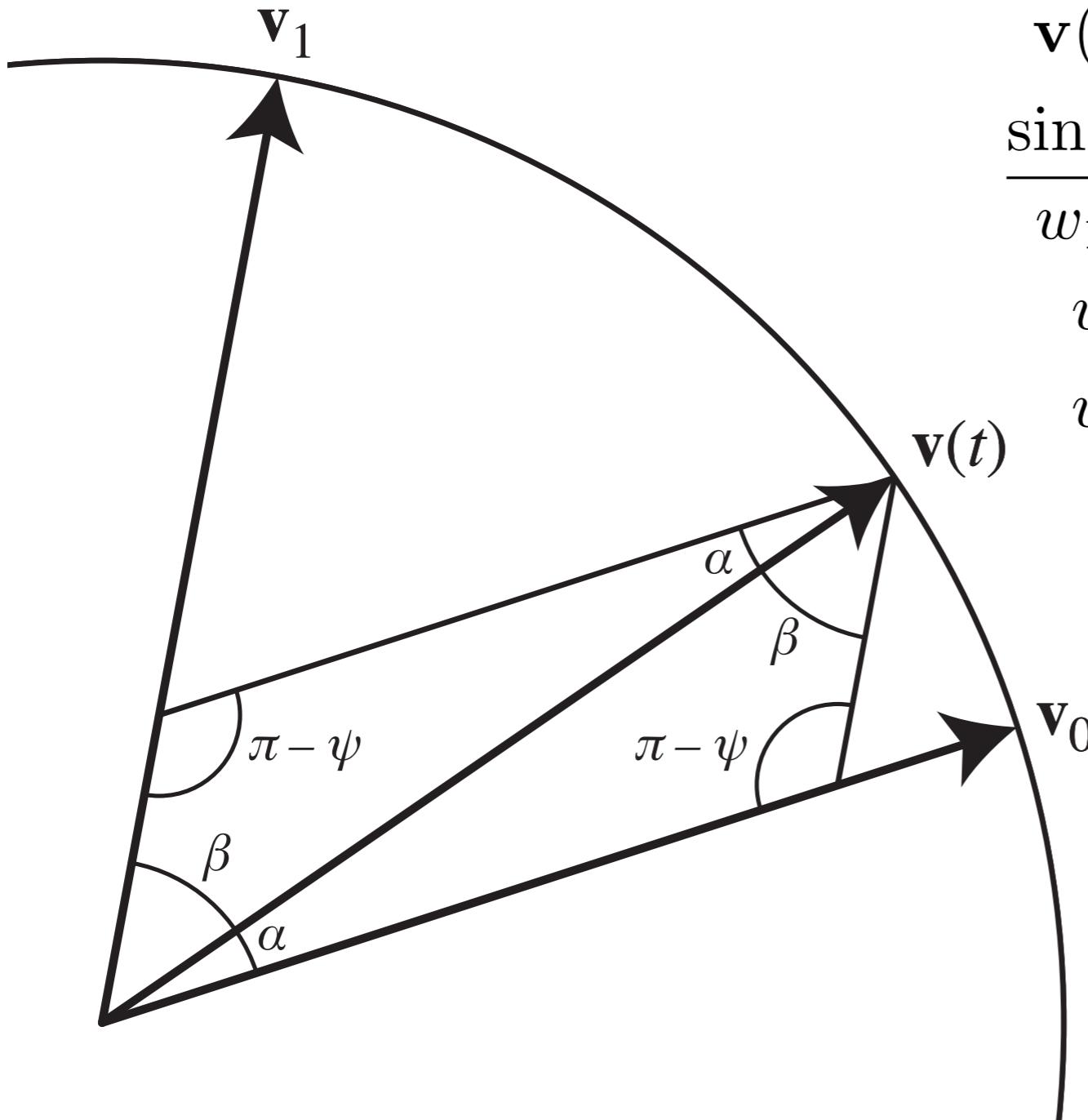
$$\frac{\sin \alpha}{w_1} = \frac{\sin \beta}{w_0} = \frac{\sin(\pi - \psi)}{1} = \sin \psi$$

$$w_0 = \sin \beta / \sin \psi$$

$$w_1 = \sin \alpha / \sin \psi$$

$$\psi = \cos^{-1}(\mathbf{v}_0 \cdot \mathbf{v}_1)$$

Spherical linear interpolation (“slerp”)



$$\alpha + \beta = \psi$$

$$\mathbf{v}(t) = w_0 \mathbf{v}_0 + w_1 \mathbf{v}_1$$

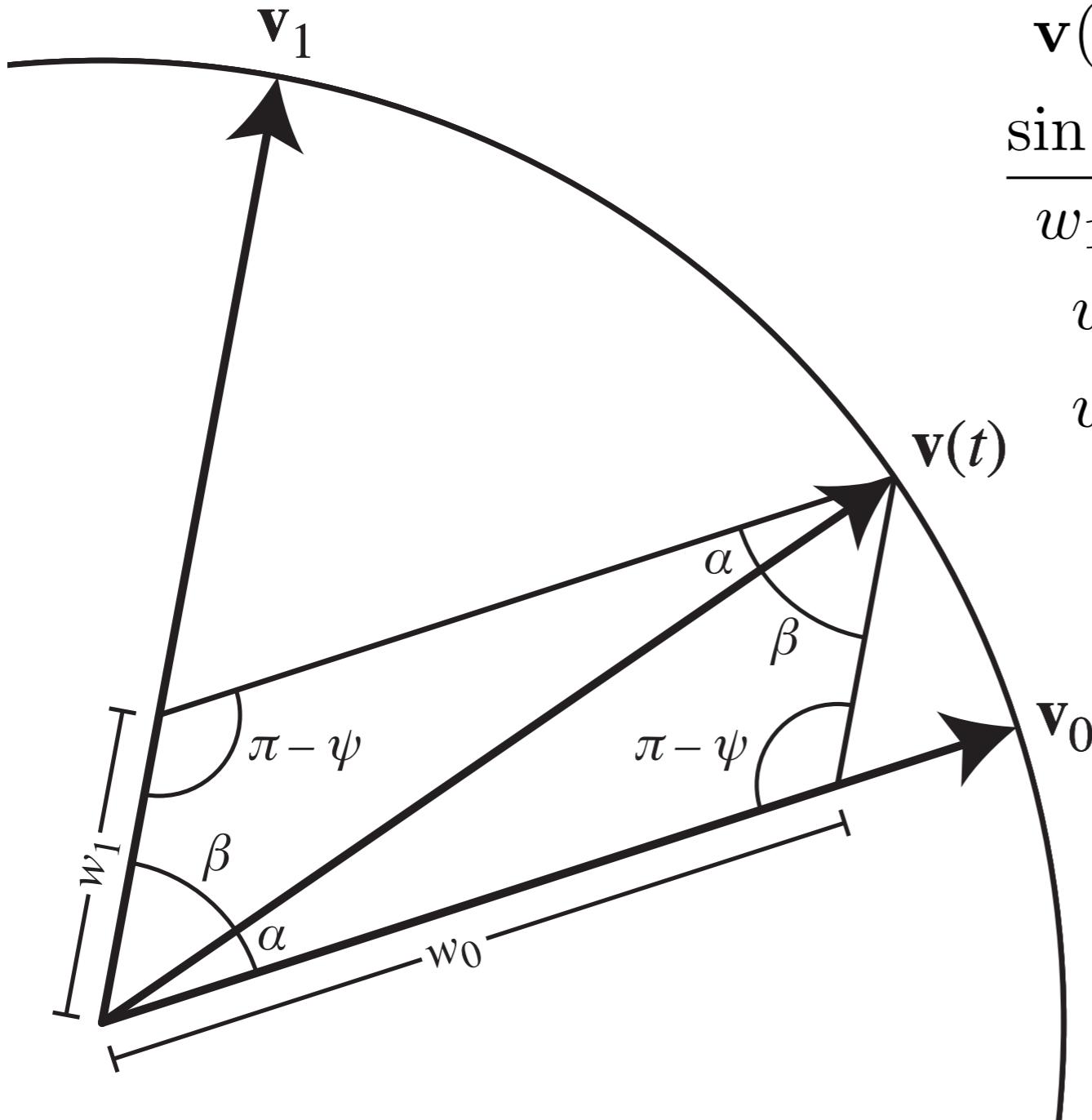
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$$w_1 = \sin \alpha / \sin \psi$$

$$\psi = \cos^{-1}(\mathbf{v}_0 \cdot \mathbf{v}_1)$$

Quaternion Interpolation

- Spherical linear interpolation naturally works in any dimension
- Traverses a great arc on the sphere of unit quaternions
 - Uniform angular rotation velocity about a fixed axis

$$\psi = \cos^{-1}(q_0 \cdot q_1)$$

$$q(t) = \frac{q_0 \sin(1-t)\psi + q_1 \sin t\psi}{\sin \psi}$$

Practical issues

- When angle gets close to zero, estimation of Ψ is inaccurate
 - slerp naturally approaches linear interpolation for small Ψ
 - so switch to linear interpolation when $q_0 \approx q_1$.
- q is same rotation as $-q$
 - if $q_0 \cdot q_1 > 0$, slerp between them
 - else, slerp between q_0 and $-q_1$

Animation

- Industry production process leading up to animation
- What animation is
- How animation works (very generally)
- Artistic process of animation
- Further topics in how it works

Approaches to animation

- Straight ahead
 - Draw/animate one frame at a time
 - Can lead to spontaneity, but is hard to get exactly what you want
- Pose-to-pose
 - Top-down process:
 - Plan shots using storyboards
 - Plan key poses first
 - Finally fill in the in-between frames

