Behaviors (2 lectures):

low level

- keyframing
- motion capture
- simulation

high level (AI)

- finite state machines
- path planning
- group behaviors

Generating Motion

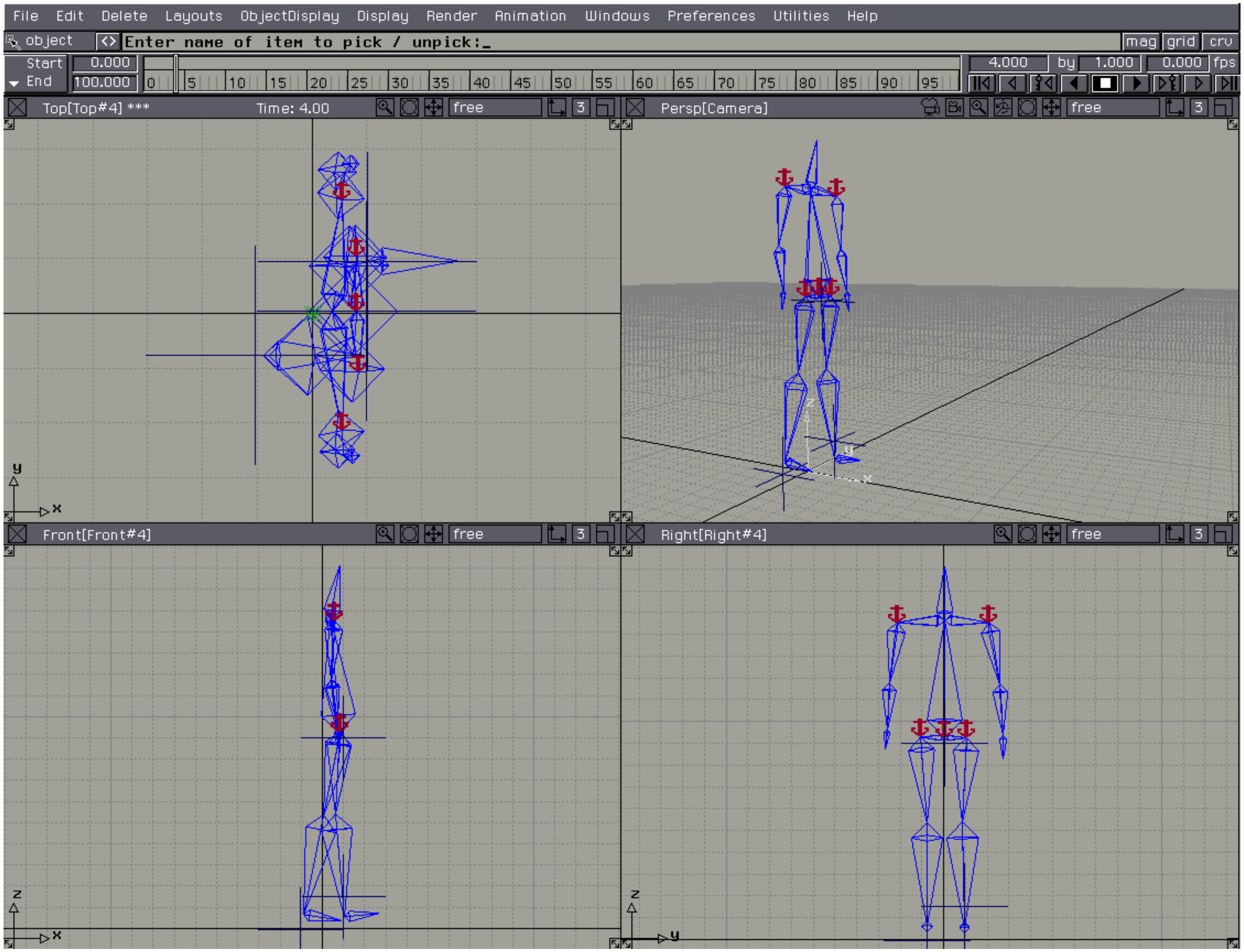
What Matters?

- quality of motion appropriate for rendering style and frame rate
- controllable from the UI
- controllable from the AI
- skills
- personality

Keyframing

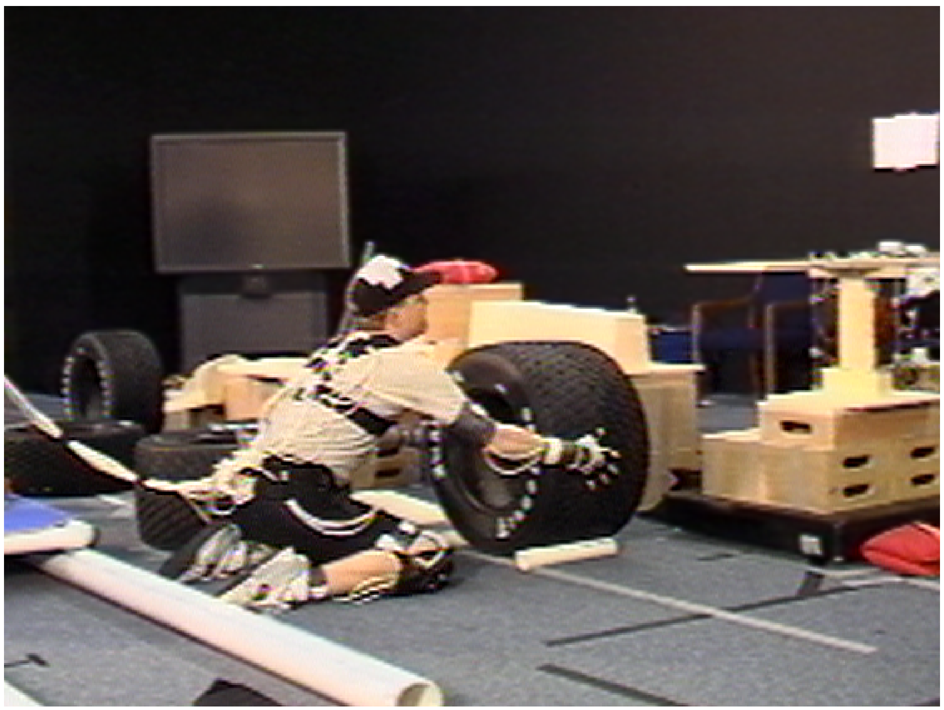
fine level of control

quality of motion depends on skill of animator



Motion Capture

natural–looking motion
hard to generalize motions
registration is difficult



images courtesy of the Microsoft Motion Capture Group

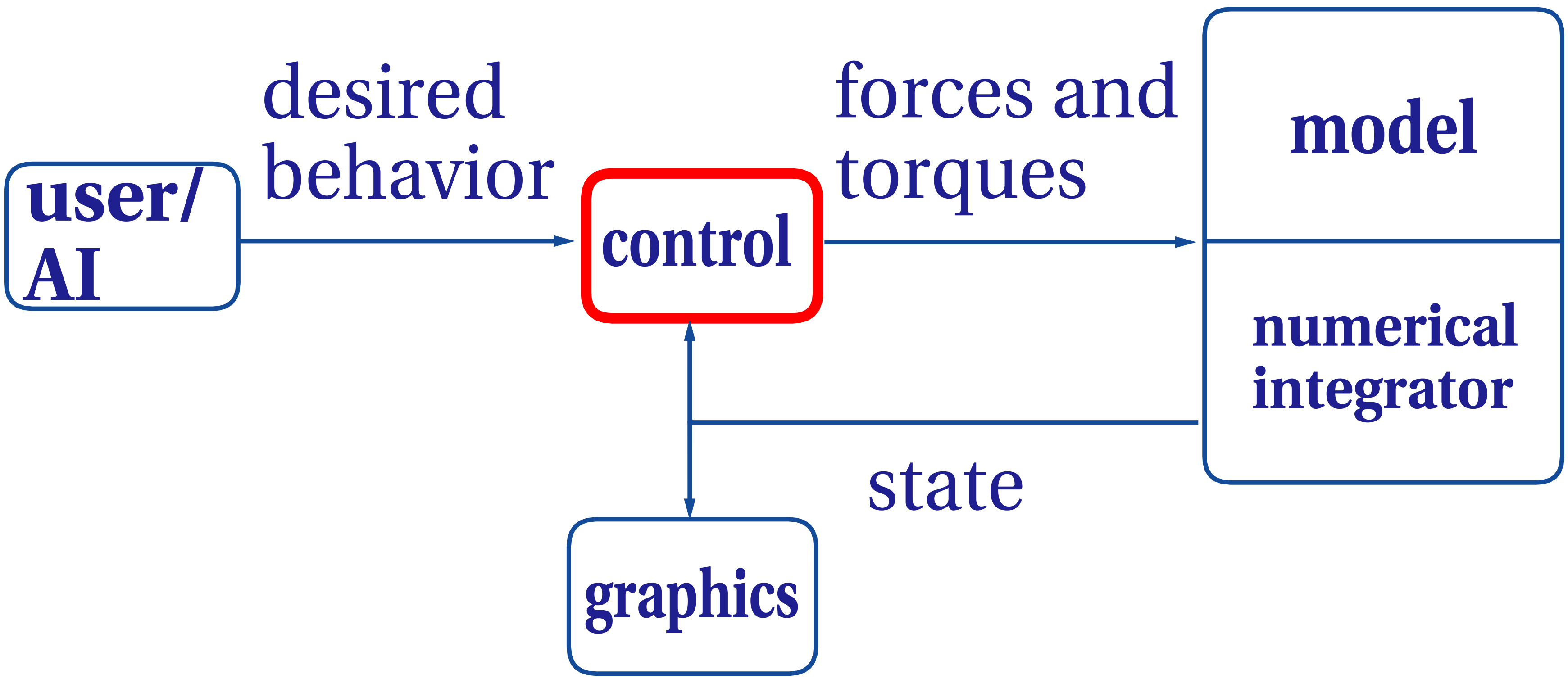
Simulation (broadly defined)

physics is hard

pseudo–physics is somewhat hard

control is very hard

generalization/interactivity



When to Use What Method?

keyframing

motion capture

simulation

When to Use What Method?

keyframing

- sprites and other simple animations
- non–human characters

motion capture

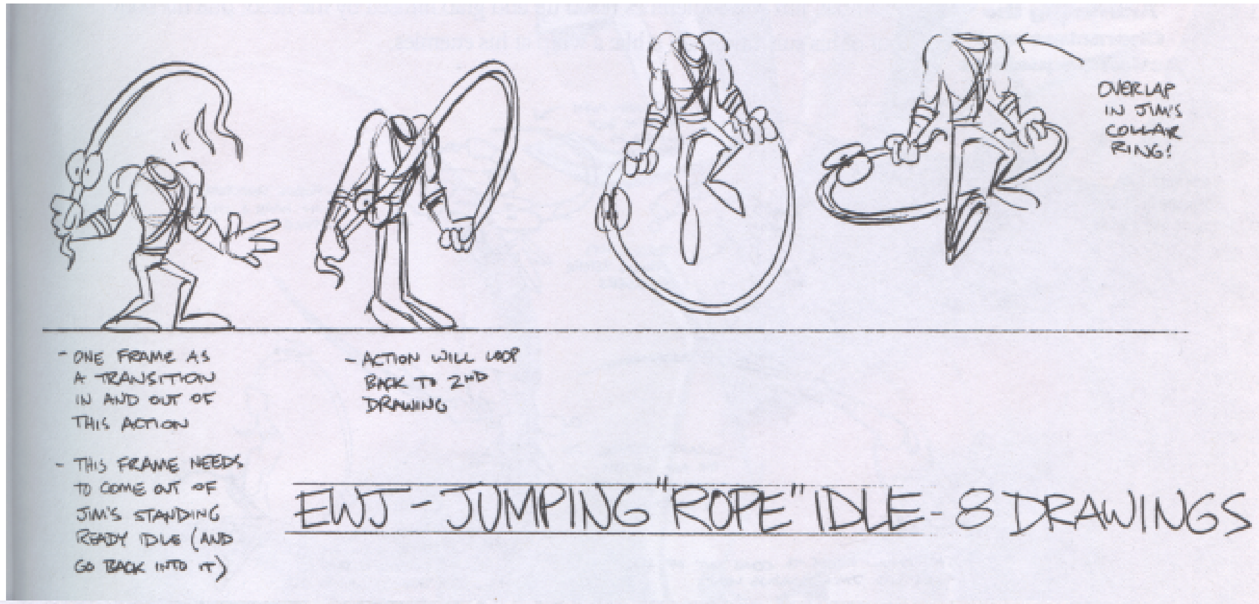
- human figures
- subtle motions, long moves