Pose-to-pose animation planning



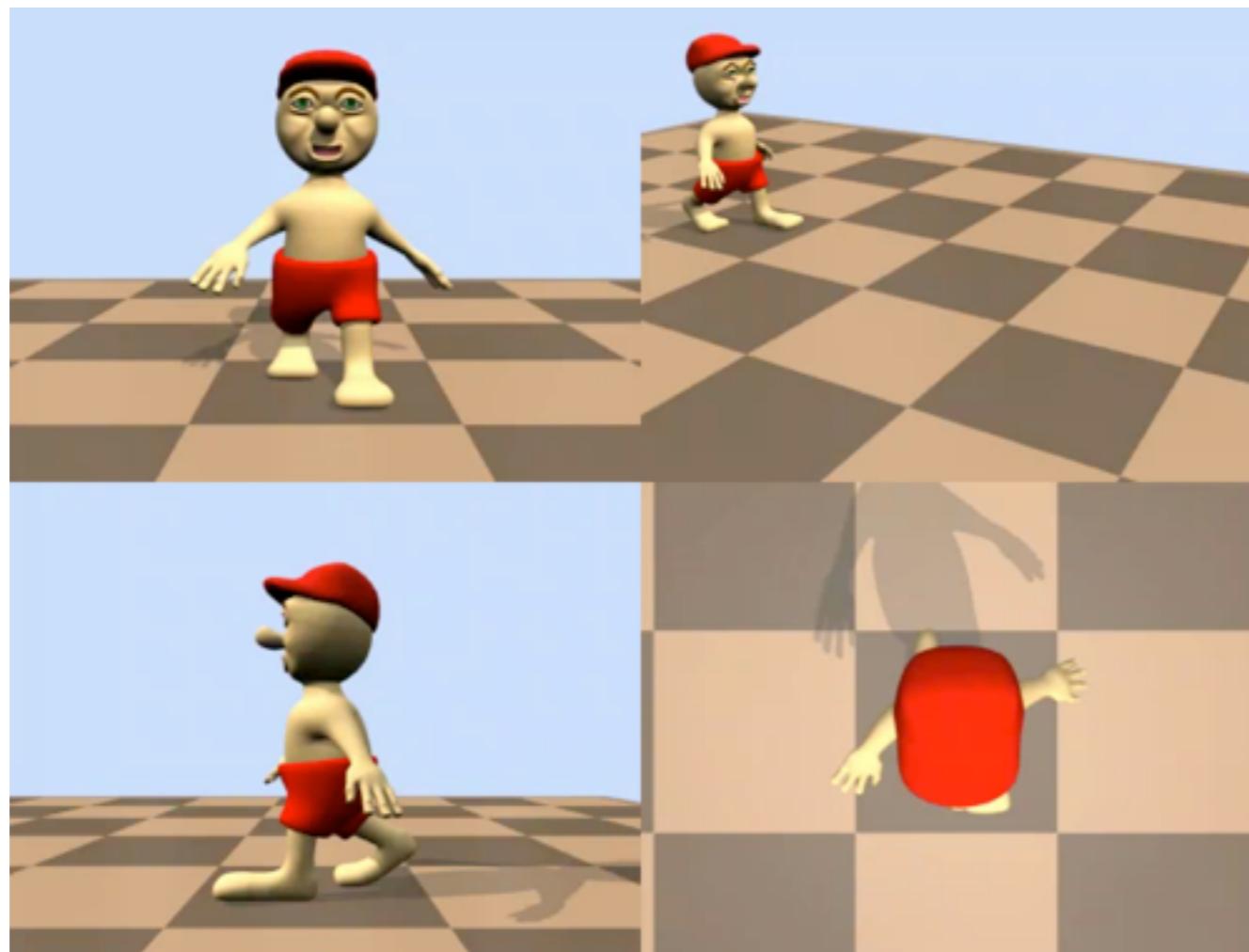
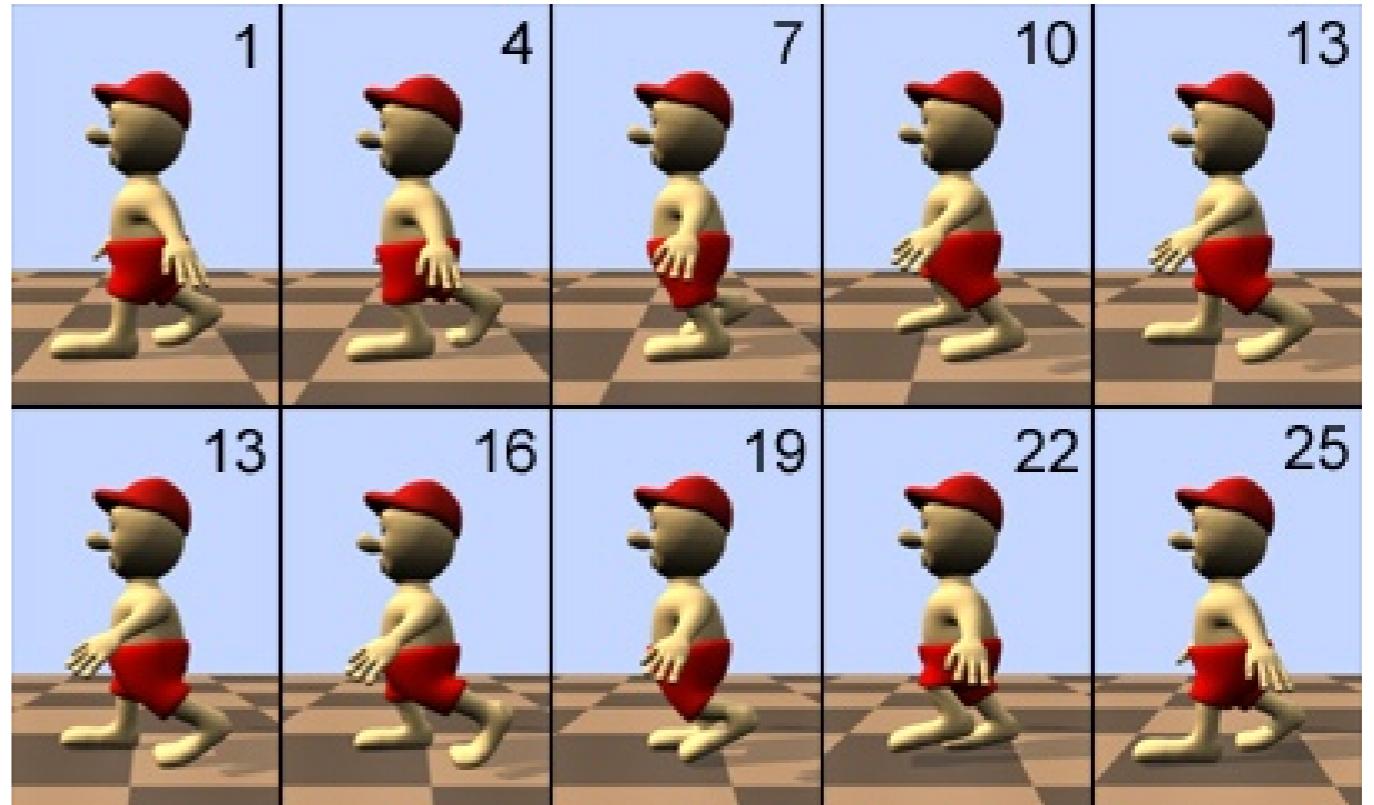
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- First work out poses that are key to the story
- Next fill in animation in between

Keyframe animation

- Keyframing is the technique used for pose-to-pose animation
 - Head animator draws key poses—just enough to indicate what the motion is supposed to be
 - Assistants do “in-betweening” and draw the rest of the frames
 - In computer animation substitute “user” and “animation software”
 - *Interpolation* is the principal operation

Walk cycle

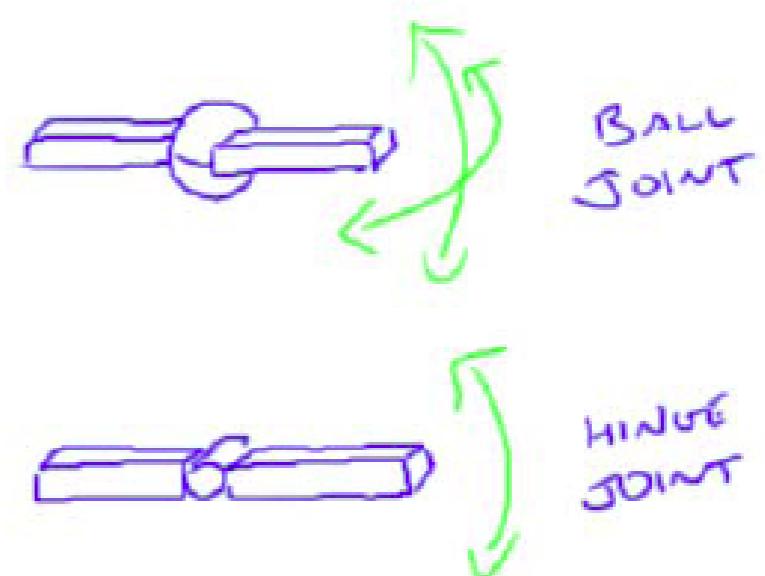
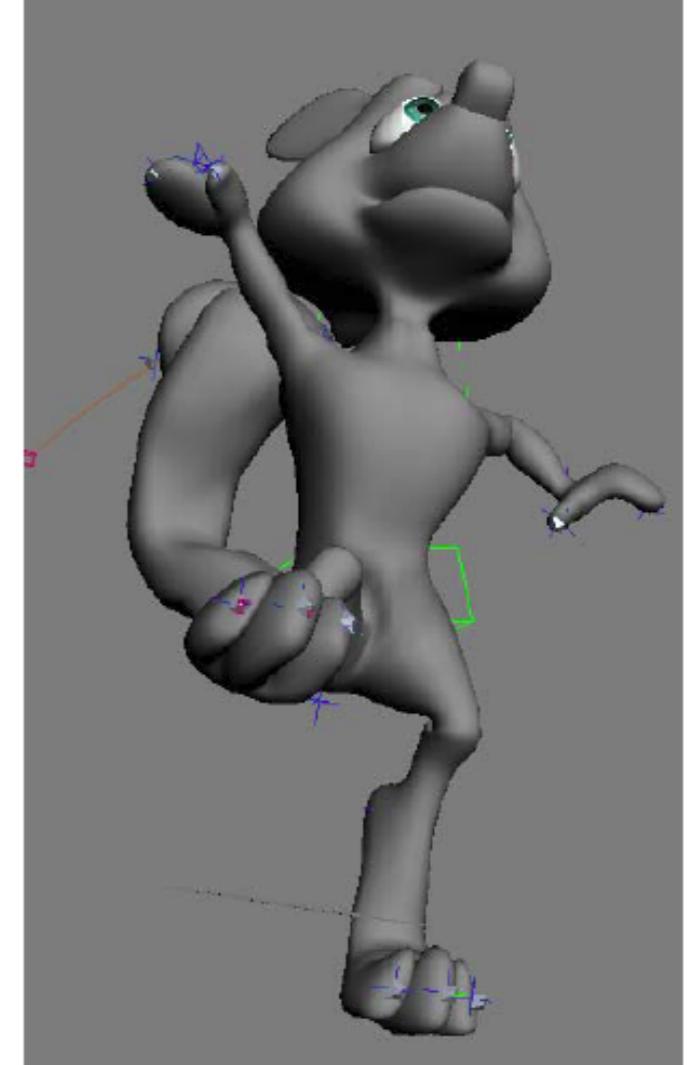
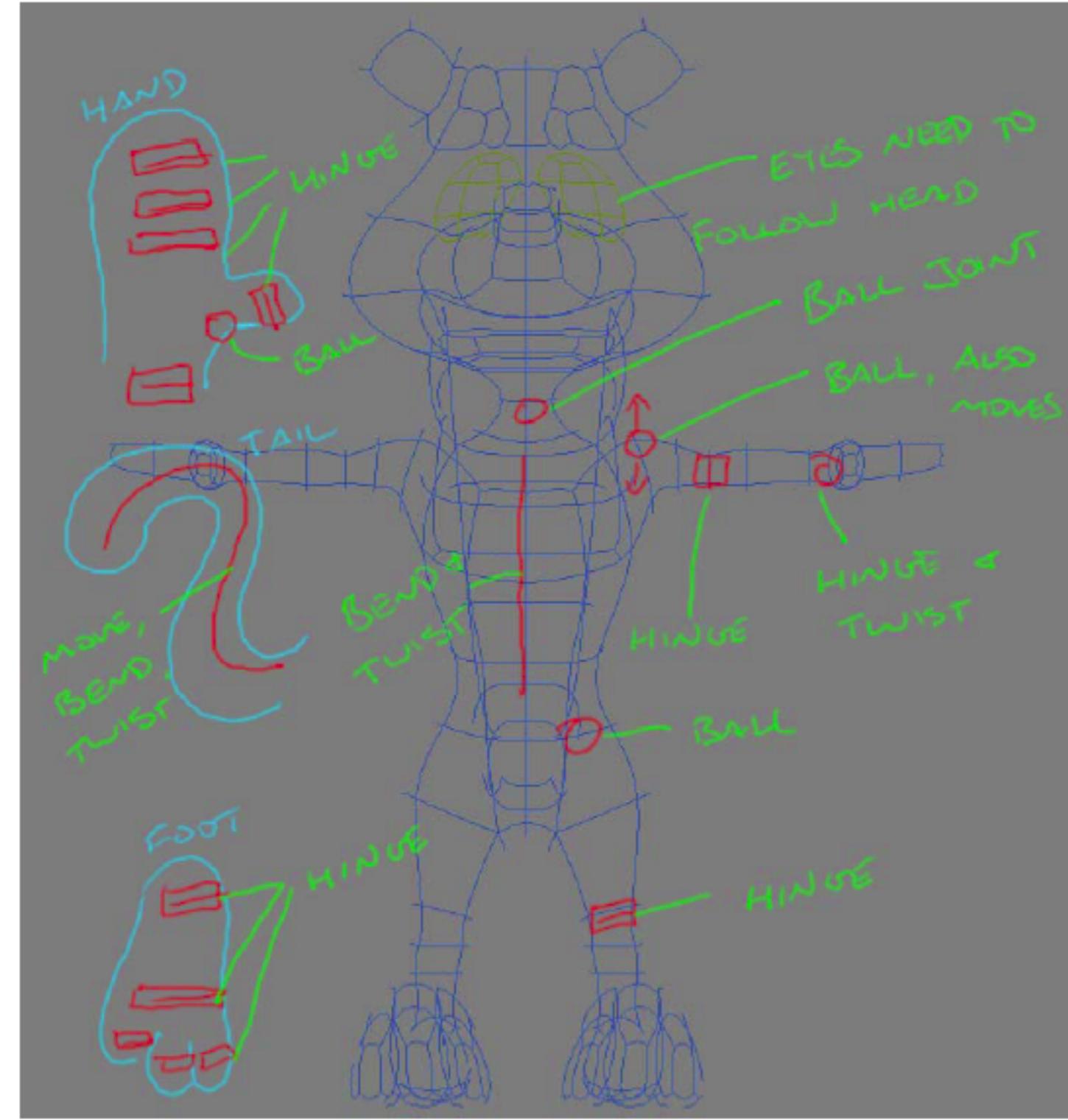


[Christopher Lutz <http://www.animationsnippets.com>]

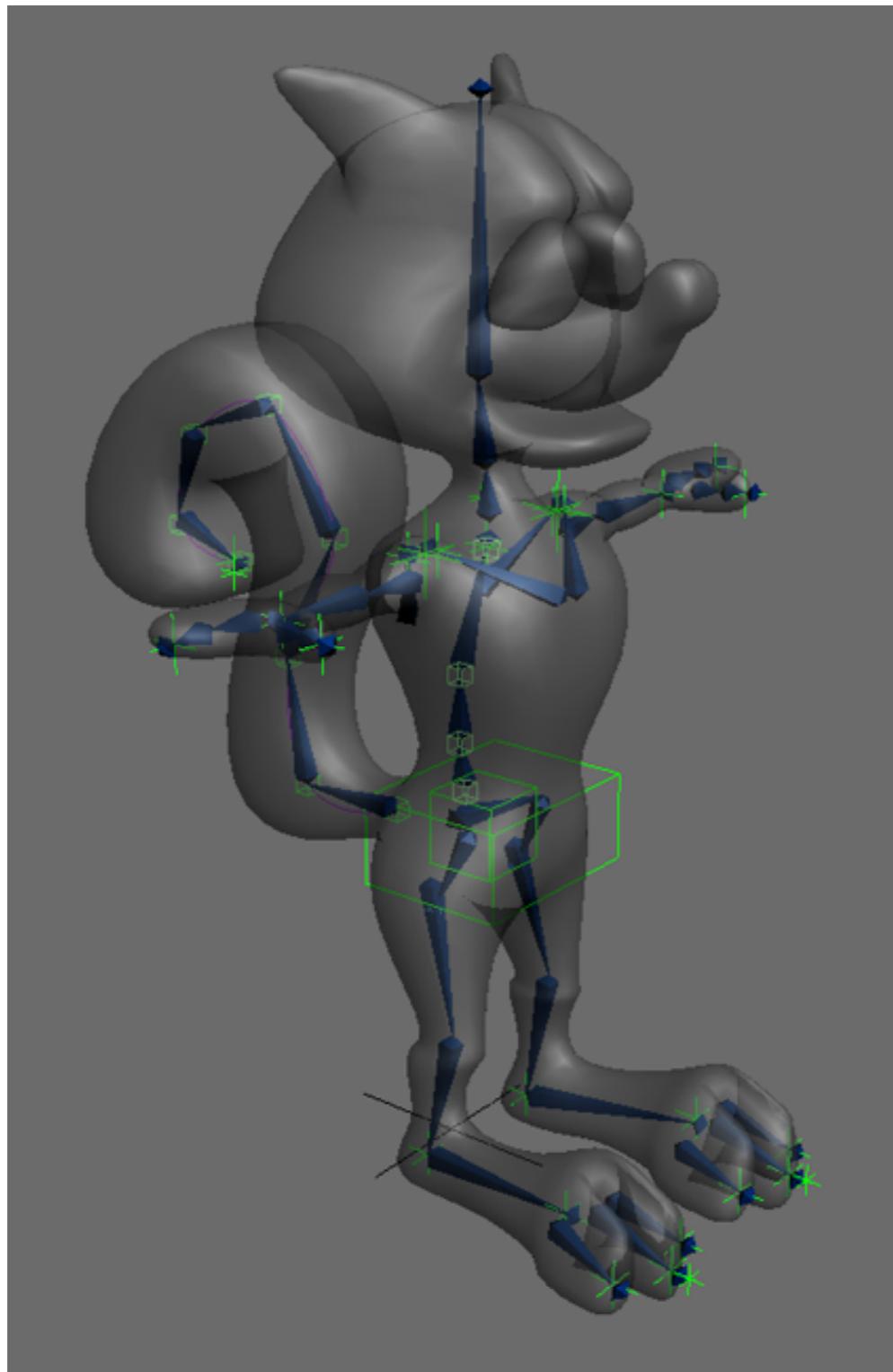
Controlling geometry conveniently

- Could animate by moving every control point at every keyframe
 - This would be labor intensive
 - It would also be hard to get smooth, consistent motion
- Better way: animate using smaller set of meaningful *degrees of freedom* (DOFs)
 - Modeling DOFs are inappropriate for animation
 - E.g. “move one square inch of left forearm”
 - Animation DOFs need to be higher level
 - E.g. “bend the elbow”

Character with DOFs



Rigged character



- Surface is deformed by a set of *bones*
- Bones are in turn controlled by a smaller set of *controls*
- The controls are useful, intuitive DOFs for an animator to use

The artistic process of animation

- What are animators trying to do?
 - Important to understand in thinking about what tools they need
- Basic principles are universal across media
 - 2D hand-drawn animation
 - 2D and computer animation
 - 3D computer animation
- Widely cited set of principles laid out by Frank Thomas and Ollie Johnston in *The Illusion of Life* (1981)
- The following slides follow Michael Comet's examples:
www.comet-cartoons.com

Animation principles: timing

- Speed of an action is crucial to the impression it makes
 - examples with same keyframes, different times:



[Michael B. Comet]

60 fr: looking around

30 fr: “no”

5 fr: just been hit

Animation principles: timing

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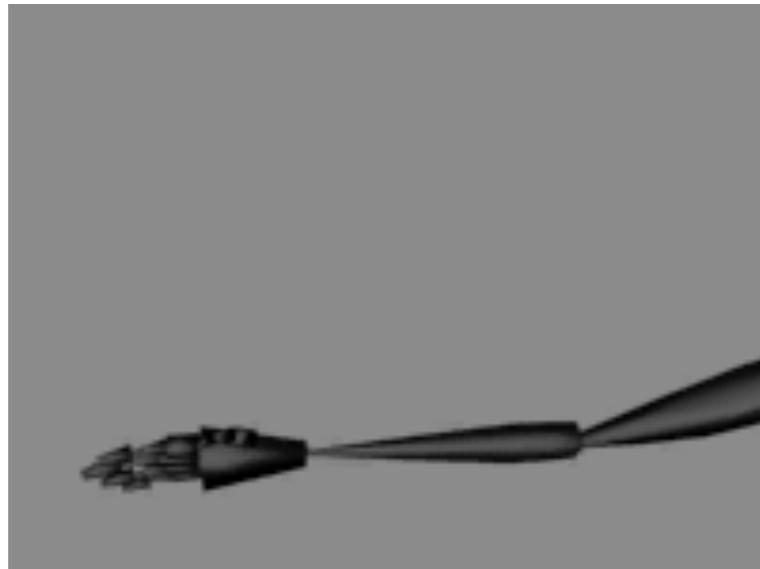
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Animation principles: ease in/out

- Real objects do not start and stop suddenly
 - animation parameters shouldn't either



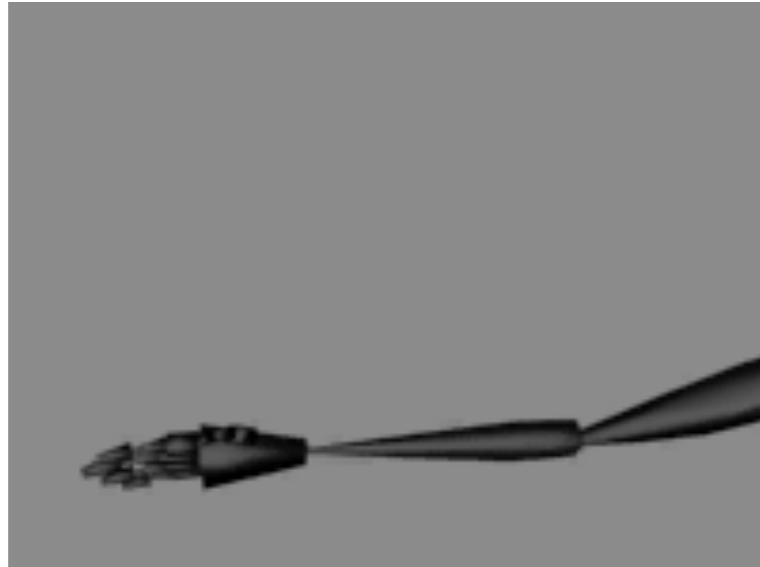
straight linear interp.

ease in/out

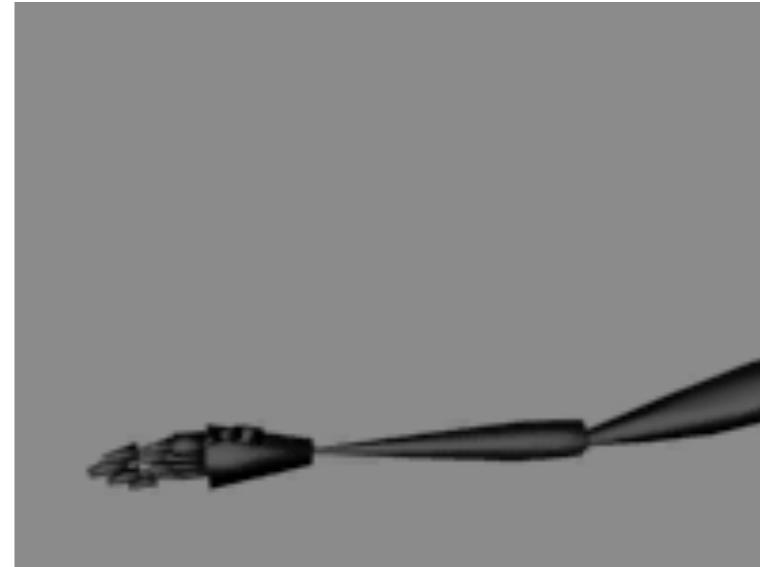
- a little goes a long way (just a few frames acceleration or deceleration for “snappy” motions)

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Animation principles: moving in arcs

- Real objects also don't move in straight lines
 - generally curves are more graceful and realistic



[Michael B. Comer]

Animation principles: moving in arcs

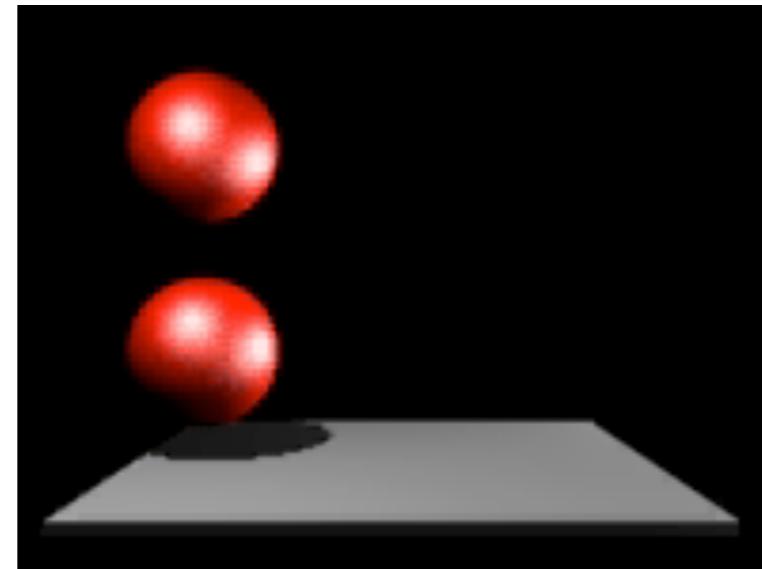
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[Michael B. Comet]

Animation principles: anticipation

- Most actions are preceded by some kind of “wind-up”

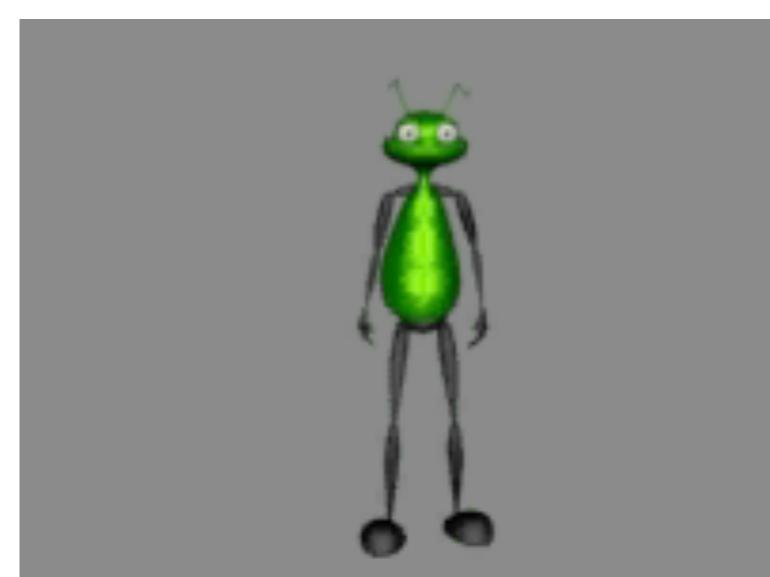
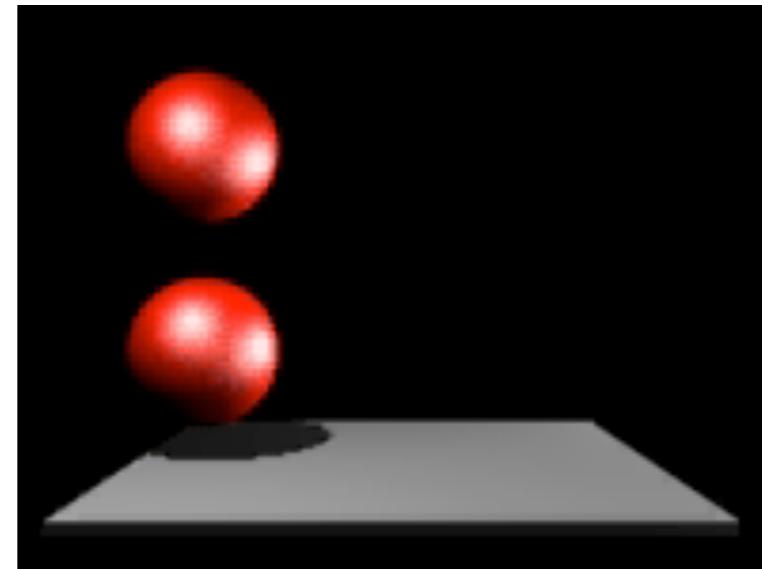