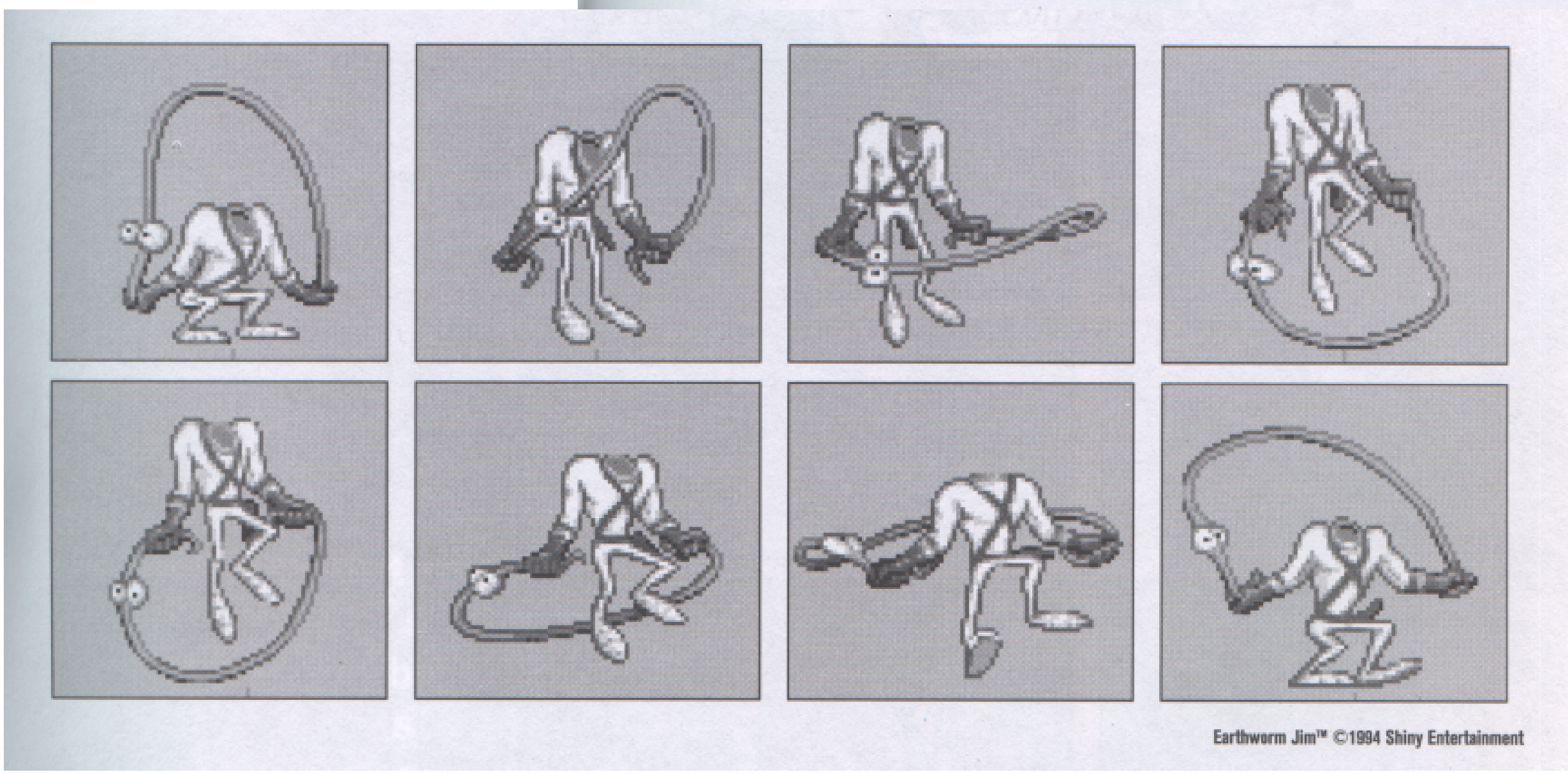
simulation

- passive simulations
- when interactivity is really important

Hand Drawn Animation: 2D

sketches
pencil tests
inking
coloring
digitize to sprites





Computer Animation: 2D or 3D

sketches

models and materials

key configurations

playback of motion
or render to sprites

Improv, Perlin, NYU

Keyframing

iterate:

adjust trajectory

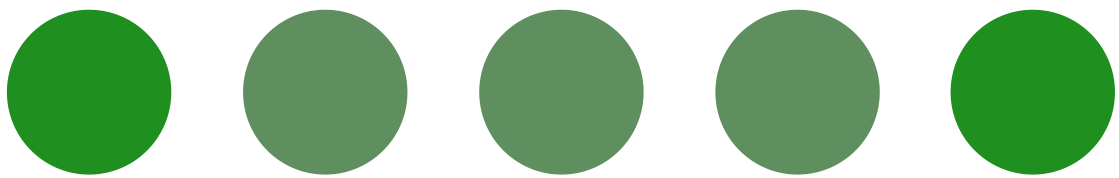
play back motion

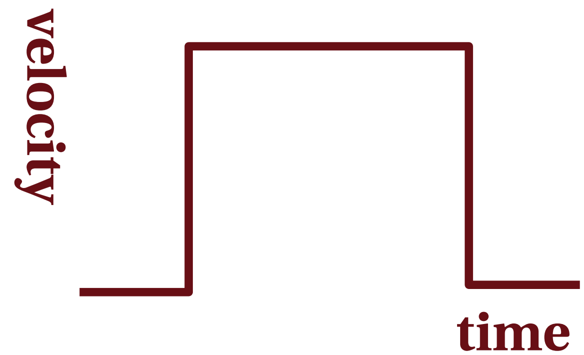
parameters:

- locations
- joint angles
- shape –– flexible objects
- material properties (color, texture)
- camera motion (for animation)
- lighting

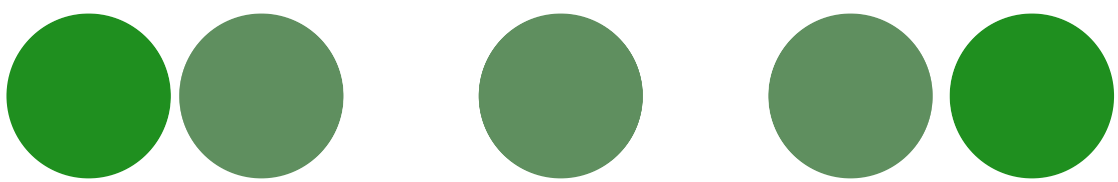
Keyframing -- Interpolation Inbetweening

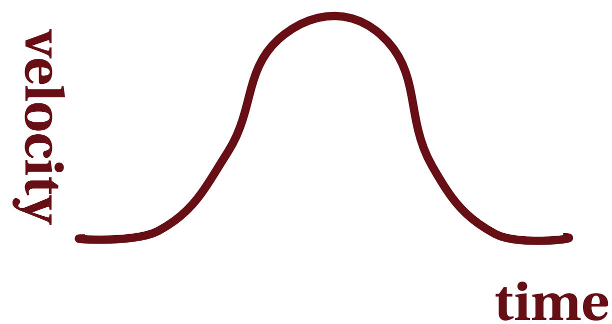
Linear



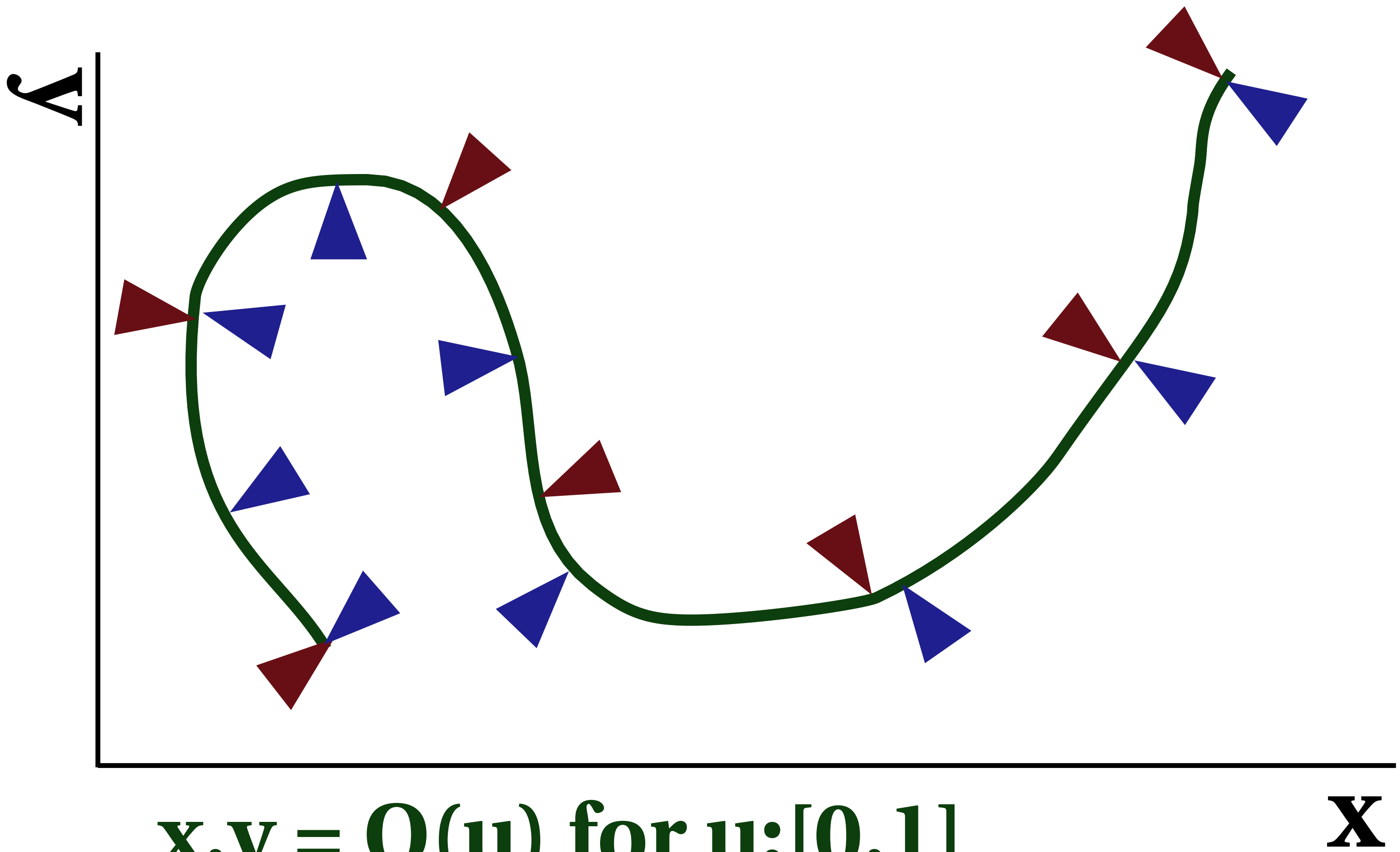


Ease in/ Ease out





Spline-driven Animation



x,y = Q(u) for u:[0,1]

equal arc lengths

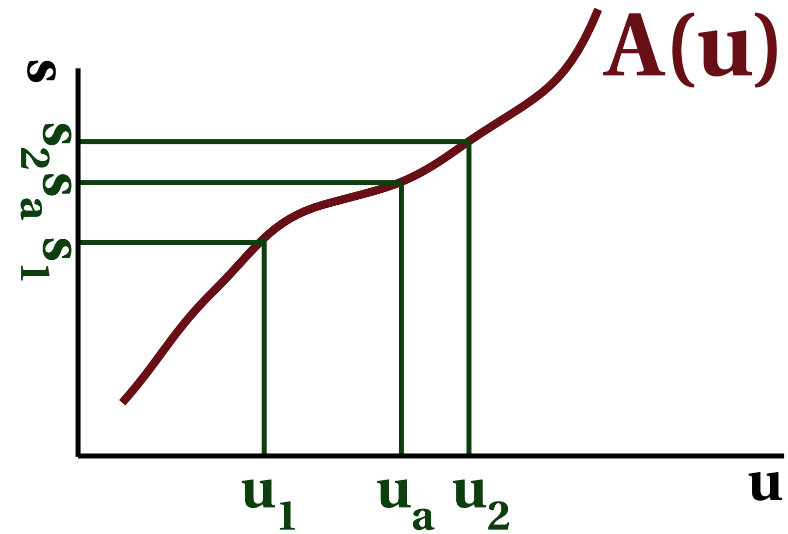
equal spacing in u

Arc–length reparametrization

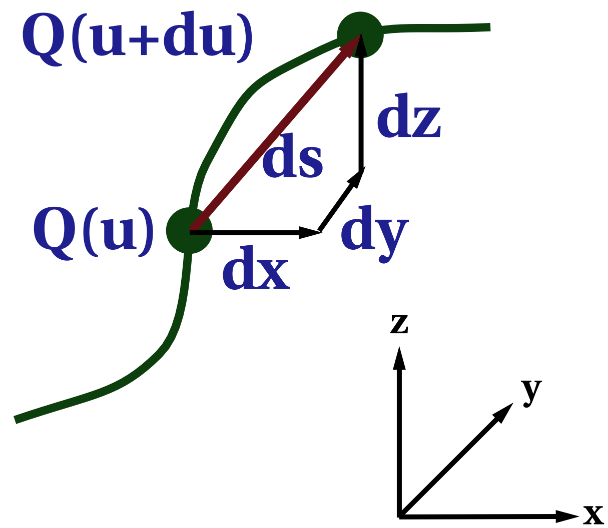
$s = A(u)$ where s is arc length

reparam: $Q(u)$ to $Q(A^{-1}(s))$

need to find $u = A^{-1}(s)$

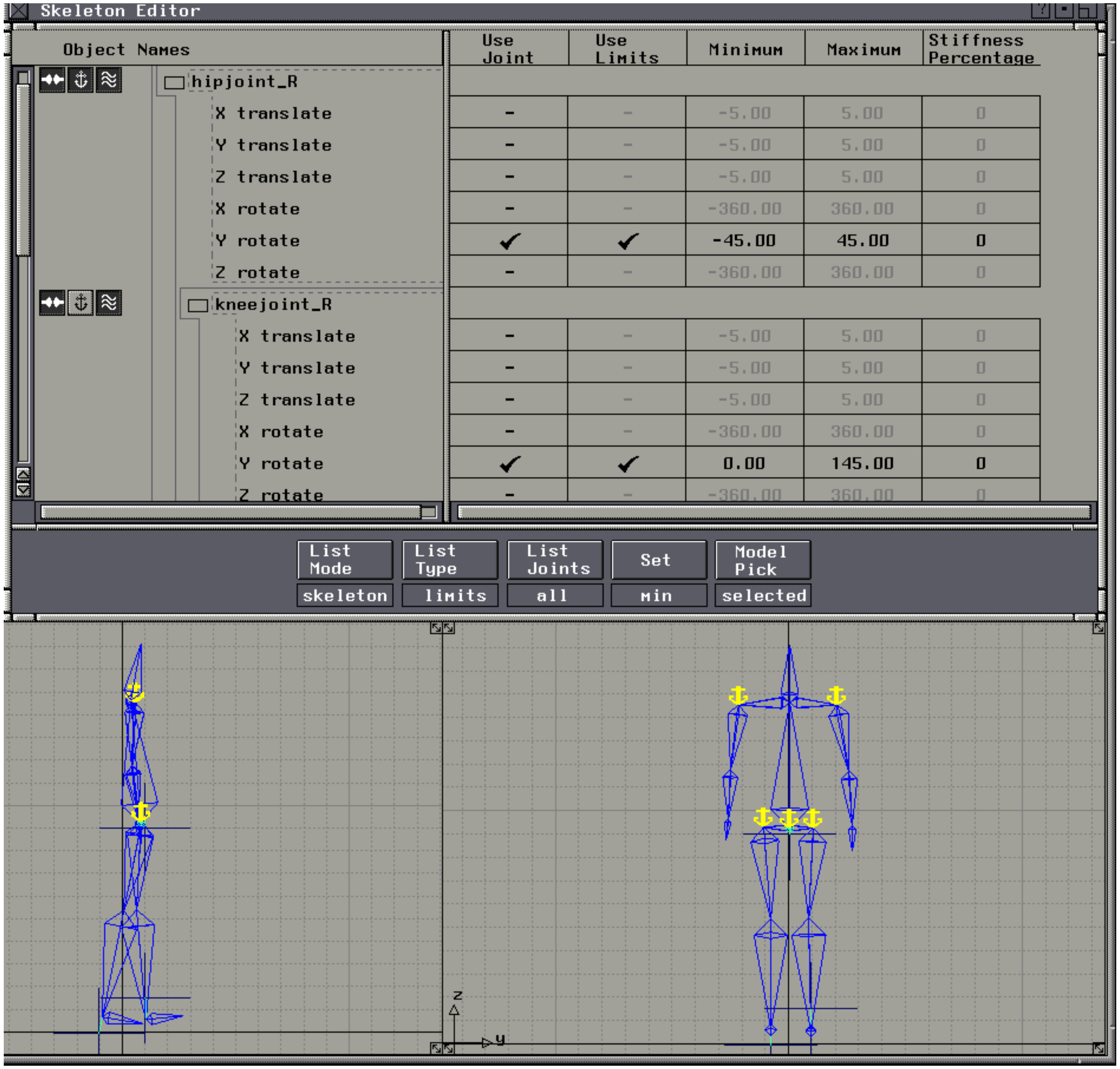


bisection search for a value of u where $A(u) = s$ with a numerical evaluation of $A(u)$ (details in Watt and Watt)

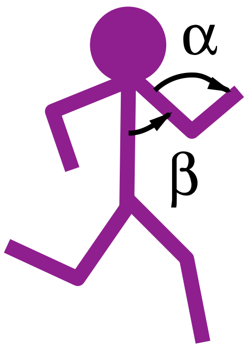


Keyframing -- Constraints

Inverse Kinematics
Joint Limits
Position Limits

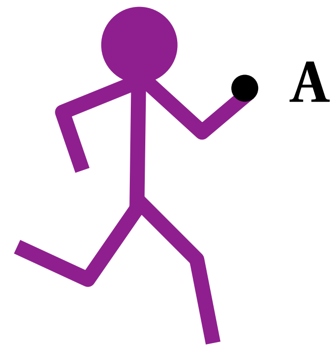


Kinematics -- the study of motion without regard to the forces that cause it.