[Michael B. Comet]

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Animation principles: anticipation

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Animation principles: exaggeration

- Animation is not about exactly modeling reality
- Exaggeration is very often used for emphasis



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Animation principles: exaggeration

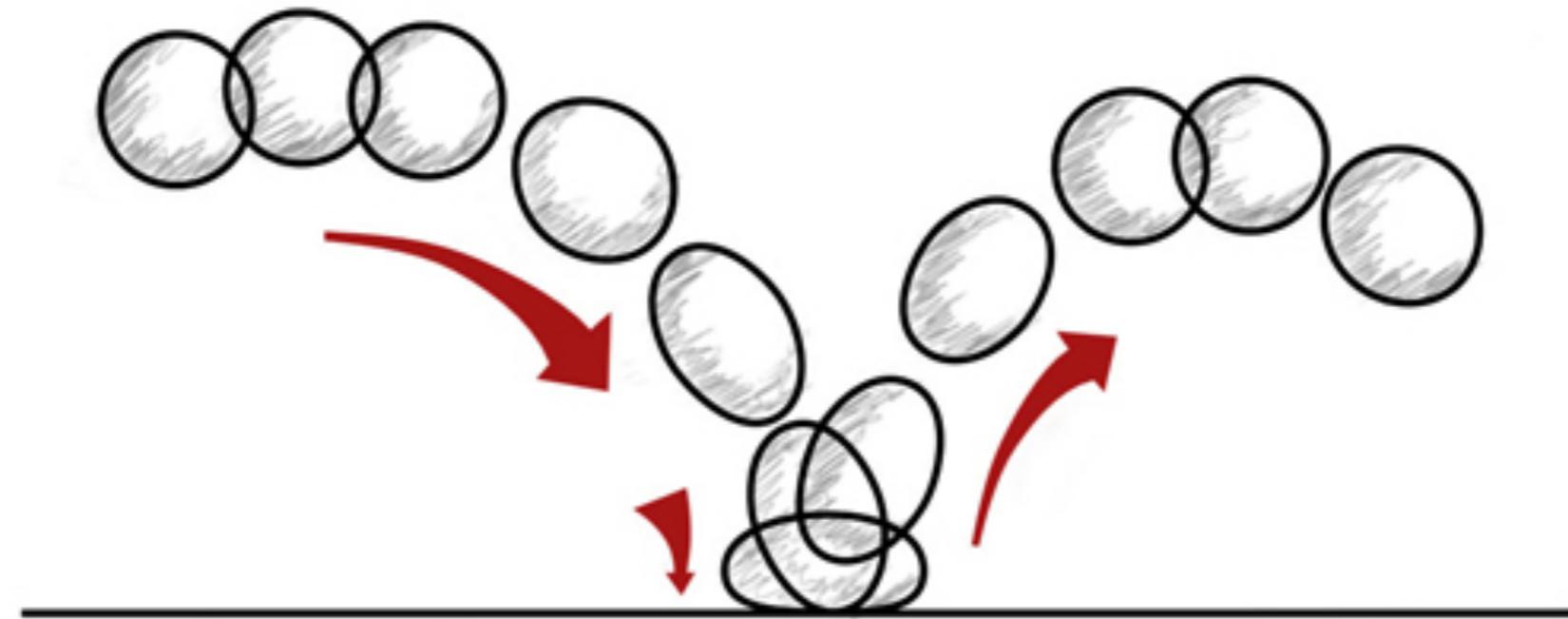
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[Michael B. Comet]

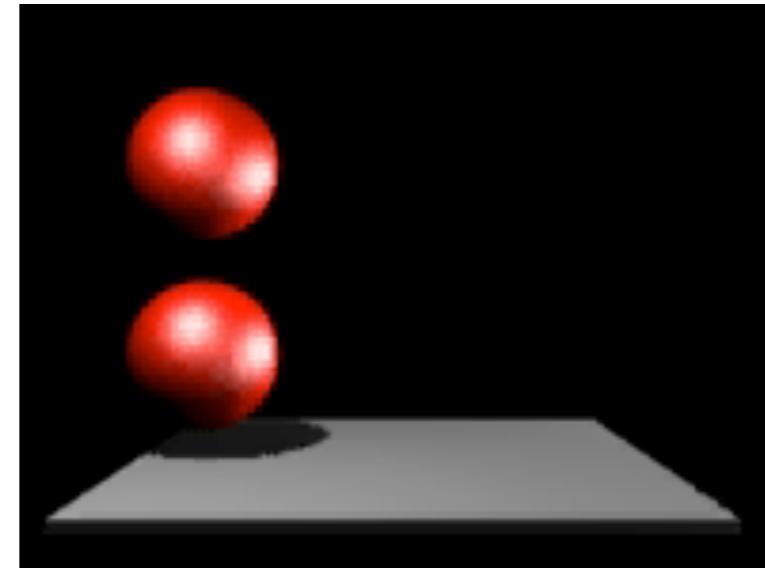
Animation principles: squash & stretch

- Objects do not remain perfectly rigid as they move
- Adding stretch with motion and squash with impact:
 - models deformation of soft objects
 - indicates motion by simulating exaggerated “motion blur”



Animation principles: follow through

- We've seen that objects don't start suddenly
- They also don't stop on a dime

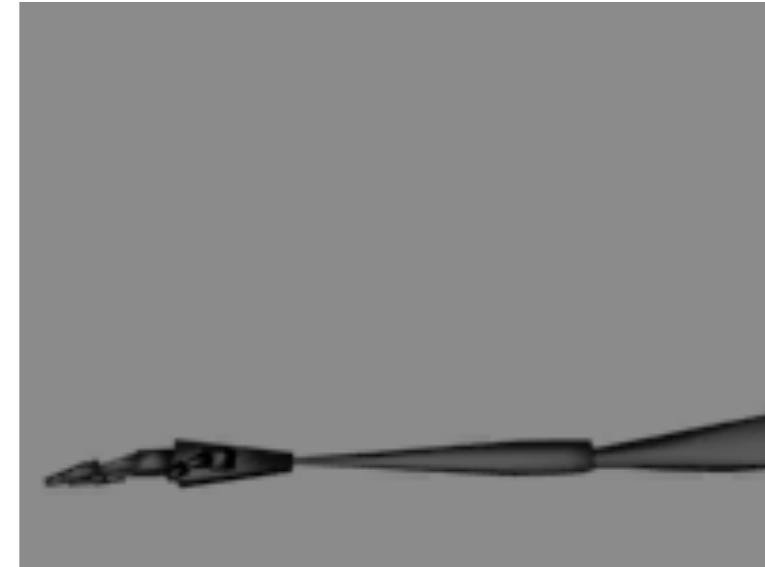
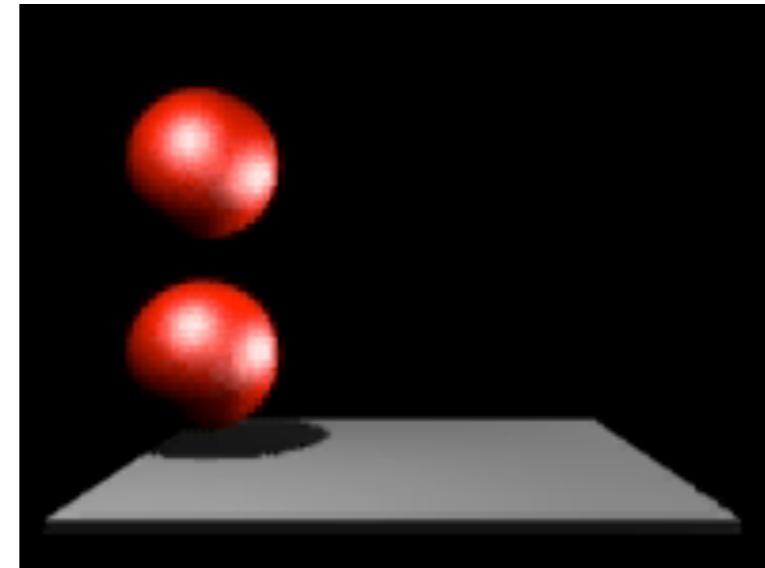


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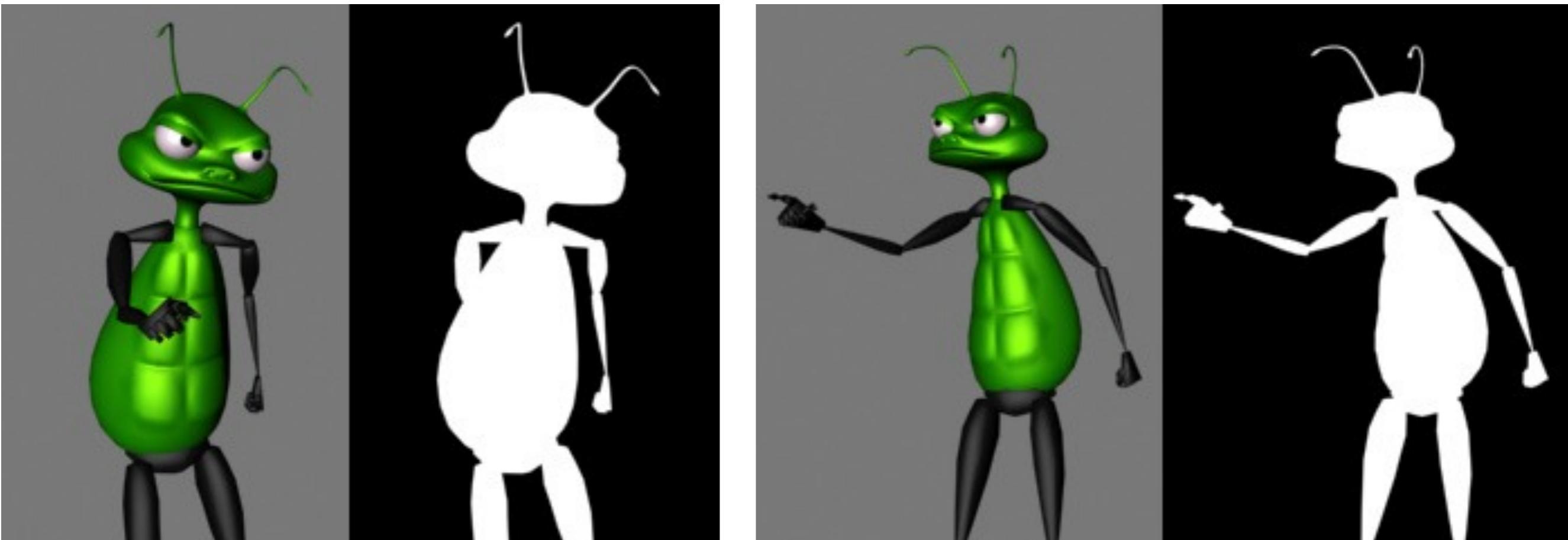
Anim. principles: overlapping action

- Usually many actions are happening at once



[Michael B. Comer]

Animation principles: staging



- Want to produce clear, good-looking 2D images
 - need good camera angles, set design, and character positions

Principles at work: weight



[Michael B. Comet]

Principles at work: weight

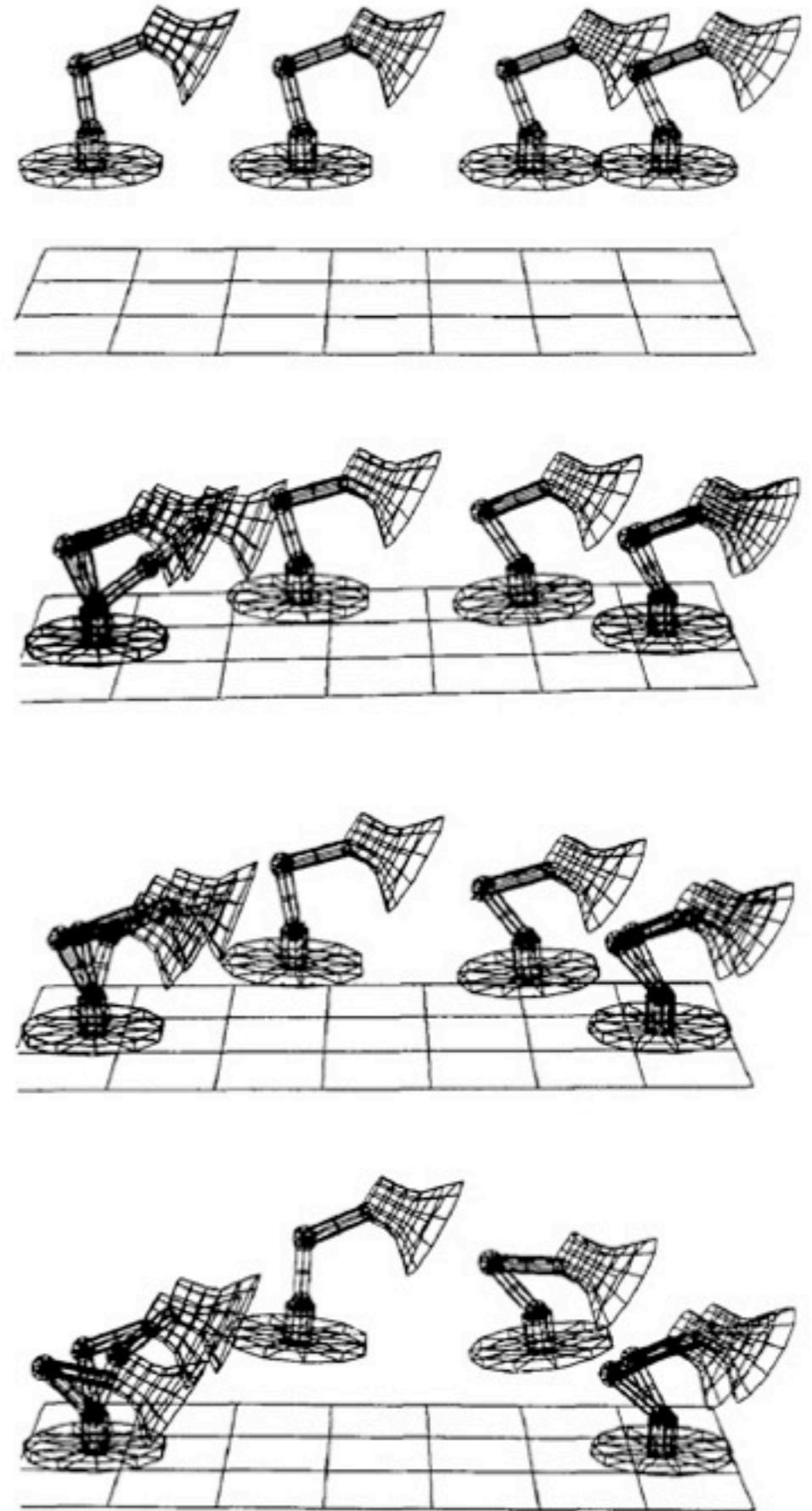
[Michael B. Comet]



Extended example: Luxo, Jr.

Computer-generated motion

- Interesting aside: many principles of character animation follow indirectly from physics
- Anticipation, follow-through, and many other effects can be produced by simply minimizing physical energy
- Seminal paper: “Spacetime Constraints” by Witkin and Kass in SIGGRAPH 1988

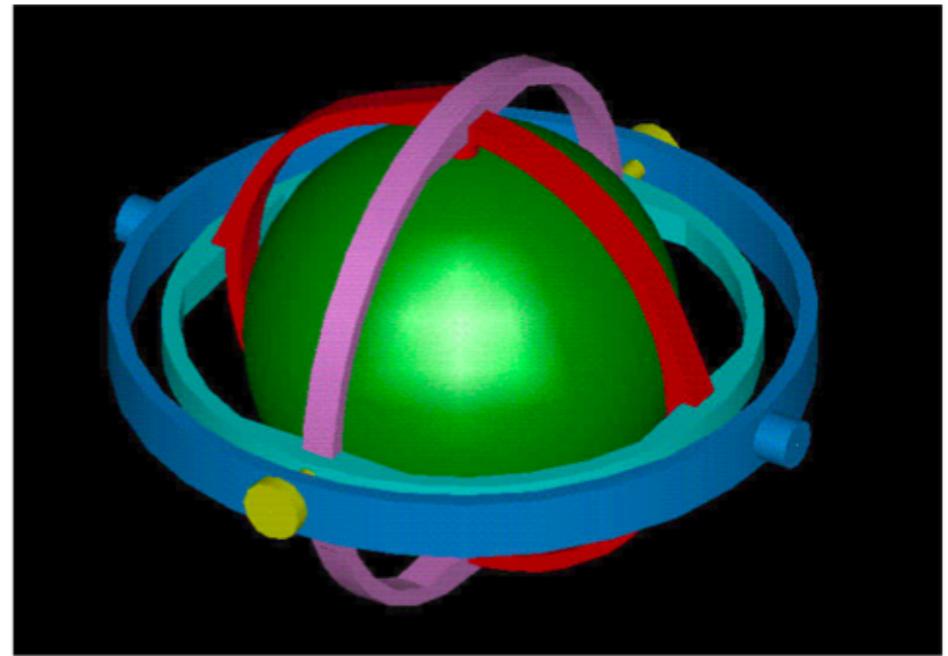


Controlling shape for animation

- Start with *modeling DOFs* (control points)
- *Deformations* control those DOFs at a higher level
 - Example: move first joint of second finger on left hand
- *Animation controls* control those DOFs at a higher level
 - Example: open/close left hand
- Both cases can be handled by the same kinds of deformers

Parameterizing rotations

- Euler angles
 - Rotate around x, then y, then z
 - Problem: gimbal lock
 - If two axes coincide, you lose one DOF
- Unit quaternions
 - A 4D representation (like 3D unit vectors for 2D sphere)
 - Good choice for interpolating rotations
- These are first examples of motion control
 - Matrix = deformation
 - Angles/quaternion = animation controls



Hierarchies and articulated figures

- Luxo as an example
 - small number of animation controls control many transformations
 - constraint: the joints hold together
- Some operations are tricky with hierarchies
 - how to ensure lampshade touches ball?
- In mechanics, the relationship between DOFs and 3D pose is *kinematics*
- Robotics as source of math. Methods
 - robots are transformation hierarchies
 - forward kinematics
 - inverse kinematics