Forward: $A = f(\alpha,\beta)$

draw graphics



Inverse: $\alpha,\beta = f^{-1}(A)$

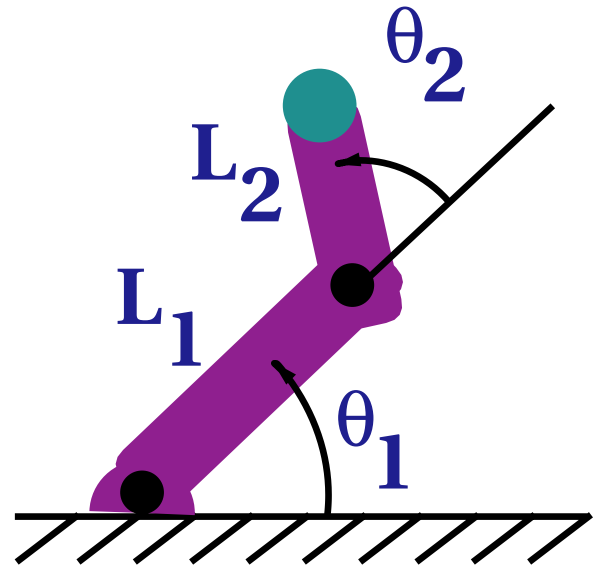
specify fewer degrees of freedom

more intuitive control of dof
- **pull on hand**
- **glue feet to the ground**

Forward Kinematics

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

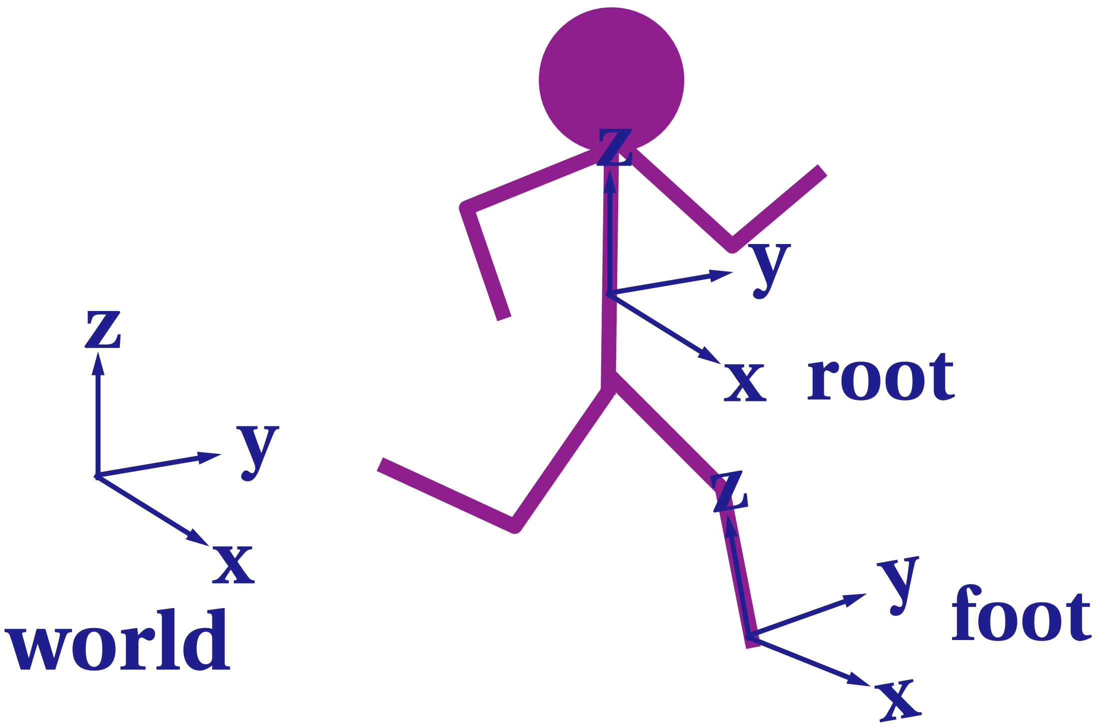
$$y = L_1 \sin\theta_1 + L_2 \sin(\theta_1 + \theta_2)$$



$$\begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} \quad & \quad \\ \quad & \quad \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} \quad & \quad \\ \quad & \quad \end{bmatrix} = \begin{bmatrix} \text{rot } \theta_1 \end{bmatrix} \begin{bmatrix} \text{trans } L_1 \end{bmatrix} \begin{bmatrix} \text{rot } \theta_2 \end{bmatrix} \begin{bmatrix} \text{trans } L_2 \end{bmatrix}$$

Coordinate Systems



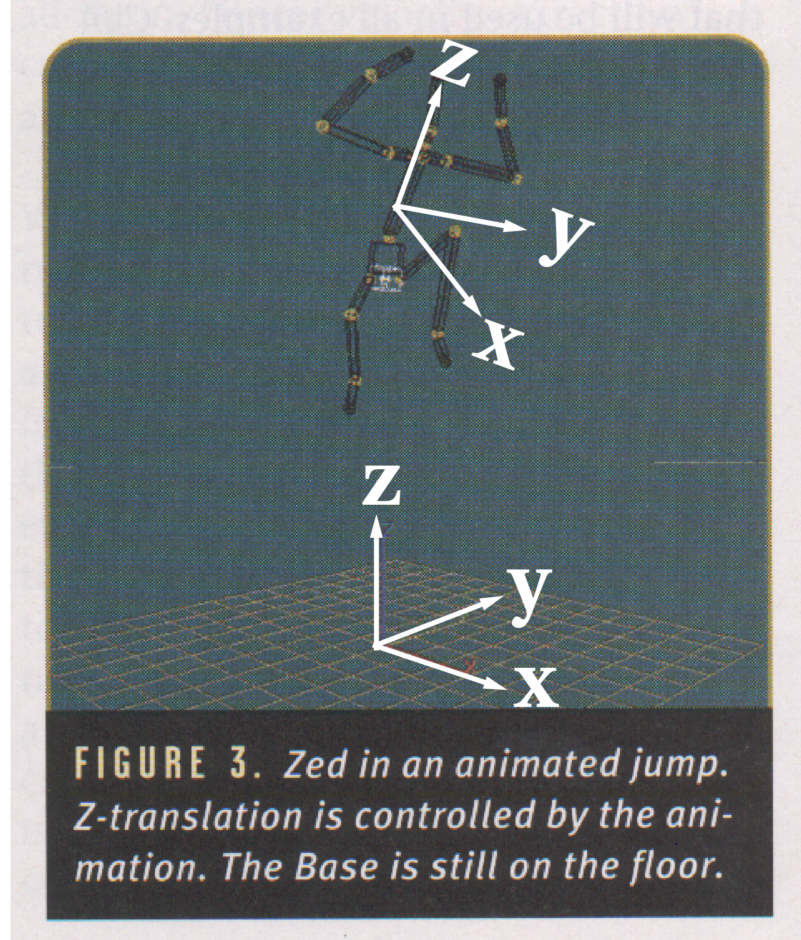


FIGURE 3. *Zed in an animated jump. Z-translation is controlled by the animation. The Base is still on the floor.*

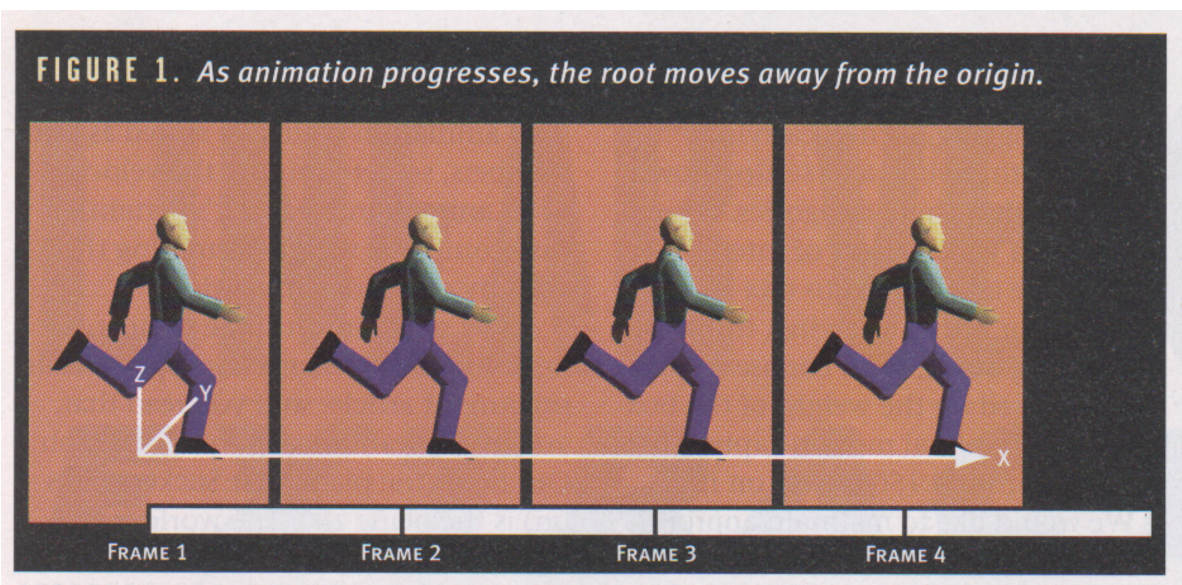


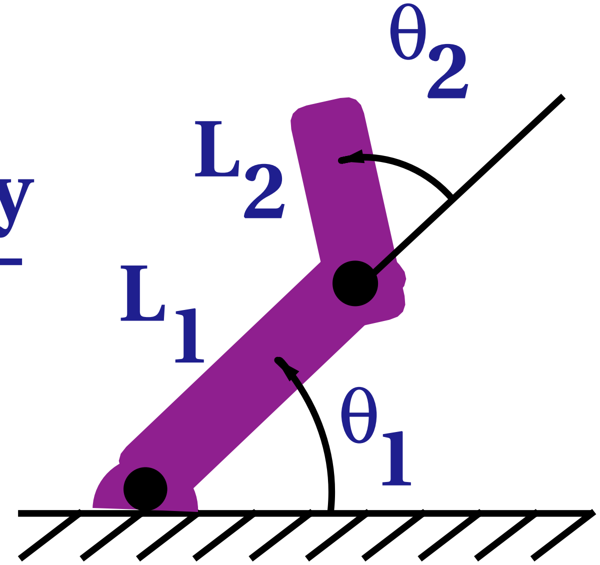
FIGURE 1. *As animation progresses, the root moves away from the origin.*

Inverse Kinematics

$$\theta_2 = \frac{\mathbf{cos}\ (\mathbf{x}^2 + \mathbf{y}^2 - \mathbf{L}_1^2 - \mathbf{L}_2^2)}{2\ \mathbf{L}_1\ \mathbf{L}_2}$$

$$\theta_1 = \frac{-(\mathbf{L}_2 \mathbf{sin}\theta_2)\mathbf{x} + (\mathbf{L}_1 + \mathbf{L}_2 \mathbf{cos}\ \theta_2)\mathbf{y}}{(\mathbf{L}_2 \mathbf{sin}\theta_2)\mathbf{y} + (\mathbf{L}_1 + \mathbf{L}_2 \mathbf{cos}\theta_2)\mathbf{x}}$$

$$\theta = \mathbf{f}^{-1}(\mathbf{x})$$

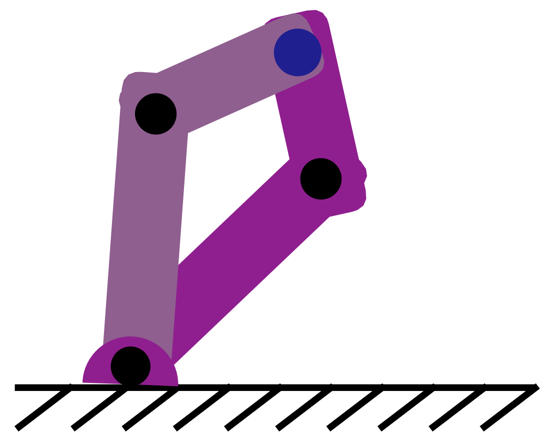


What makes IK hard?

many dof--non-linear, transcendantal equations

redundancies

- choose solution that is "closest" to current configuration
- move outermost links the most
- energy minimization
- minimum time

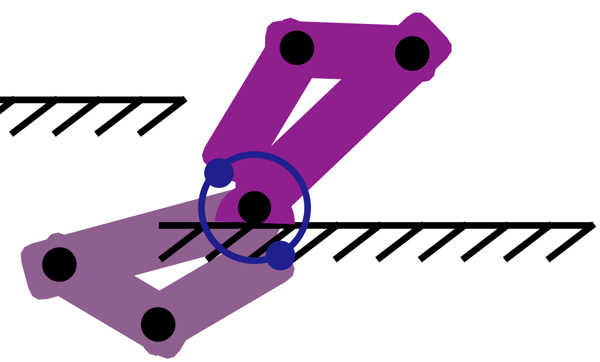


singularities

- ill-conditioned near singularities
- high state space velocities for low cartesian velocities

goal of "natural looking" motion

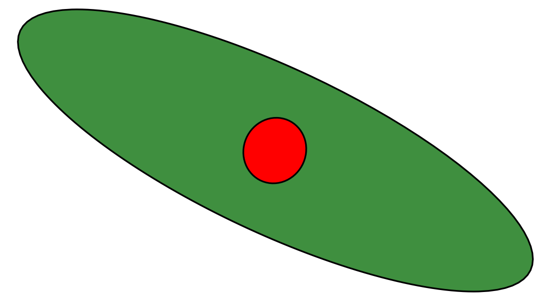
- minimum jerk



Motion Capture

What do we need to know?

x, y, z
pitch, roll, yaw

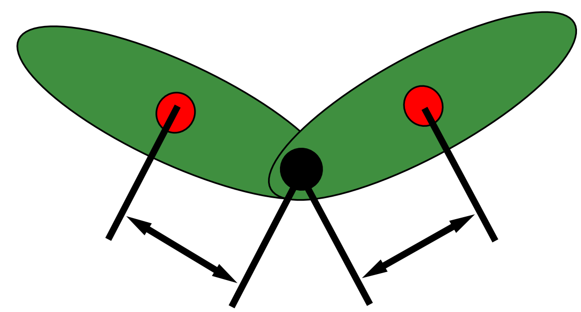


Errors cause

joints to come apart

links to grow/shrink

bad contact points



Sampling Rate and Accuracy

Motion Capture

Goals

- realistic motion
- lots of different motions (300–1000)
- contact

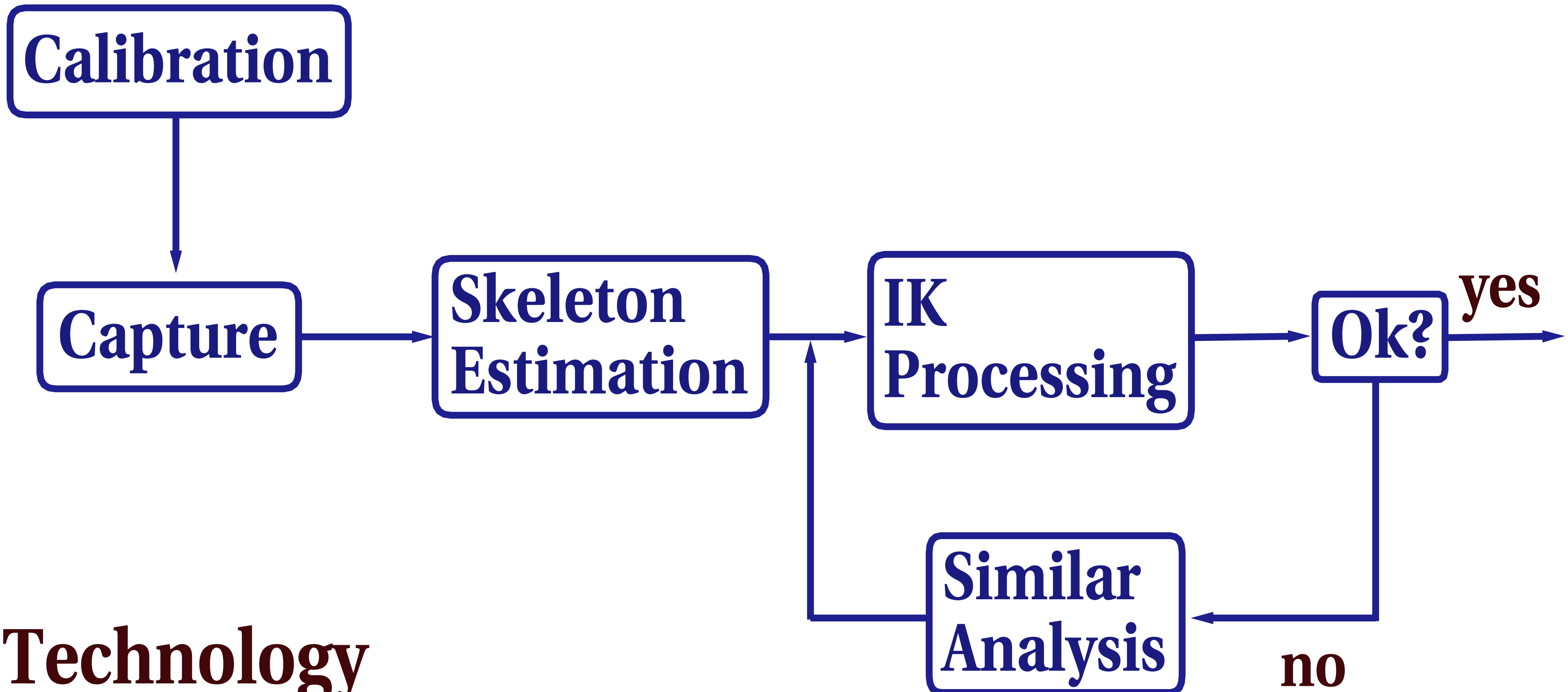
Appropriate game genres

- sports
- fighting

Applications

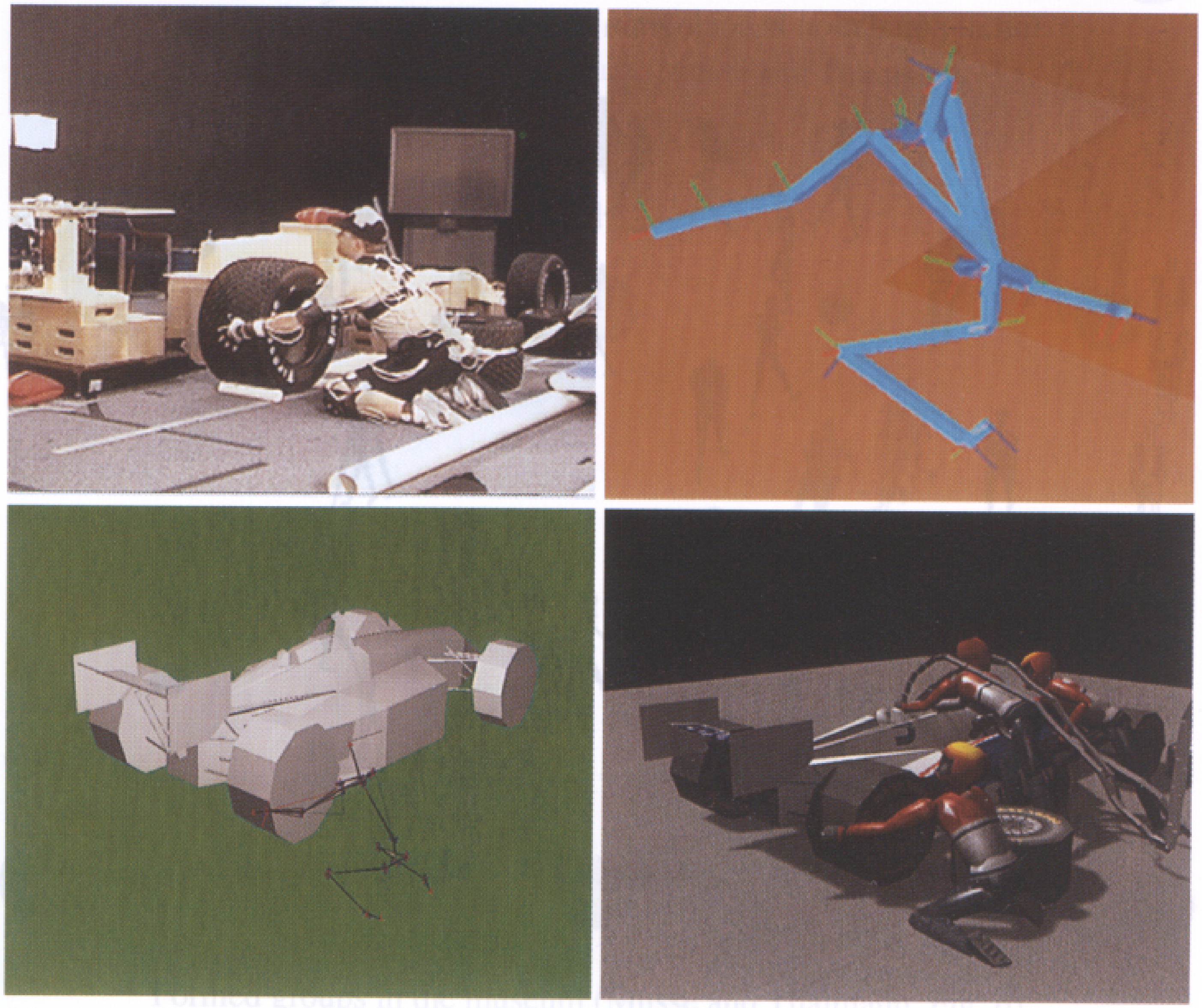
movies
tv shows
video games
performance animation

Production Pipeline



Technology
Calibration
Skeleton Estimation
Remaining Issues: modifying and controlling

Production Pipeline

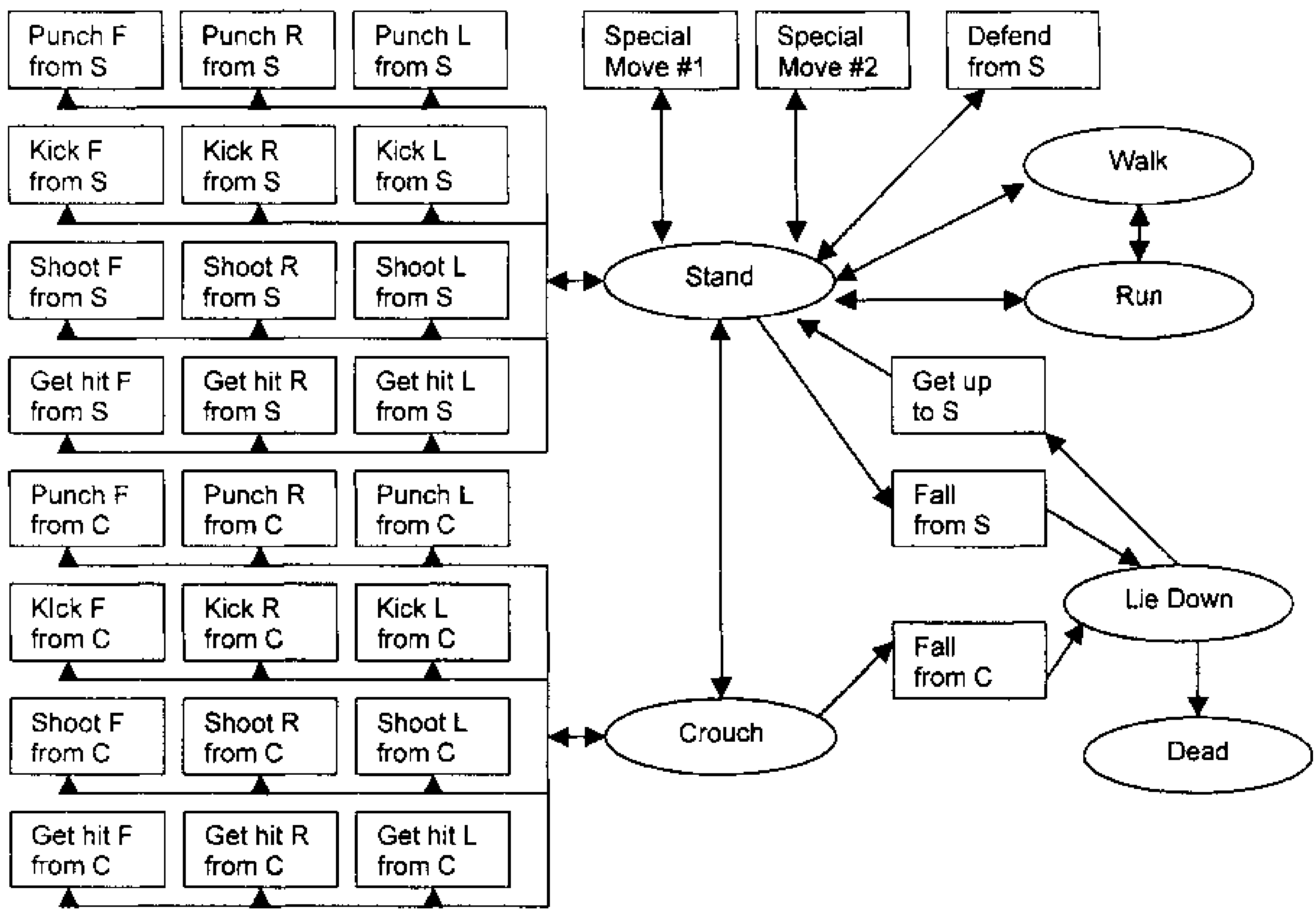


Various phases of the motion capture process (Bodenheimer et al., Fig. 11)

Plan out Shoots Carefully

- know needed actions (80–100 takes/day)
  - bridges between actions
  - speed of actions
  - starting/ending positions
- hire the right actor
  - watch for idiosyncracies in motion
  - good match in proportions
- marker/sensor placement
  - capture enough information
  - watch for marker movement
- check data part way through shoot
- videotape everything

Superguy's flowchart:



Technology

passive reflection--Peak

hand or semi-automatically digitized

time consuming

no glossy or reflective materials

tight clothing

occlusion of markers by props

higher frames/second

Technology

passive reflection––Acclaim, Motion Analysis,...