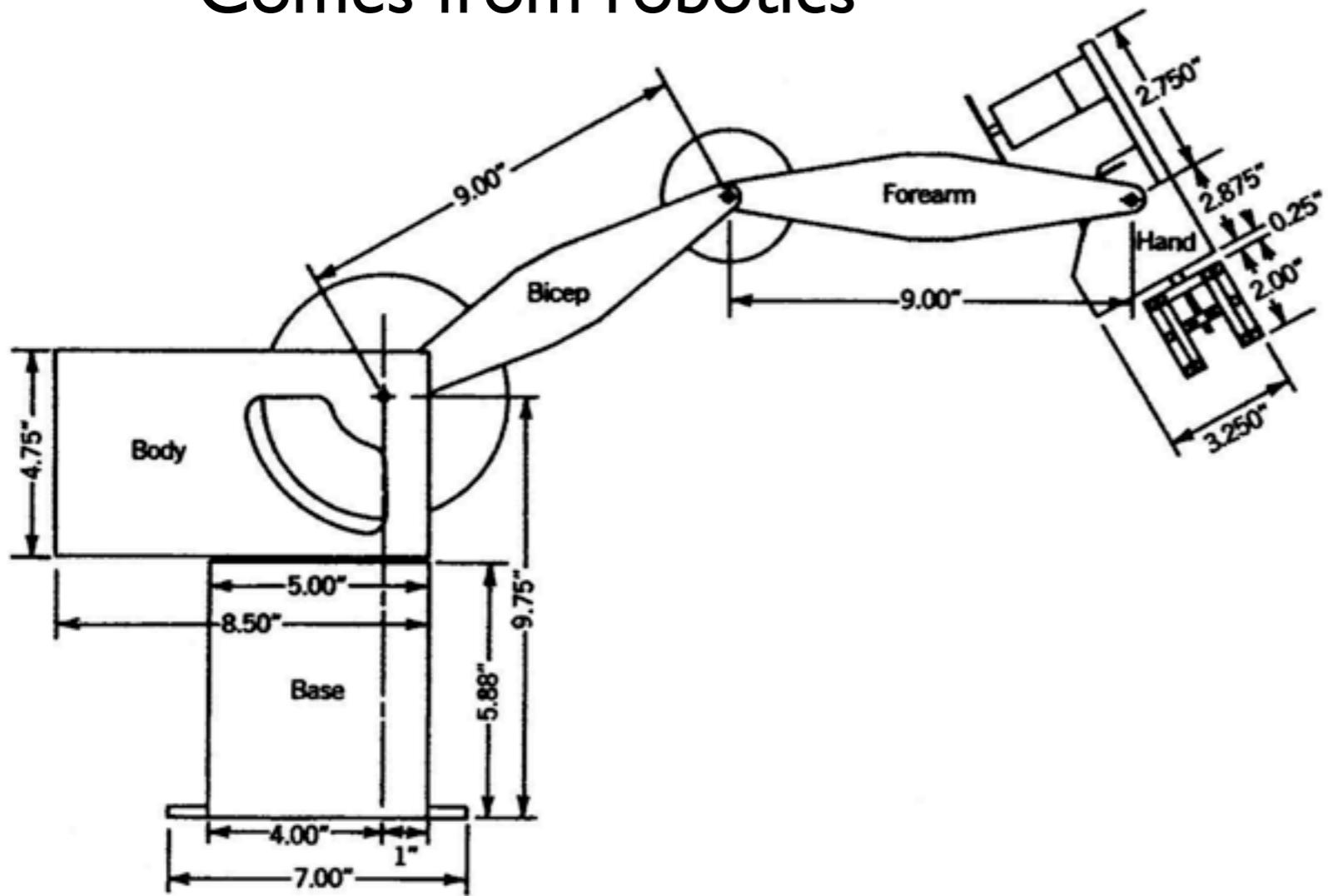
Forward Kinematics



Inverse Kinematics

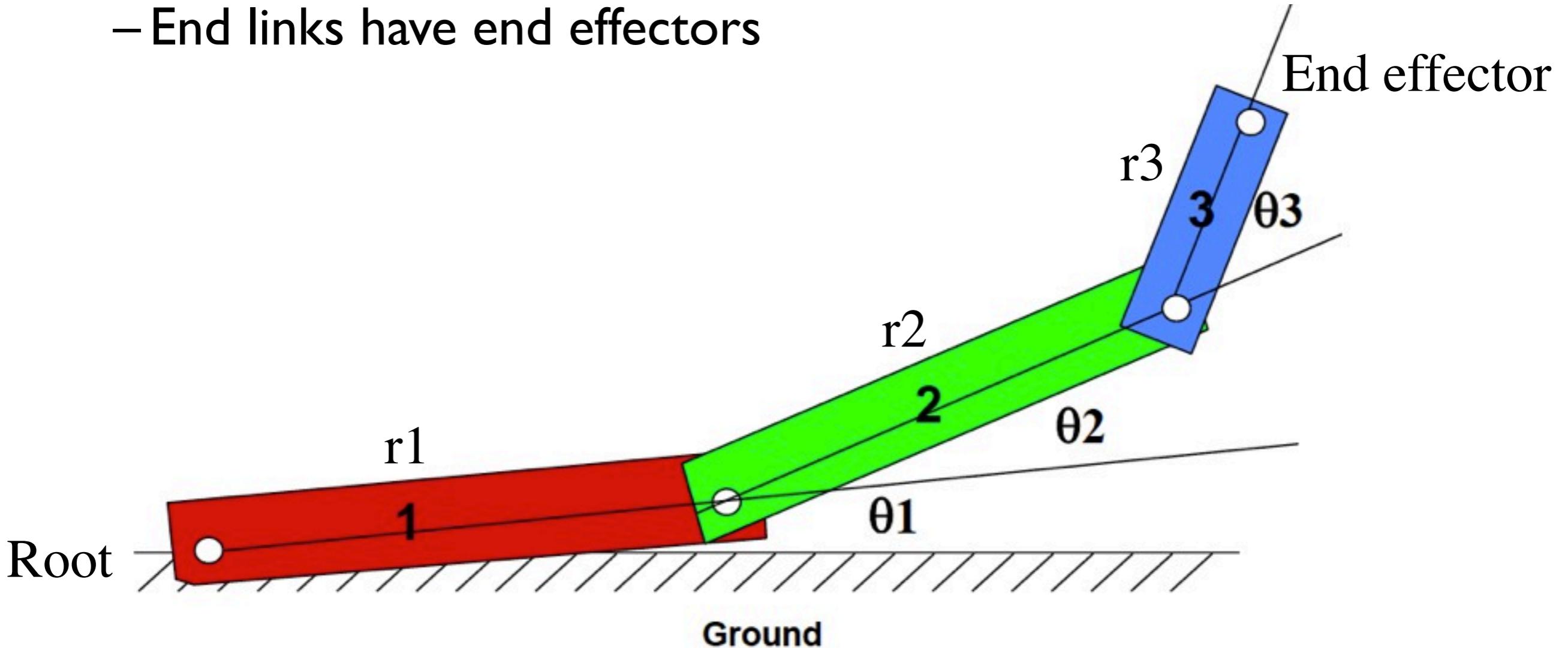
Forward Kinematics

- Articulated body
 - Hierarchical transforms
 - Comes from robotics

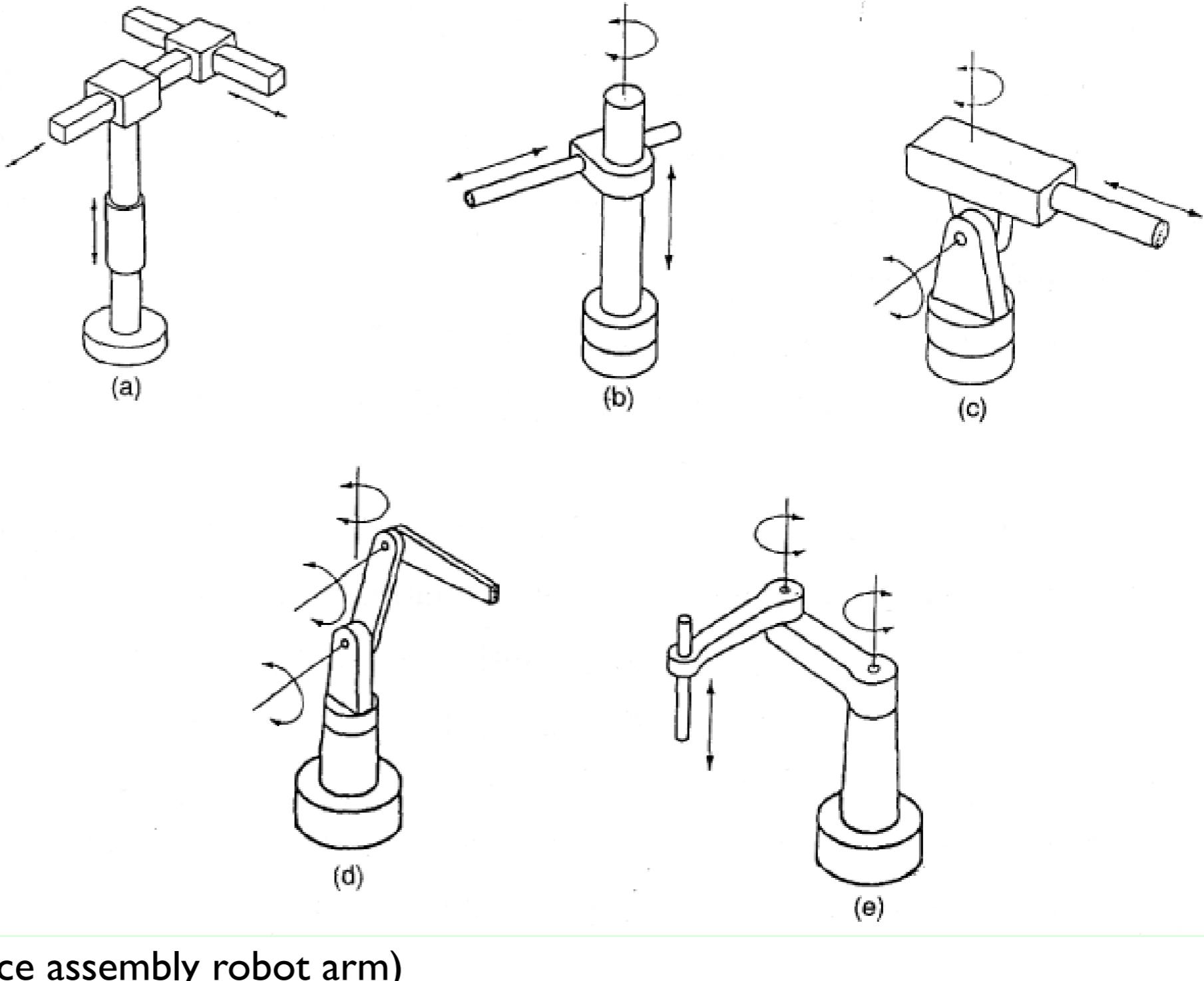


Rigid Links and Joint Structure

- Links connected by joints
 - Joints are purely rotational (single DOF)
 - Links form a tree (no loops)
 - End links have end effectors



Articulation in robotics



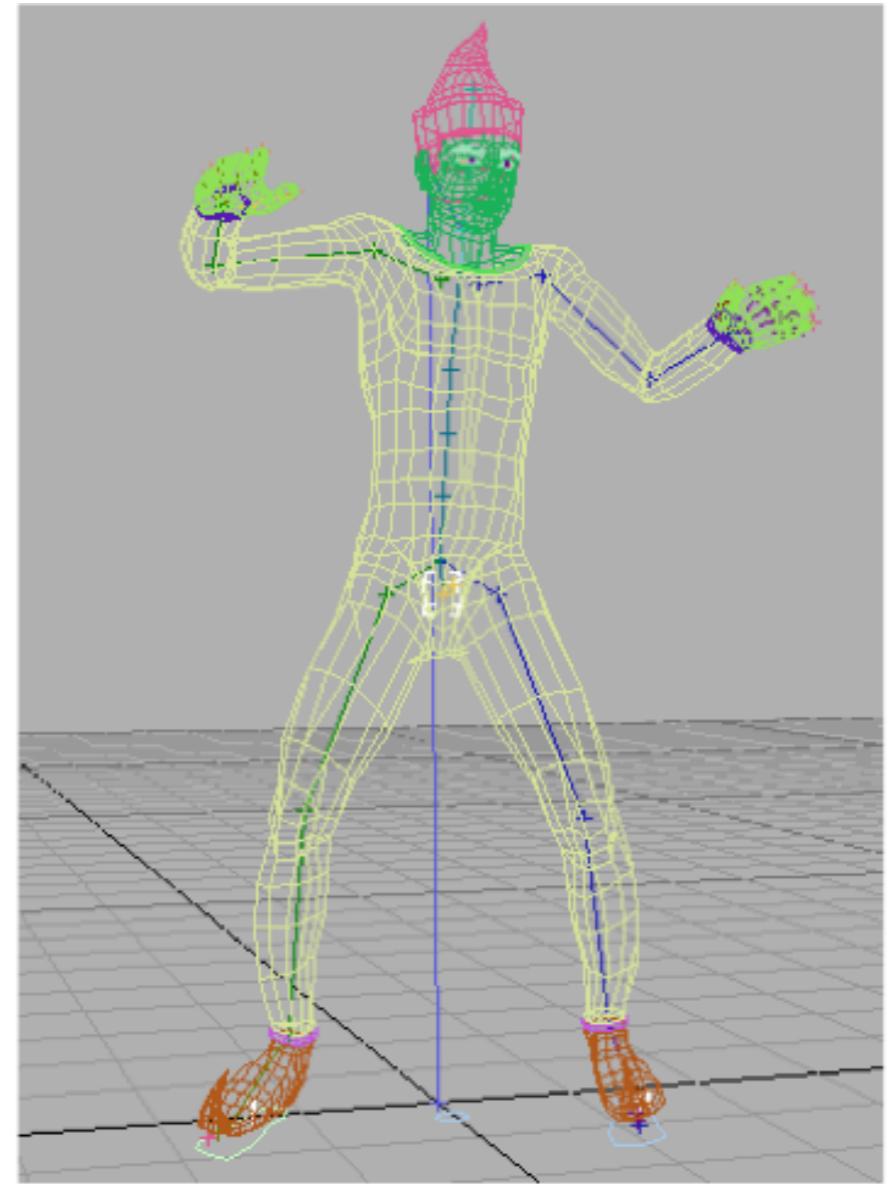
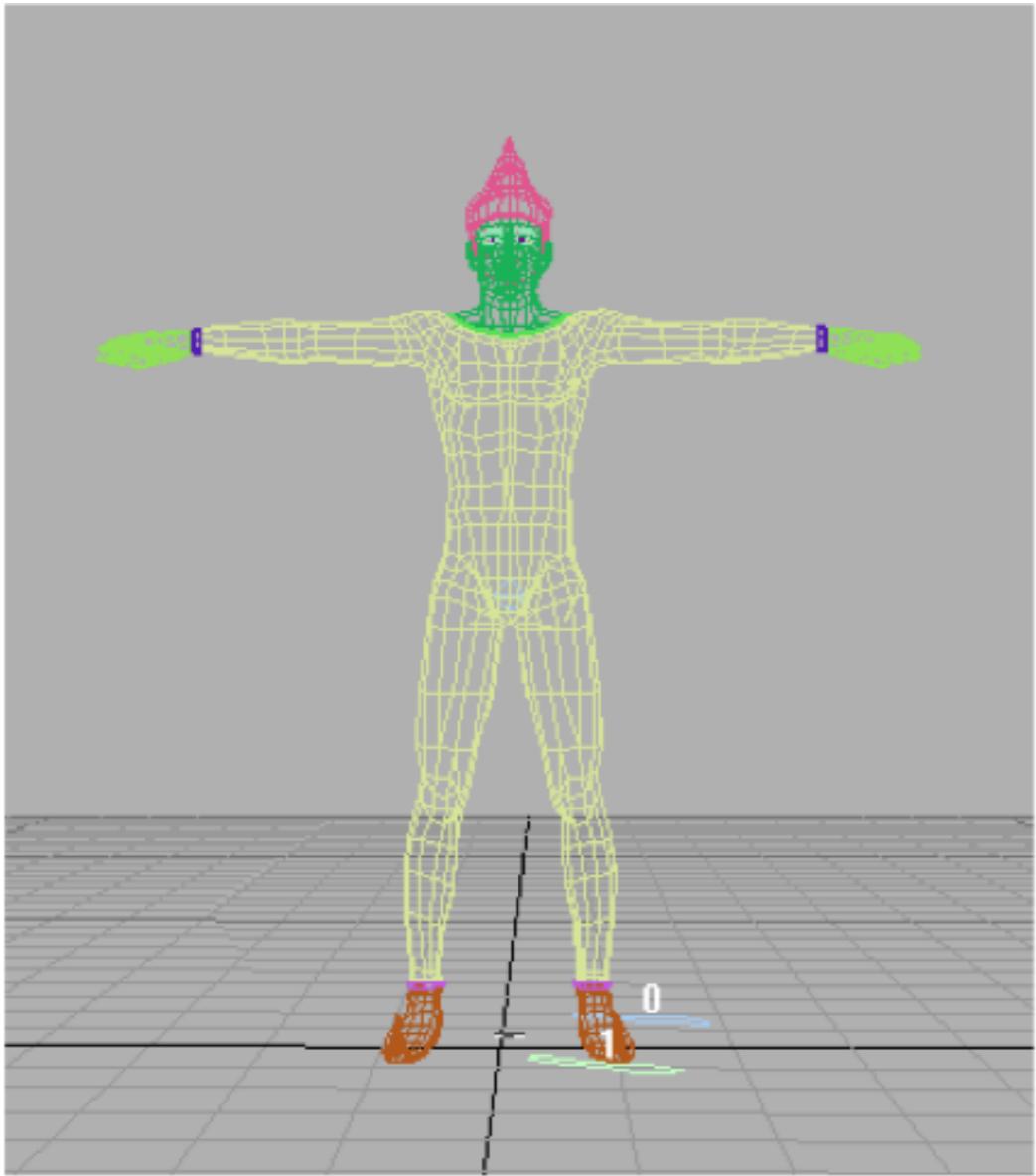
- a. rectangular or cartesian
- b. cylindrical or post-type
- c. spherical or polar
- d. joint-arm or articulated
- e. SCARA (selective compliance assembly robot arm)

Basic surface deformation methods

- Mesh skinning: deform a mesh based on an underlying skeleton
- Blend shapes: make a mesh by combining several meshes
- Both use simple linear algebra
 - Easy to implement—first thing to try
 - Fast to run—used in games
- The simplest tools in the offline animation toolbox

Mesh skinning

- A simple way to deform a surface to follow a skeleton



[Sébastien Dominié | NVIDIA]