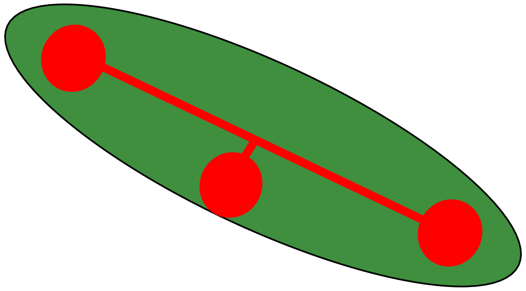
automatically digitized

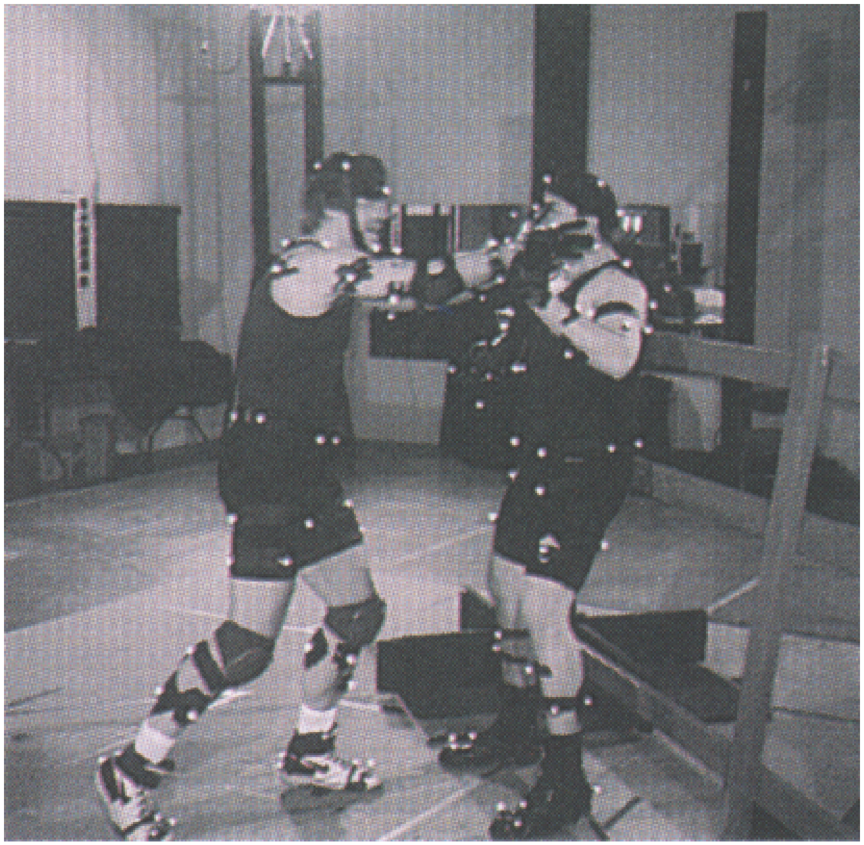
240 Hz

not real–time

3+ markers/body part for 6 dof

2+ cameras for 3d position data

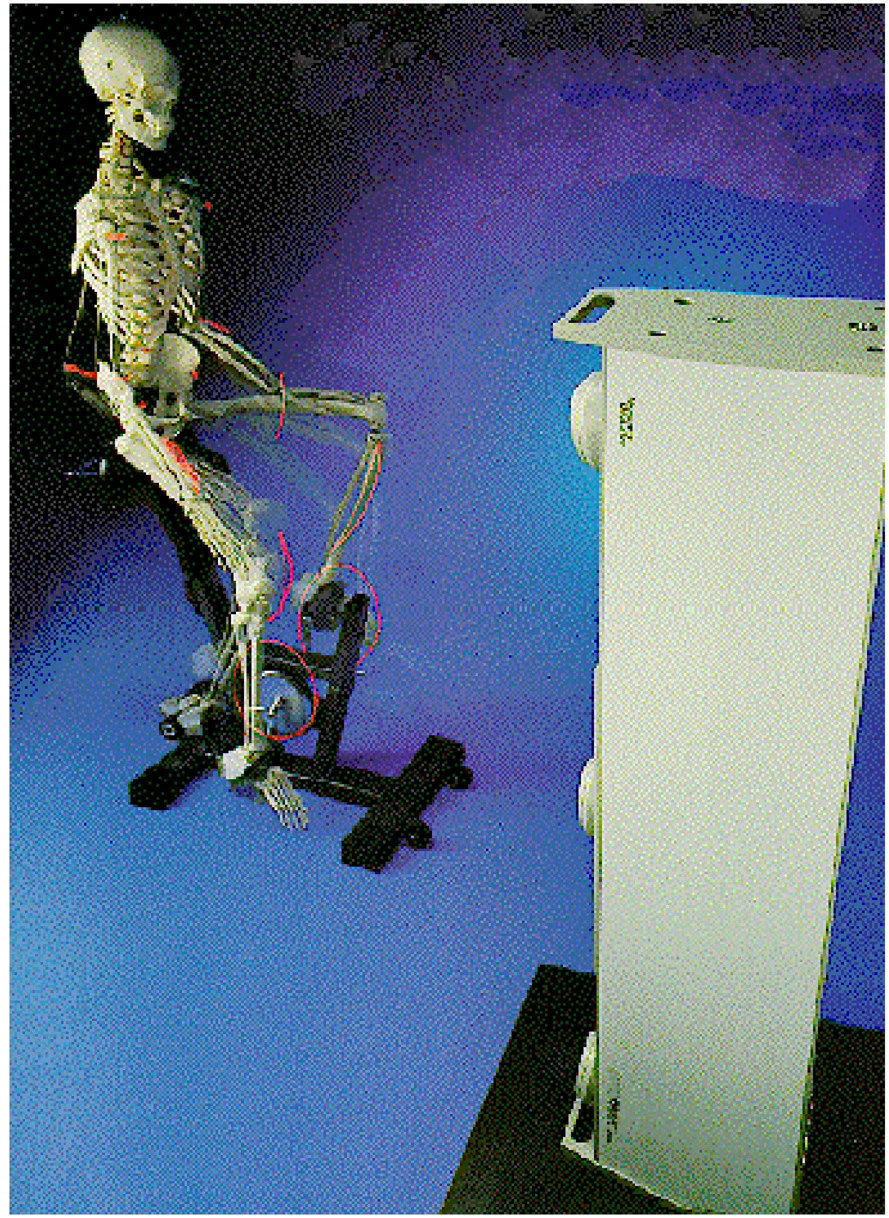




Technology

active light sources –– Optotrak

automatically digitized
correspondence
256 markers
3,500 markers/second



Technology

electromechanical transducers

Accension flock of birds

Polhemus Fastrak

limited range/resolution

pigtail (new wireless system)

metal in the environment

(treadmill, rebar!)

no identification problem

6 dof information

realtime

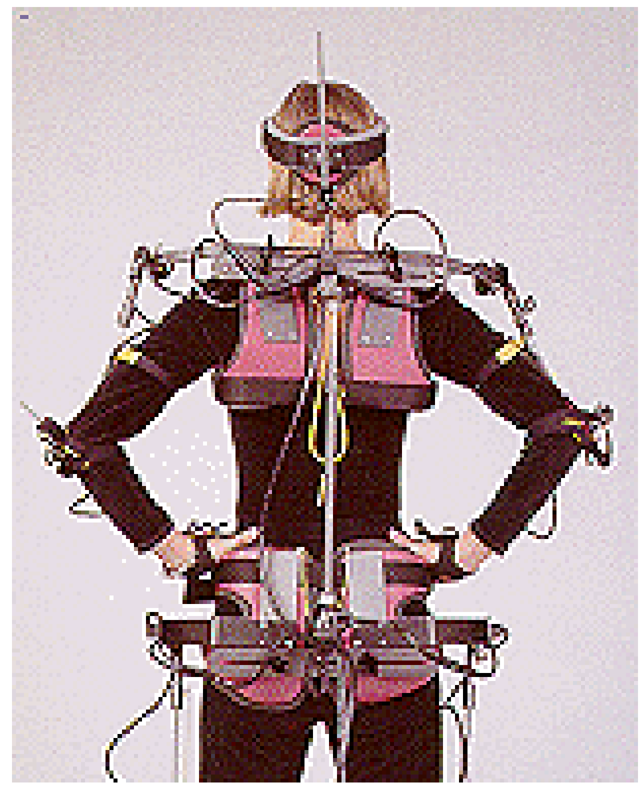
lower frequency: 30 to 144 Hz

few markers: ~13–18

Technology

exoskeleton + angle sensors
Analogous

pigtail
no identification problem
realtime
high frequency: 500Hz
not range limited
fit
rigid body approximation

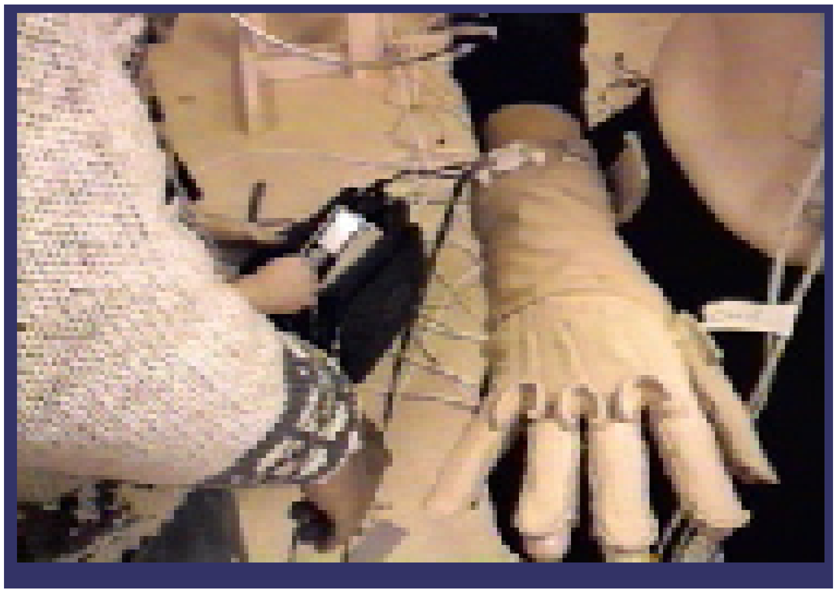


Technology

mechanical motion capture

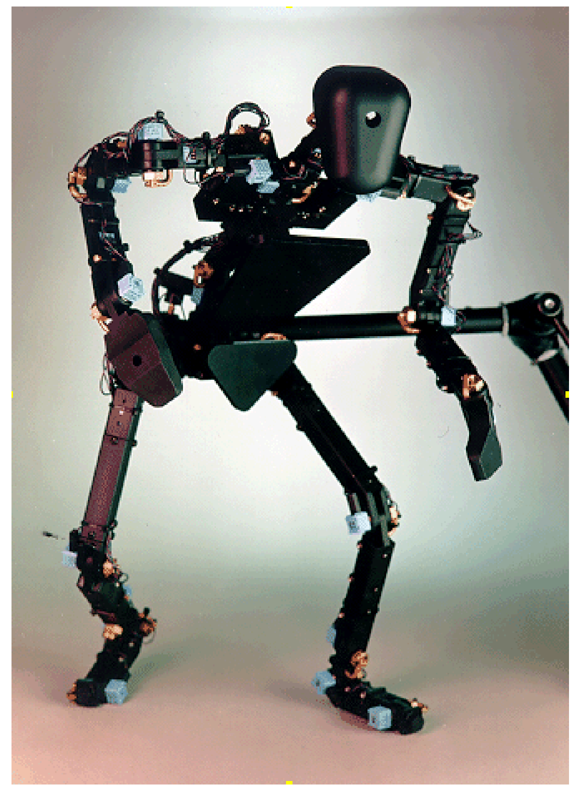
dataglove

low accuracy
focused resolution



monkey

high accuracy
high data rate
not realistic motion
no paid actor



Technology Issues:

resolution/range of motion

calibration

accuracy

occlusion/correspondence

Animation Issues:

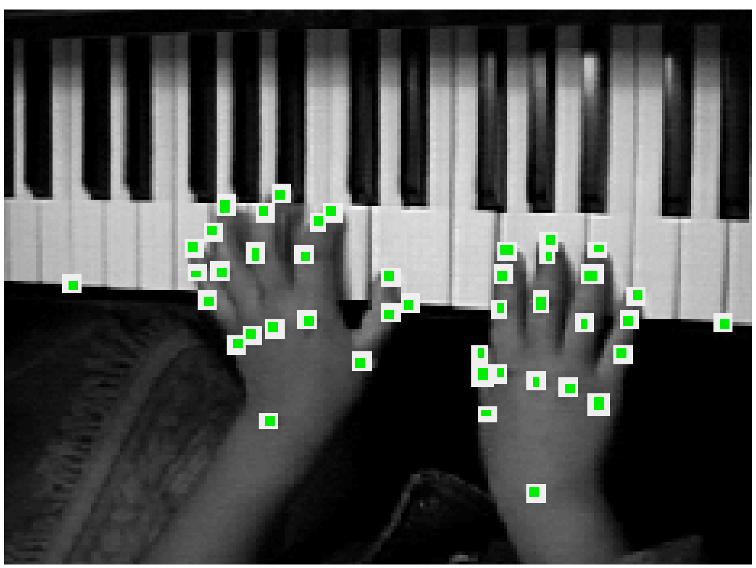
style

scaling

generalization

Resolution

positioning of camera



Marker Placement

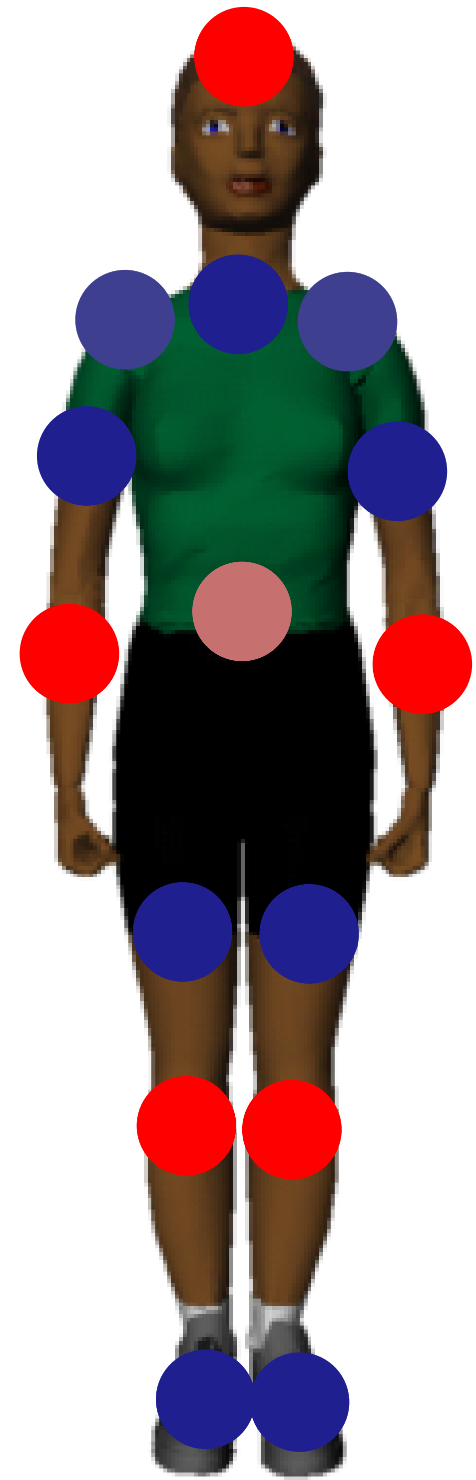
location should move rigidly with joint

stay away from bulging muscles, loose skin

shoulders: skeletal motion not closely tied to motion on skin

Calibration

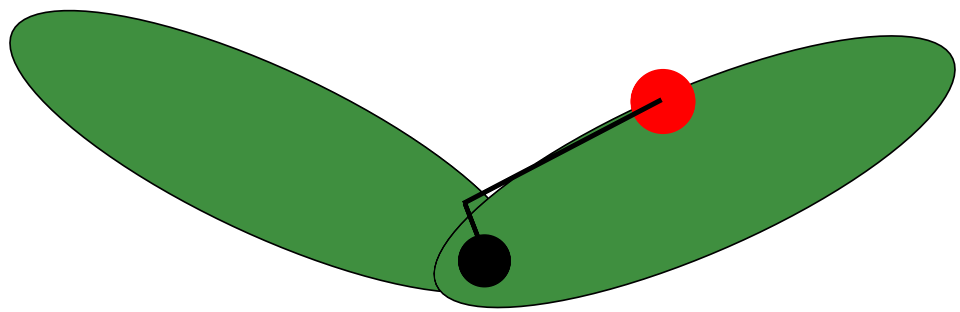
zero position
fine calibration by hand



Finding Joint Locations

move markers to joint centers

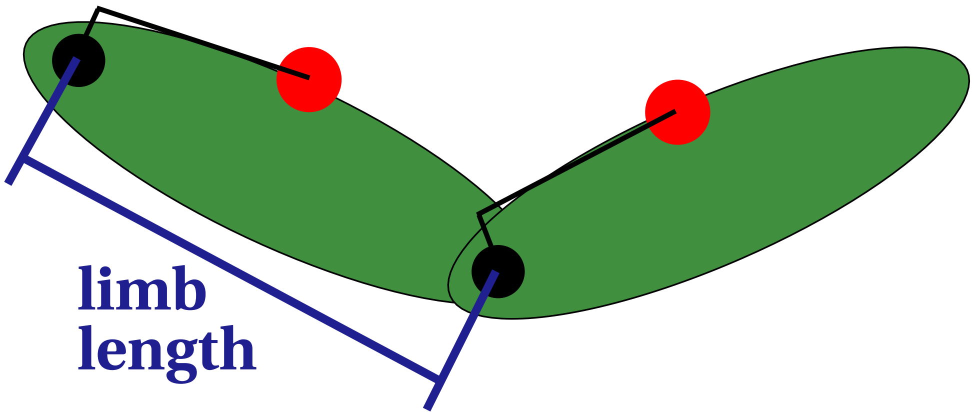
assume rigid links, rotary joints



shoulder?

Extract Best Limb Lengths

use estimator to compute limb length



minimize or reject outliers

IK for Joint Angles

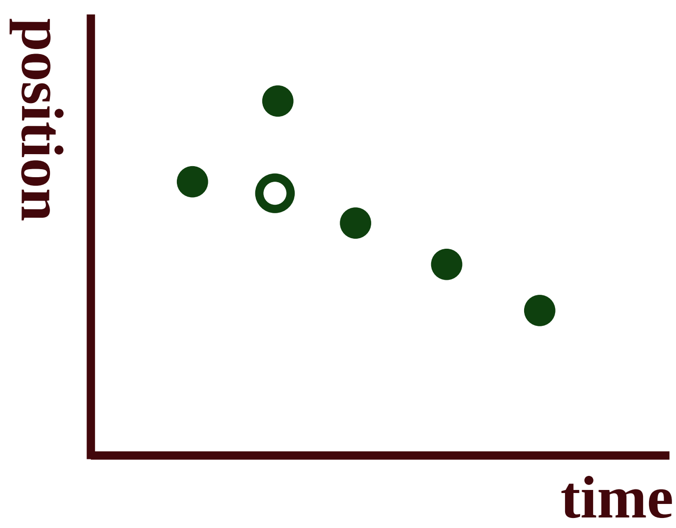
- non–linear optimization
- joint angles should be smooth
  - to allow resampling
- minimize deviation between
  - recorded data and model

$$F(\theta) = \text{sum}\ (w_p(P-P')^2 + w_o(O-O')^2 + w_c c^2)$$

Accuracy

marker movement
sensor noise
skew in measurement time
data recording rate

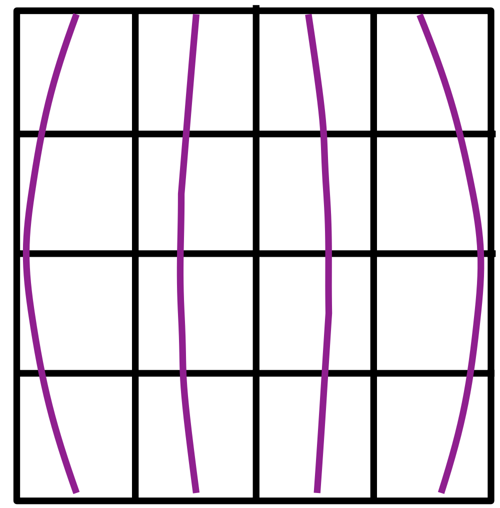
filtering (requires high data rate)