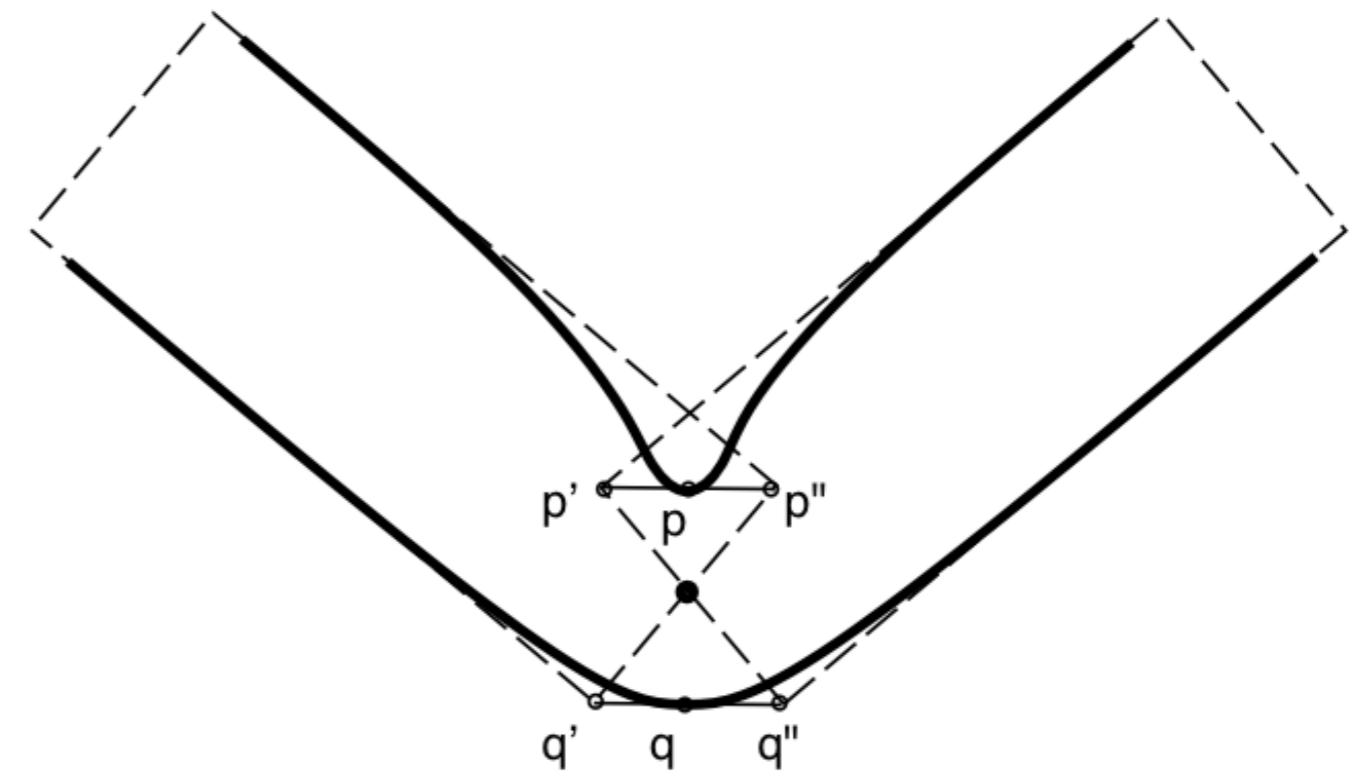
Mesh skinning math: setup

- Surface has control points \mathbf{p}_i
 - Triangle vertices, spline control points, subdiv base vertices
- Each bone has a transformation matrix M_j
 - Normally a rigid motion
- Every point–bone pair has a weight w_{ij}
 - In practice only nonzero for small # of nearby bones
 - The weights are provided by the user

Mesh skinning math

- Deformed position of a point is a weighted sum
 - of the positions determined by each bone's transform alone
 - weighted by that vertex's weight for that bone

$$\mathbf{p}'_i = \sum_j w_{ij} M_j \mathbf{p}_i$$



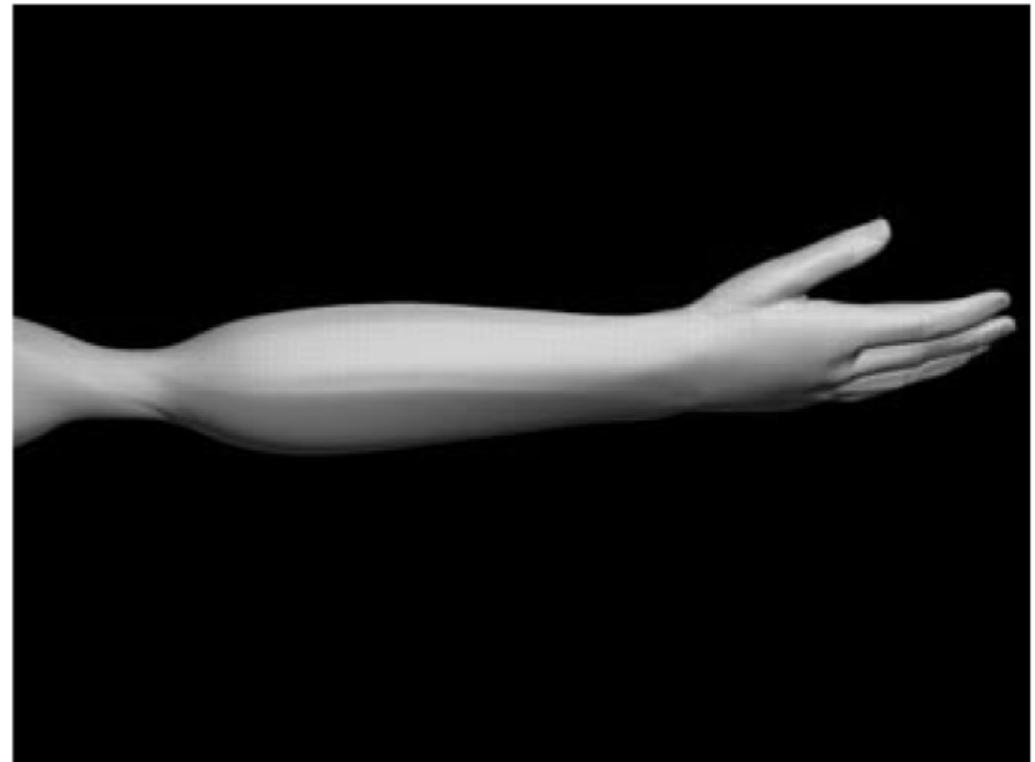
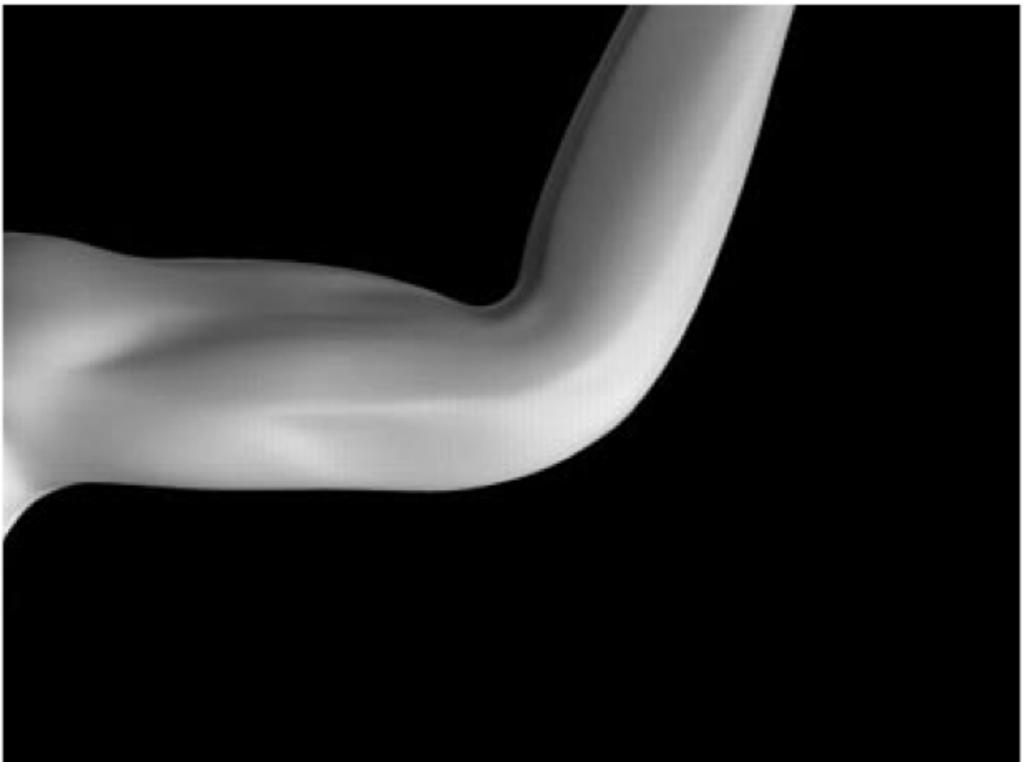
[Lewis et al. SIGGRAPH 2000]

Mesh skinning

- Simple and fast to compute
 - Can even compute in the vertex stage of a graphics pipeline
- Used heavily in games
- One piece of the toolbox for offline animation
 - Many other deformers also available

Mesh skinning: classic problems

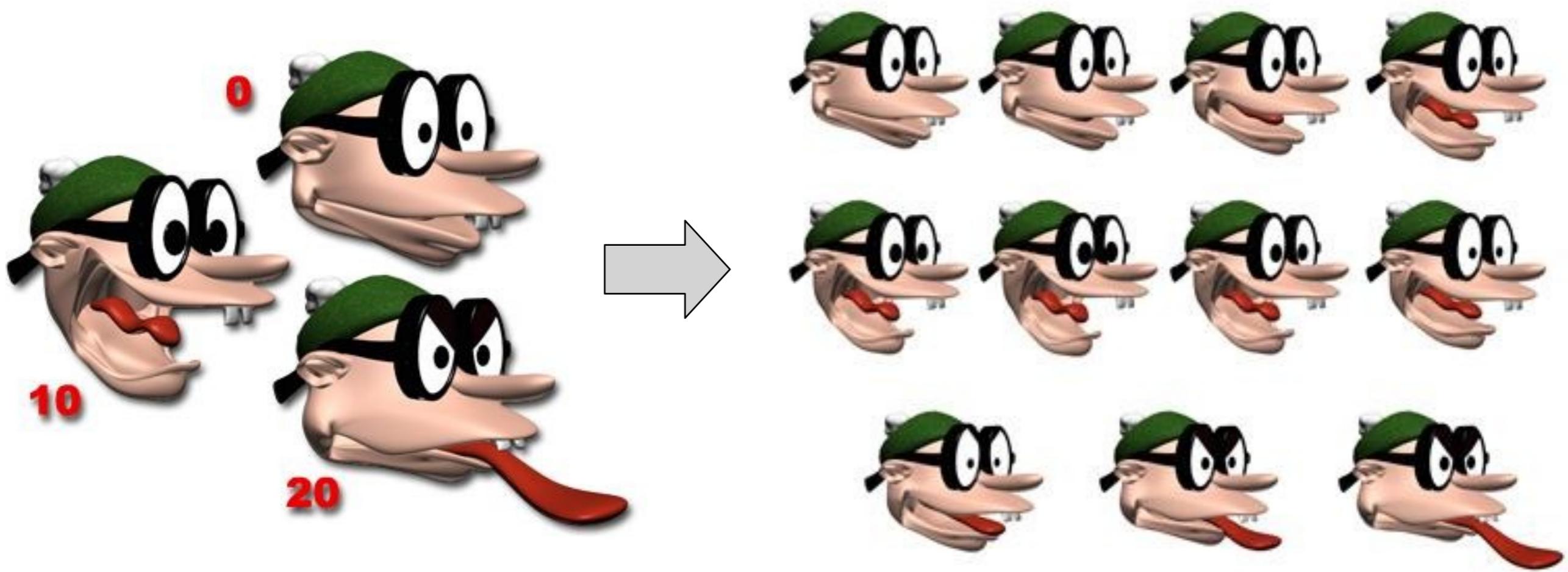
- Surface collapses on the inside of bends and in the presence of strong twists
 - Average of two rotations is not a rotation!
 - Add more bones to keep adjacent bones from being too different, or change the blending rules.