Camera Calibration

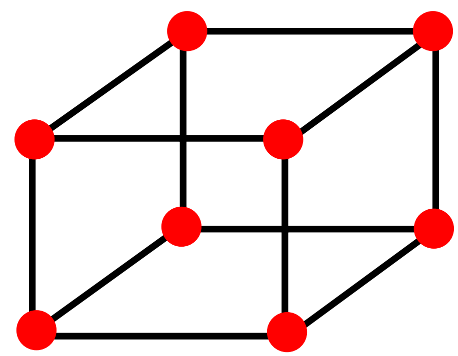
internal camera parameters

optical distortion of lens



external parameters

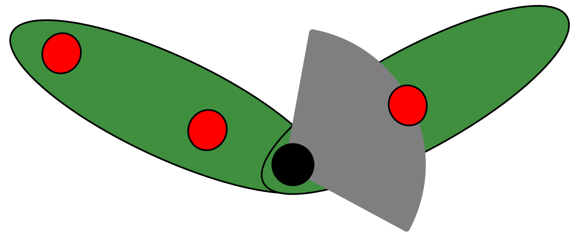
position and orientation



correlation between multiple cameras

Model–based Techniques

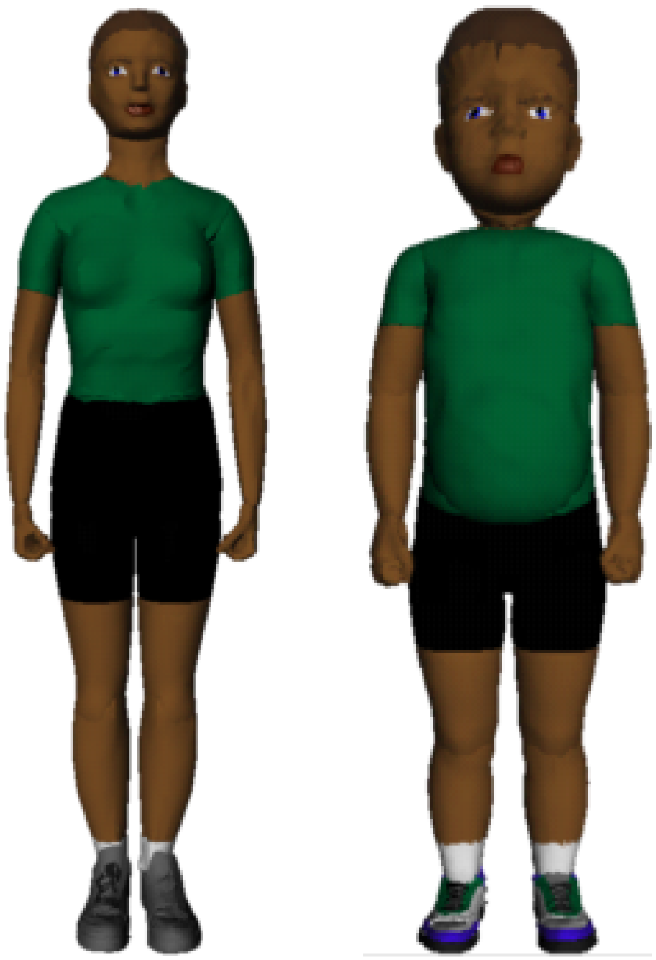
restricted search space for markers

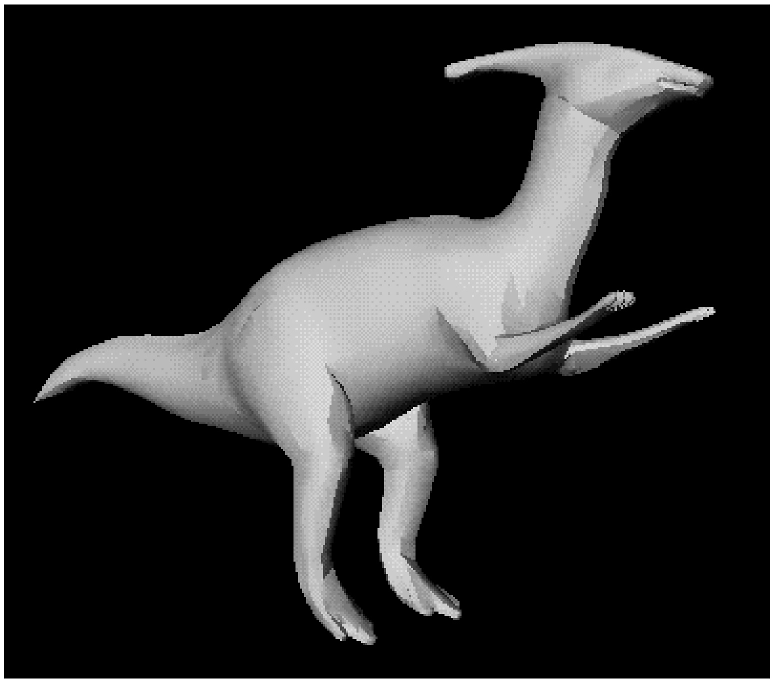


dynamics (velocity integration)
model of behavior
model of bodies for occlusion

Animation Issues: scaling

- contact
- movement style
- inverse kinematics

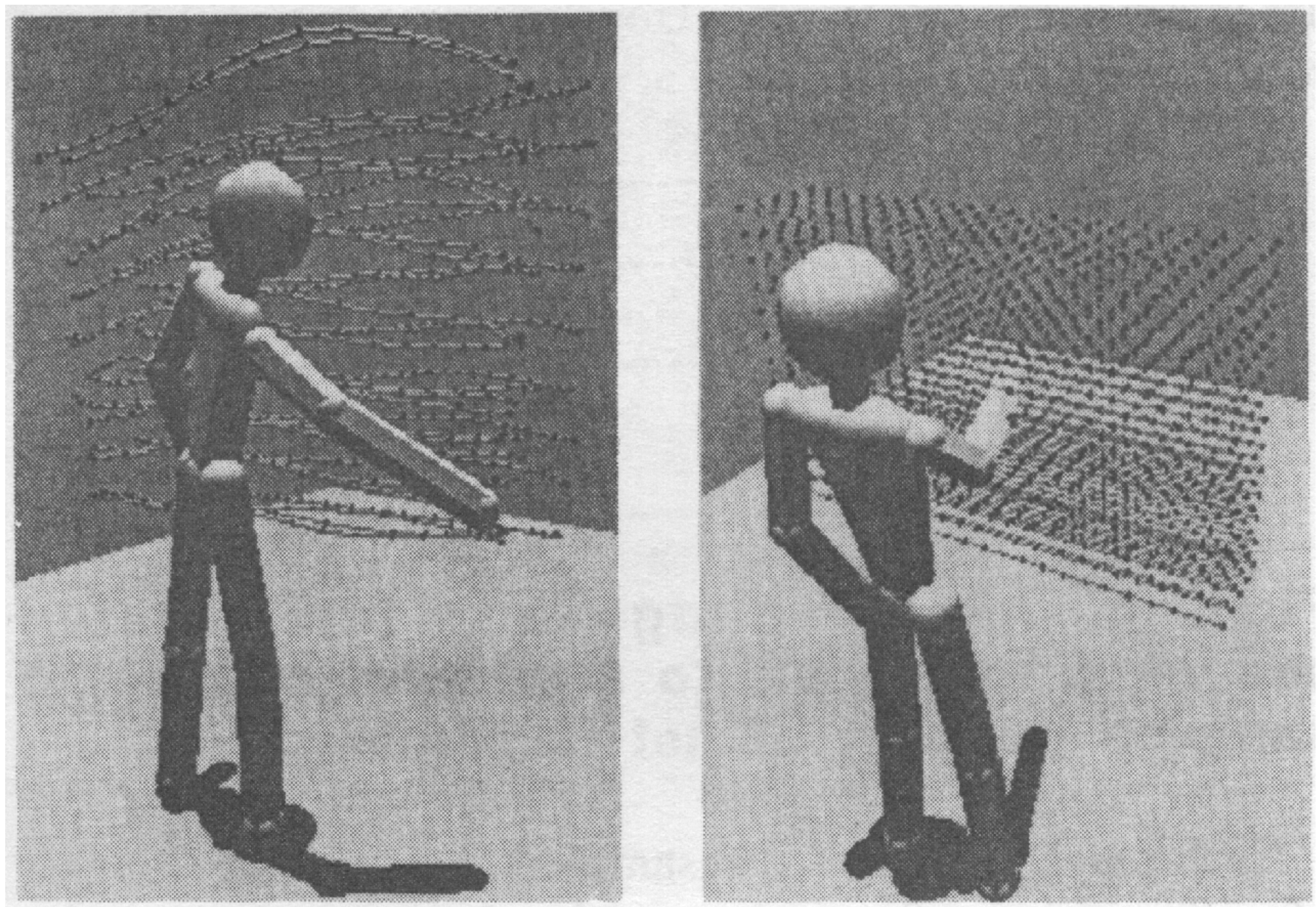




Animation Issues: generalization

Interpolation Synthesis for Articulated Figure Motion

Wiley and Hahn
Vrais '96



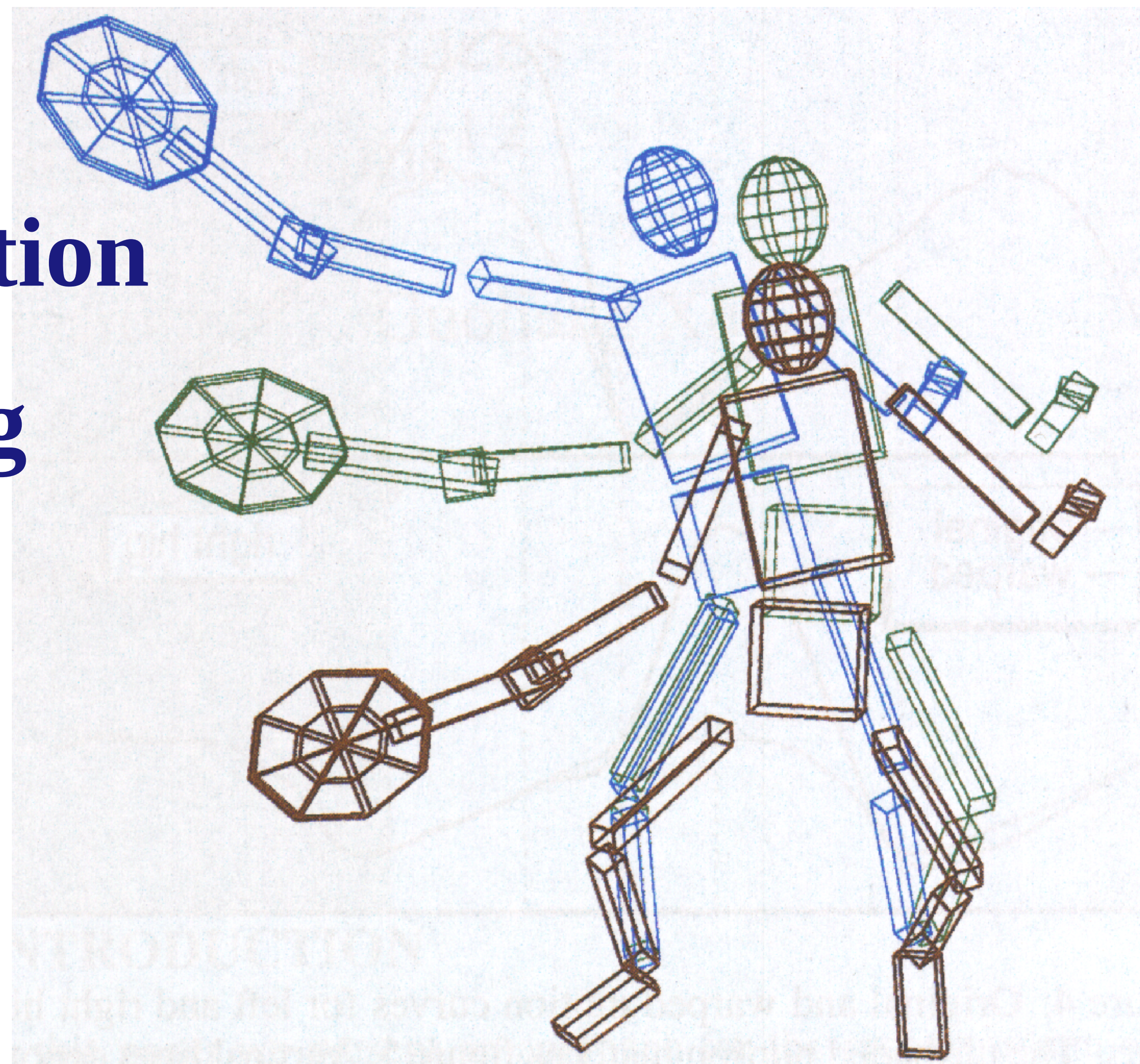
Initial Data　　Resampled Data

Animation Issues: generalization

Motion Warping
Witkin and Popovic, Siggraph ’95

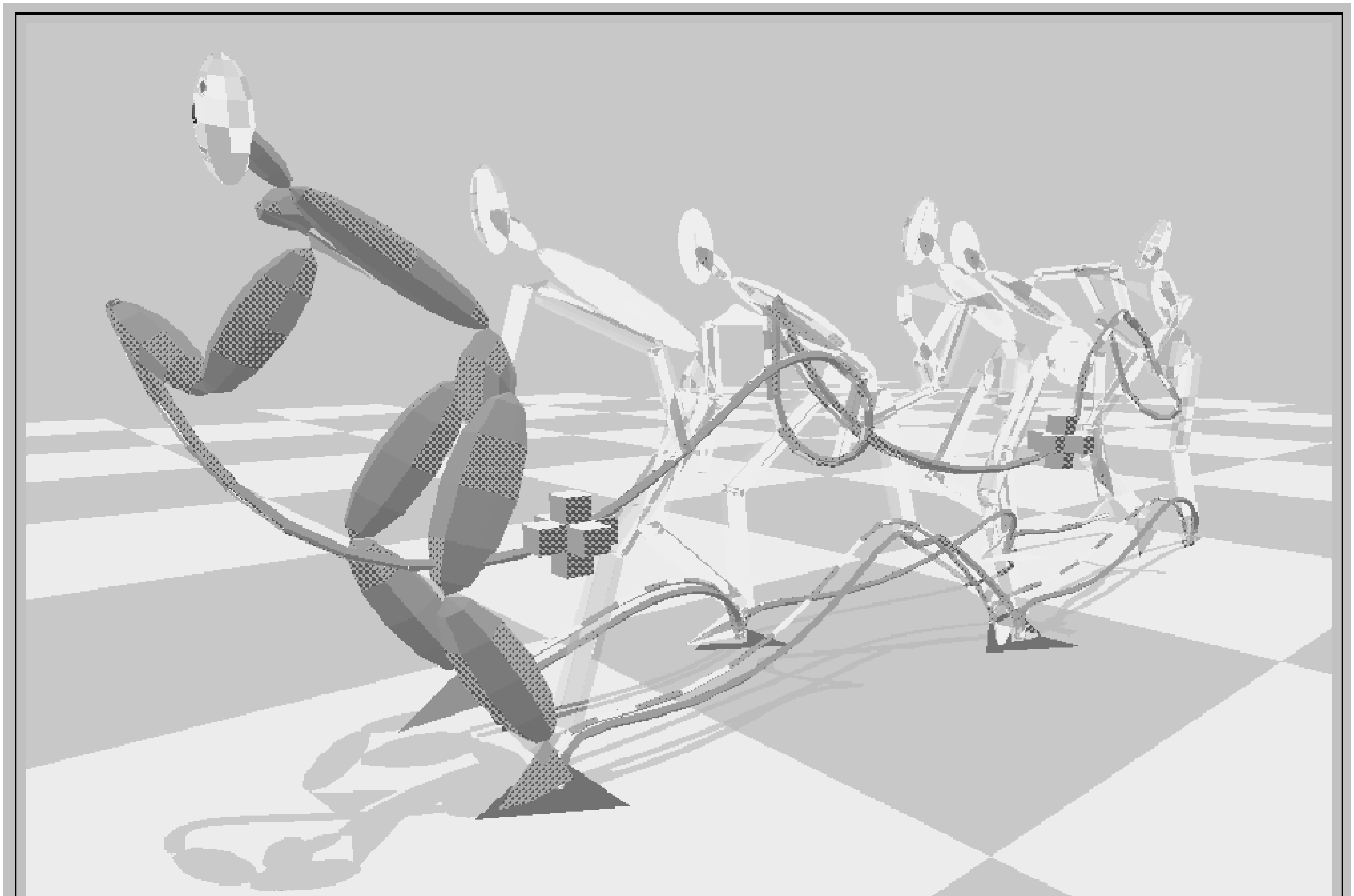
keyframes as constraints in a smooth deformation

keyframe placing the ball on the racket at impact



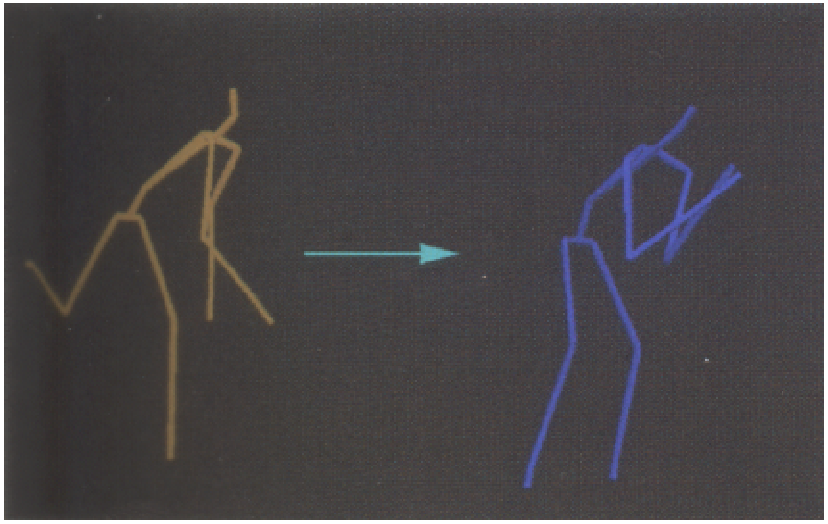
Animation Issues: generalization

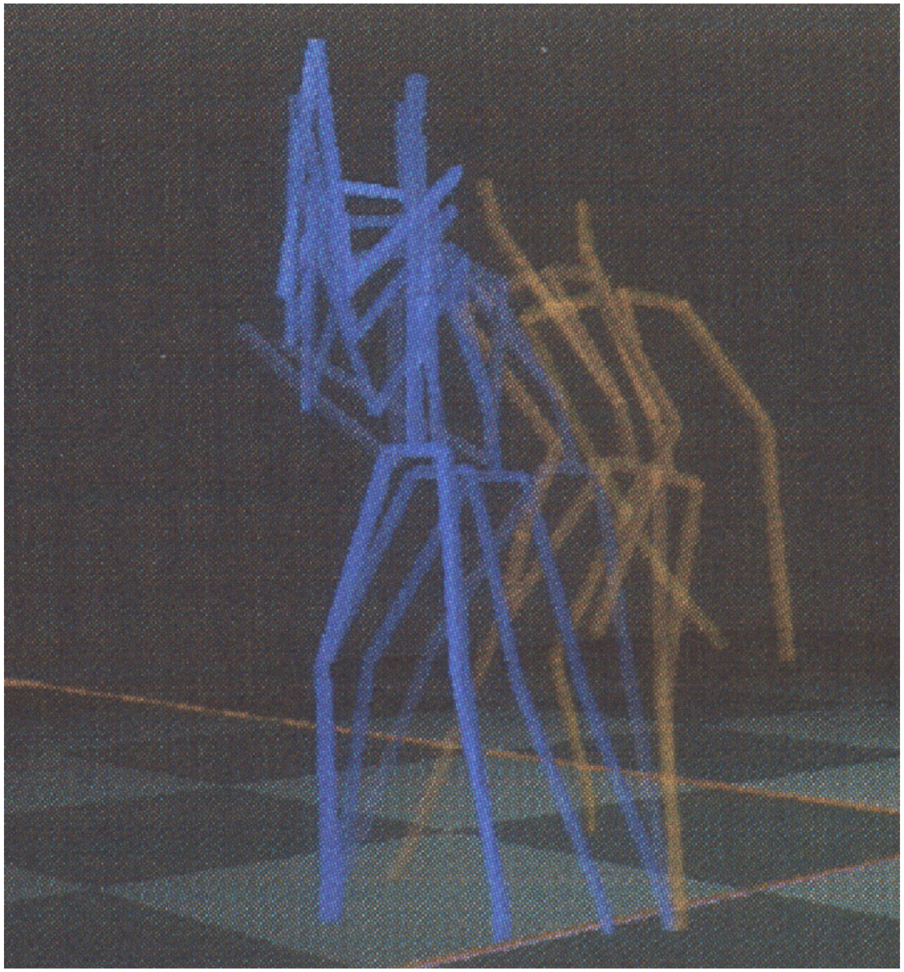
Motion Editing with Spacetime Constraints
Gleicher
1997 Symposium on Interactive 3D Graphics



Animation Issues: blending

Efficient Generation of Motion Transitions using Spacetime Constraints
Rose, Guenter, Bodenheimer, Cohen
Siggraph '96