[Lewis et al. SIGGRAPH 2000]

Blend shapes

- Another very simple surface control scheme
- Based on interpolating among several key poses
 - Aka. blend shapes or morph targets

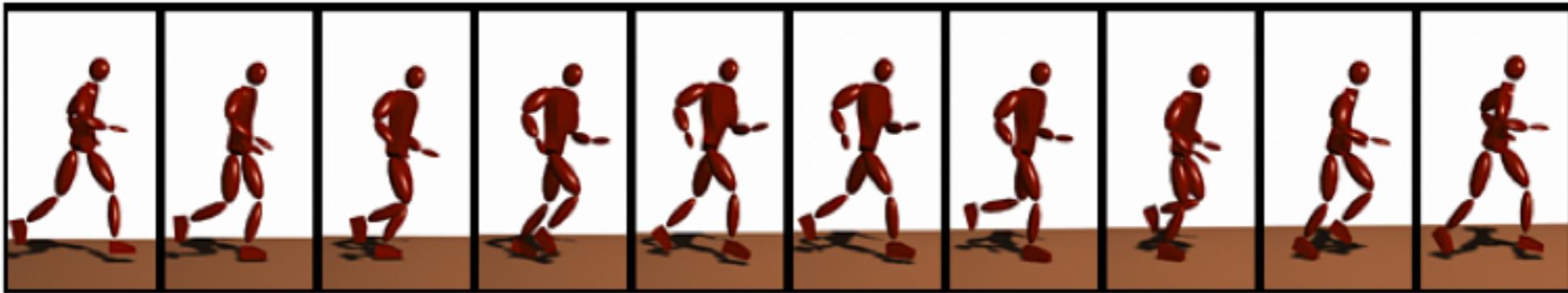


[3D Studio Max example]

Blend shapes math

- Simple setup
 - User provides key shapes—that is, a position for every control point in every shape: \mathbf{p}_{ij} for point i , shape j
 - Per frame: user provides a weight w_j for each key shape
 - Must sum to 1.0
- Computation of deformed shape
$$\mathbf{p}'_i = \sum_j w_j \mathbf{p}_{ij}$$
- Works well for relatively small motions
 - Often used for facial animation
 - Runs in real time; popular for games

Motion capture



- A method for creating complex motion quickly: measure it from the real world

[thanks to Zoran Popović for many visuals]

Motion capture in movies



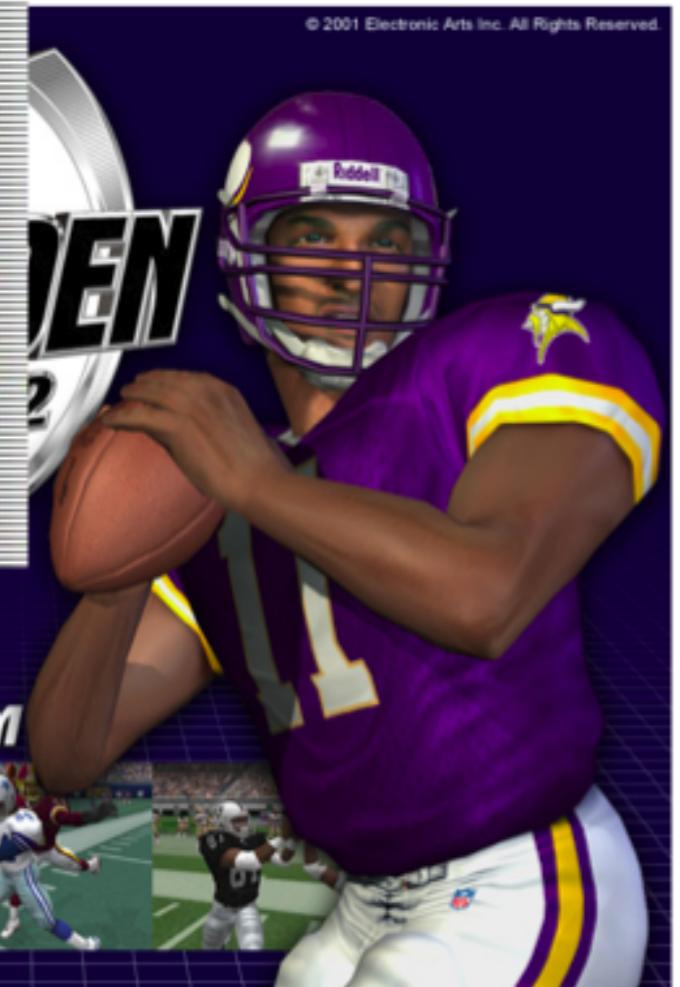
[Final Fantasy]

Motion capture in movies



[*The Two Towers* | New Line Productions]

Motion capture in games



Magnetic motion capture

- Tethered
- Nearby metal objects cause distortions
- Low freq. (60Hz)



Mechanical motion capture

- Measures joint angles directly
- Works in any environment
- Restricts motion

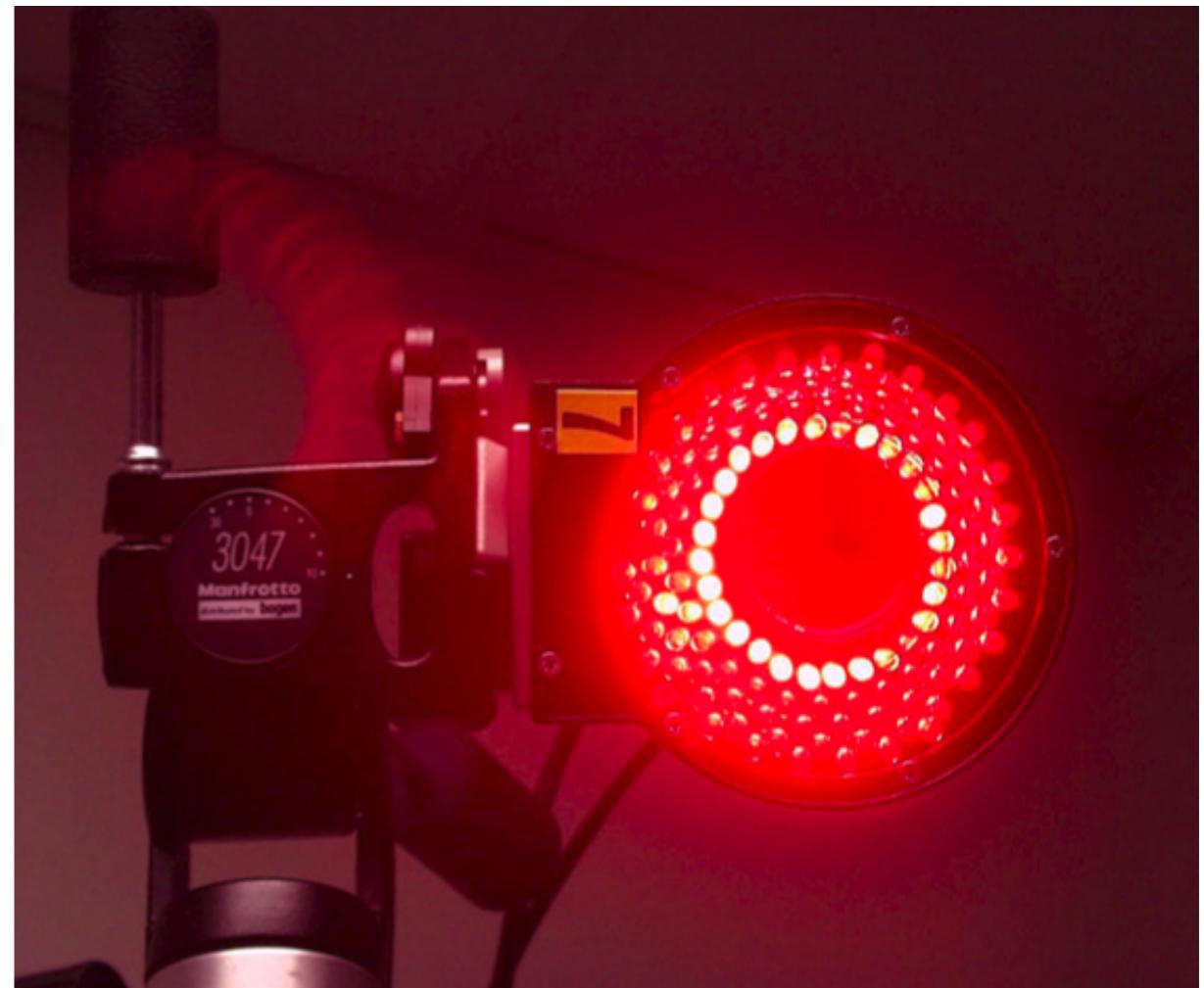


Optical motion capture

- Passive markers on subject



Retroreflective markers



Cameras with IR illuminators

- Markers observed by cameras
 - Positions via triangulation

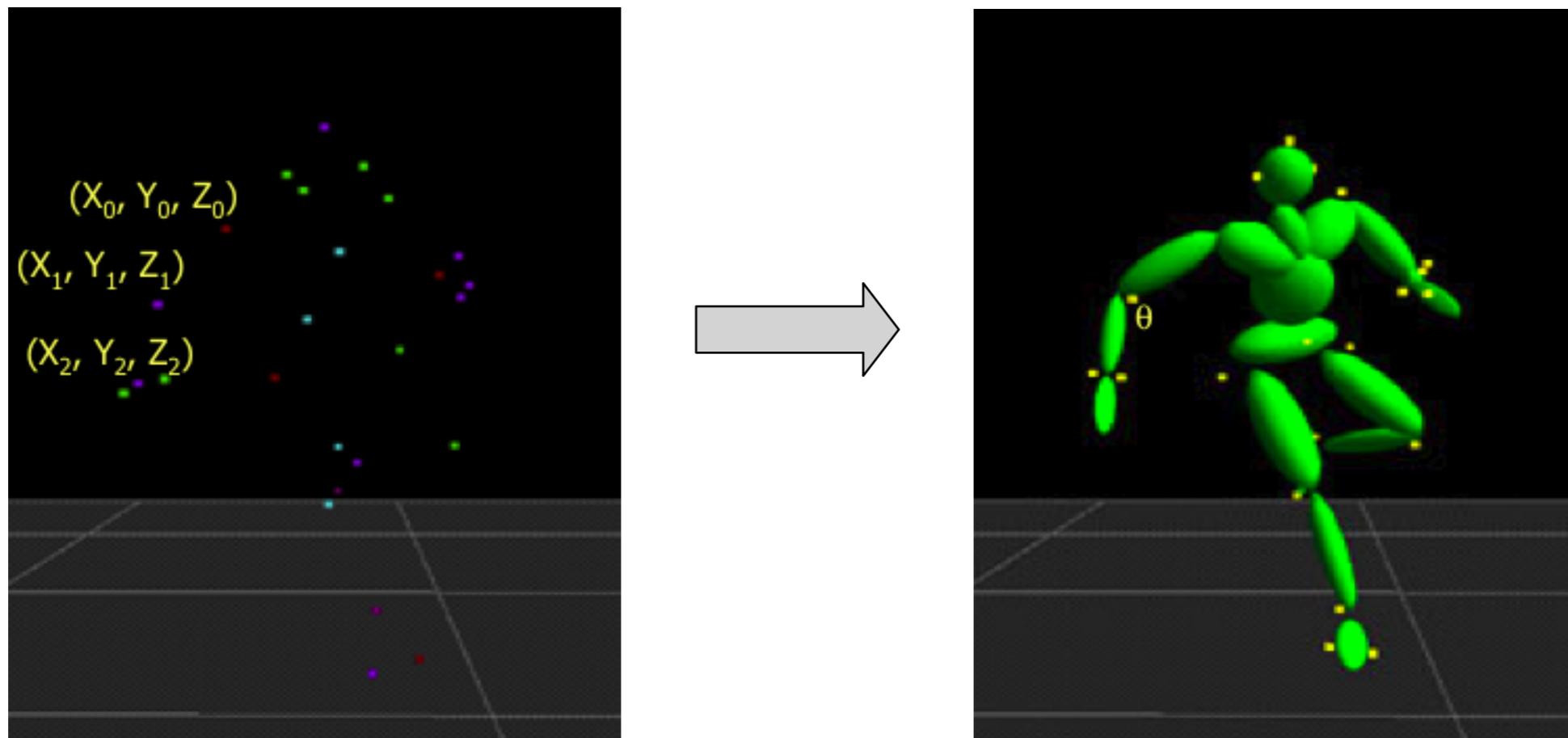
Optical motion capture

- 8 or more cameras
- Restricted volume
- High frequency (240Hz)
- Occlusions are troublesome



From marker data to usable motion

- Motion capture system gives inconvenient raw data
 - Optical is “least information” case: accurate position but:
 - Which marker is which?
 - Where are the markers are relative to the skeleton?



Motion capture data processing

- Marker identification: which marker is which
 - Start with standard rest pose
 - Track forward through time (but watch for markers dropping out due to occlusion!)
- Calibration: match skeleton, find offsets to markers
 - Use a short sequence that exercises all DOFs of the subject
 - A nonlinear minimization problem
- Computing joint angles: explain data using skeleton DOFs
 - A inverse kinematics problem per frame!

Motion capture in context

- Mocap data is very realistic
 - Timing matches performance exactly
 - Dimensions are exact
- But it is not enough for good character animation
 - Too few DOFs
 - Noise, errors from nonrigid marker mounting
 - Contains no exaggeration
 - Only applies to human-shaped characters
- Therefore mocap data is generally a starting point for skilled animators to create the final product