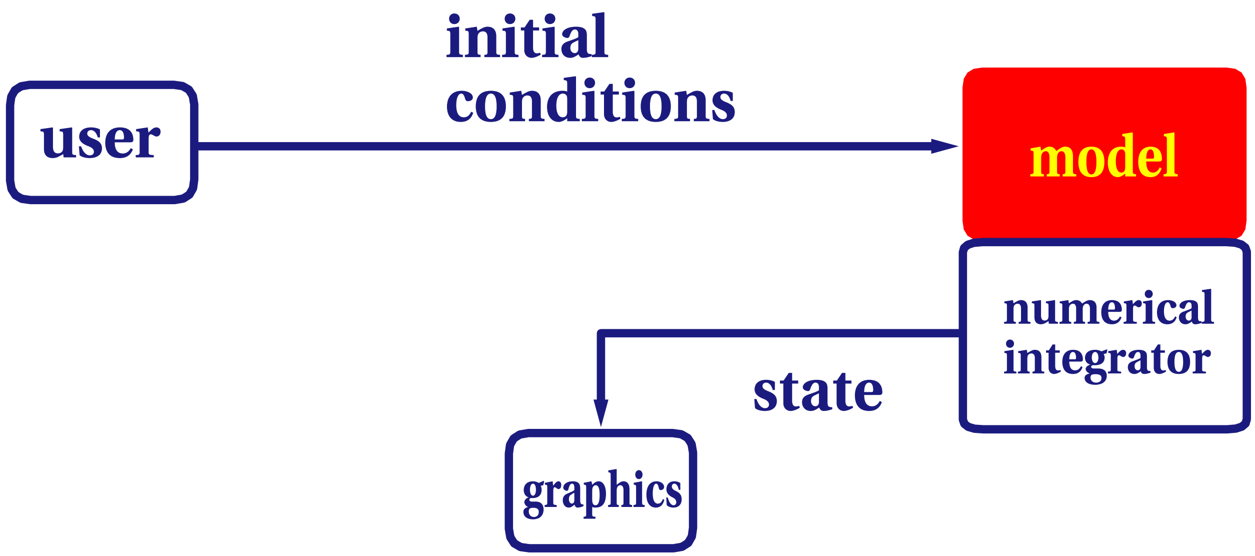
Simulation

modeling the real world with (simple) physics

- realism
- a set of rules
- better interactivity

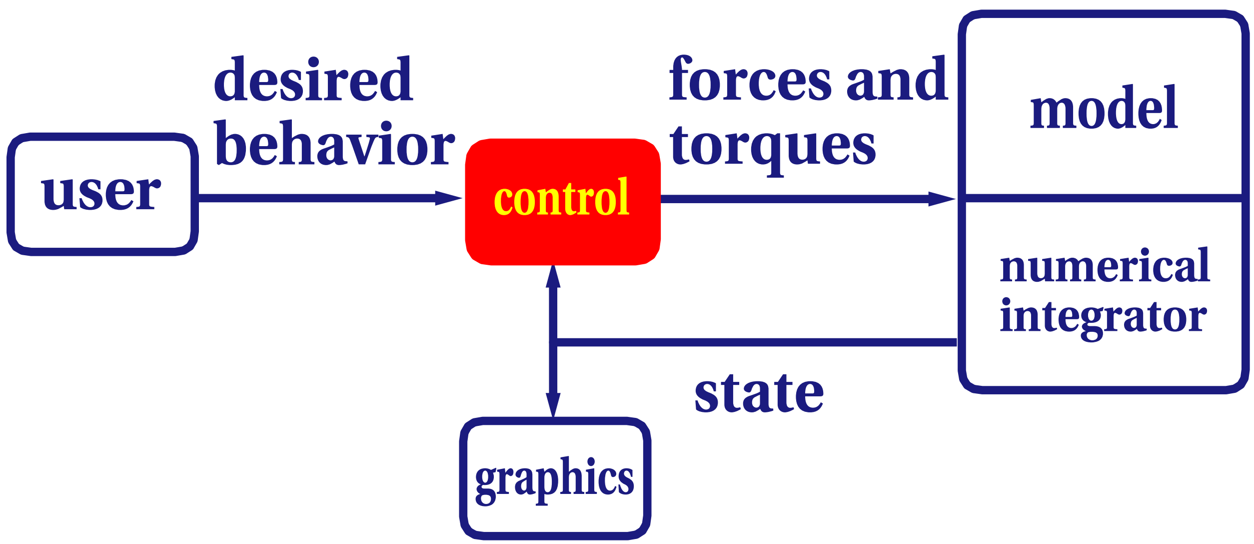
Objects or Characters?

Passive––no muscles or motors



particle systems
leaves
water spray
clothing

Active––internal source of energy



running human
trotting dog
swimming fish

Equations of Motion:

- water
- explosions
- rigid body models

Control Systems:

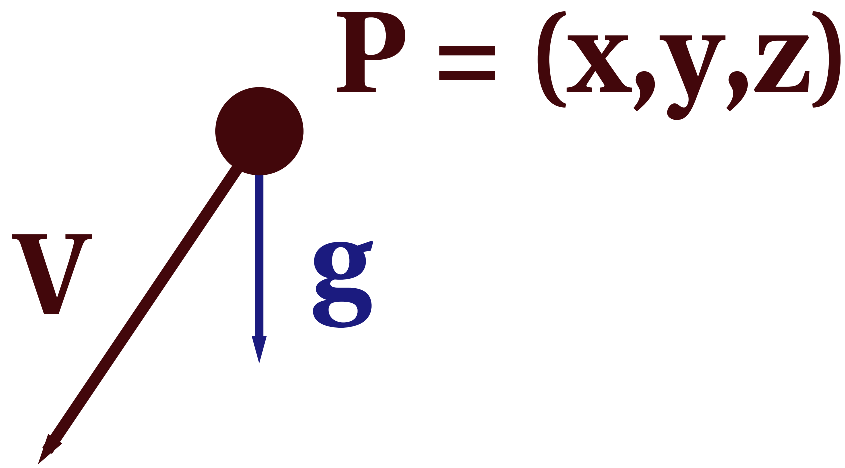
- wide variety of behaviors
- transitions between behaviors
- controllable by AI or UI
- robust

Equations of Motion:

$$\mathbf{A} = \mathbf{g}$$

$$\mathbf{V'} = \mathbf{V} + \mathbf{A}\Delta t$$

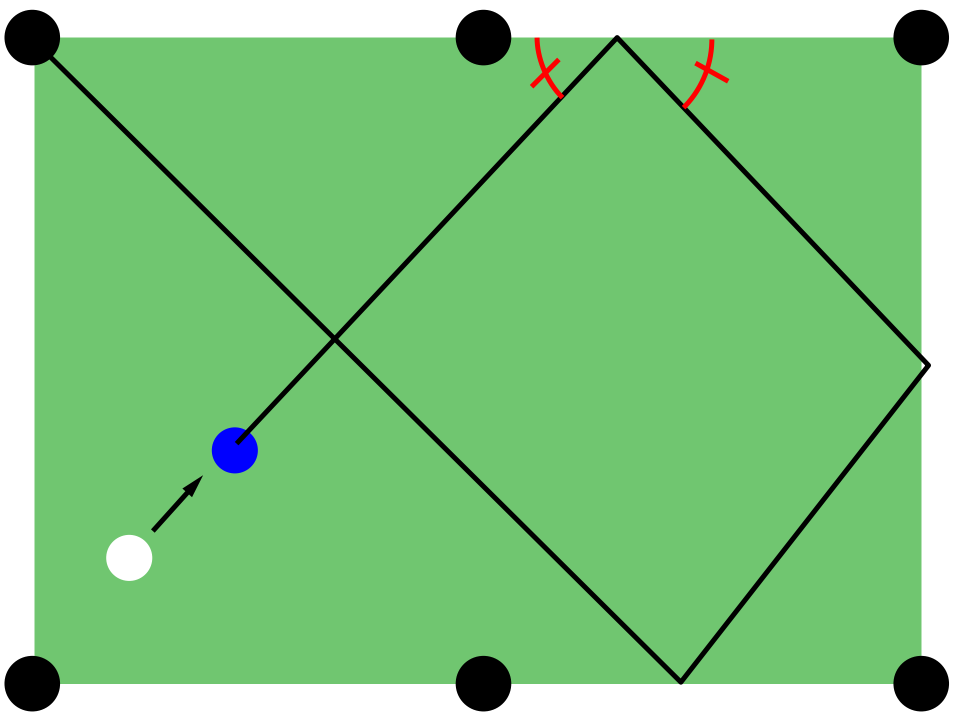
$$\mathbf{P'} = \mathbf{P} + \frac{\mathbf{V}+\mathbf{V'}}{2}\Delta t$$



Integrating in a 2d world

object.x += 2
object.xd = 2 pixels/timestep = 60p/s
timestep = 1/30fps

Pool Game



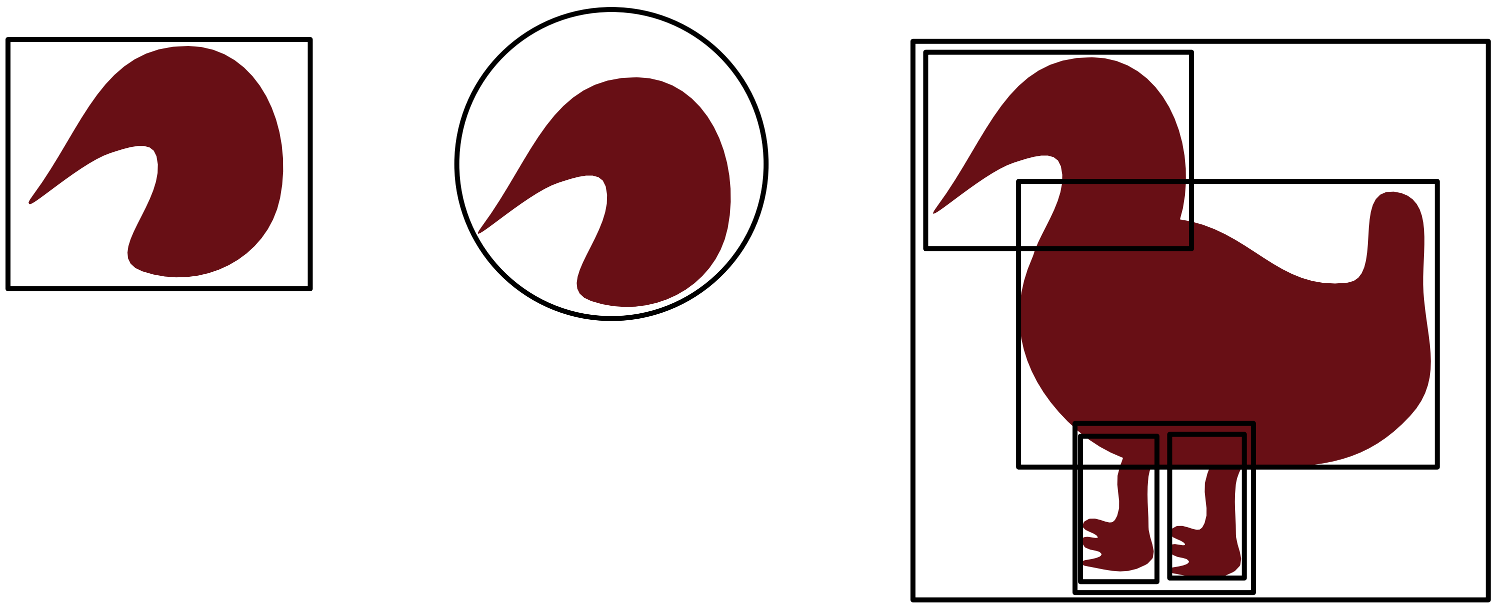
vertical wall:
xd = –xd
horizontal wall:
yd = –yd

Collision Detection

- essential for many games
  - shooting
  - kicking
  - car crashes
- expensive -- n^2 tests

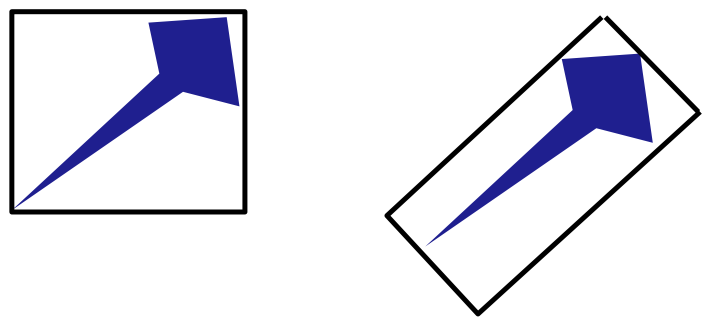
Efficiency Hacks/Cheats

- fewer tests--exploit spatial coherence
  - use bounding boxes/spheres
  - hierarchies of bounding boxes

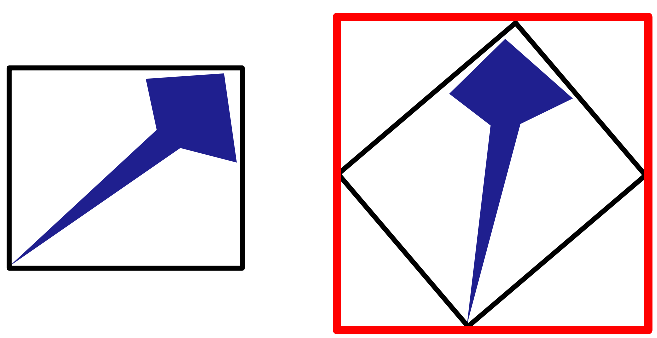


Bounding Boxes

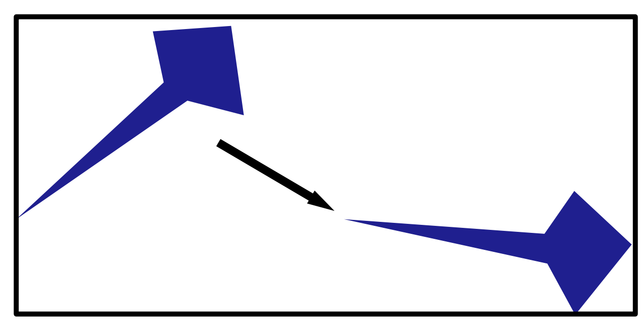
axis-aligned vs object-aligned



axis-aligned change as object moves
approximate by rotating bbox



swept volume

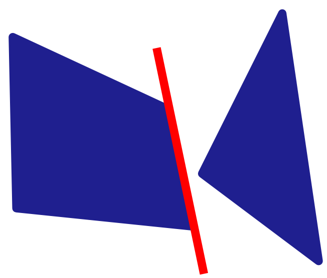


Collision Detection

convex objects

look for separating plane

test all faces

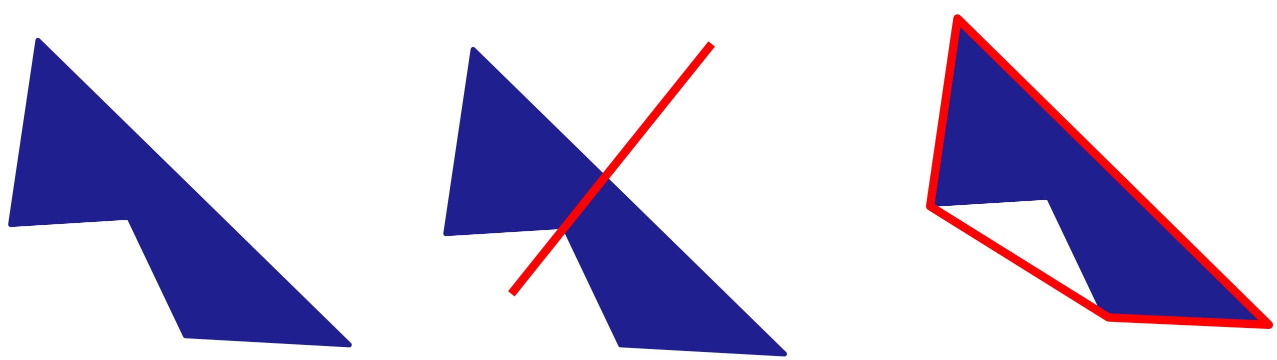


test all edge from obj 1/vertex from obj2 pairs

save separating plane for next iteration

Collision Detection

- concave objects
  - break apart
  - convex hull
    - automatic or artist–created



Efficiency Hacks/Cheats

cheaper tests --exploit temporal coherence

Efficiency Hacks/Cheats

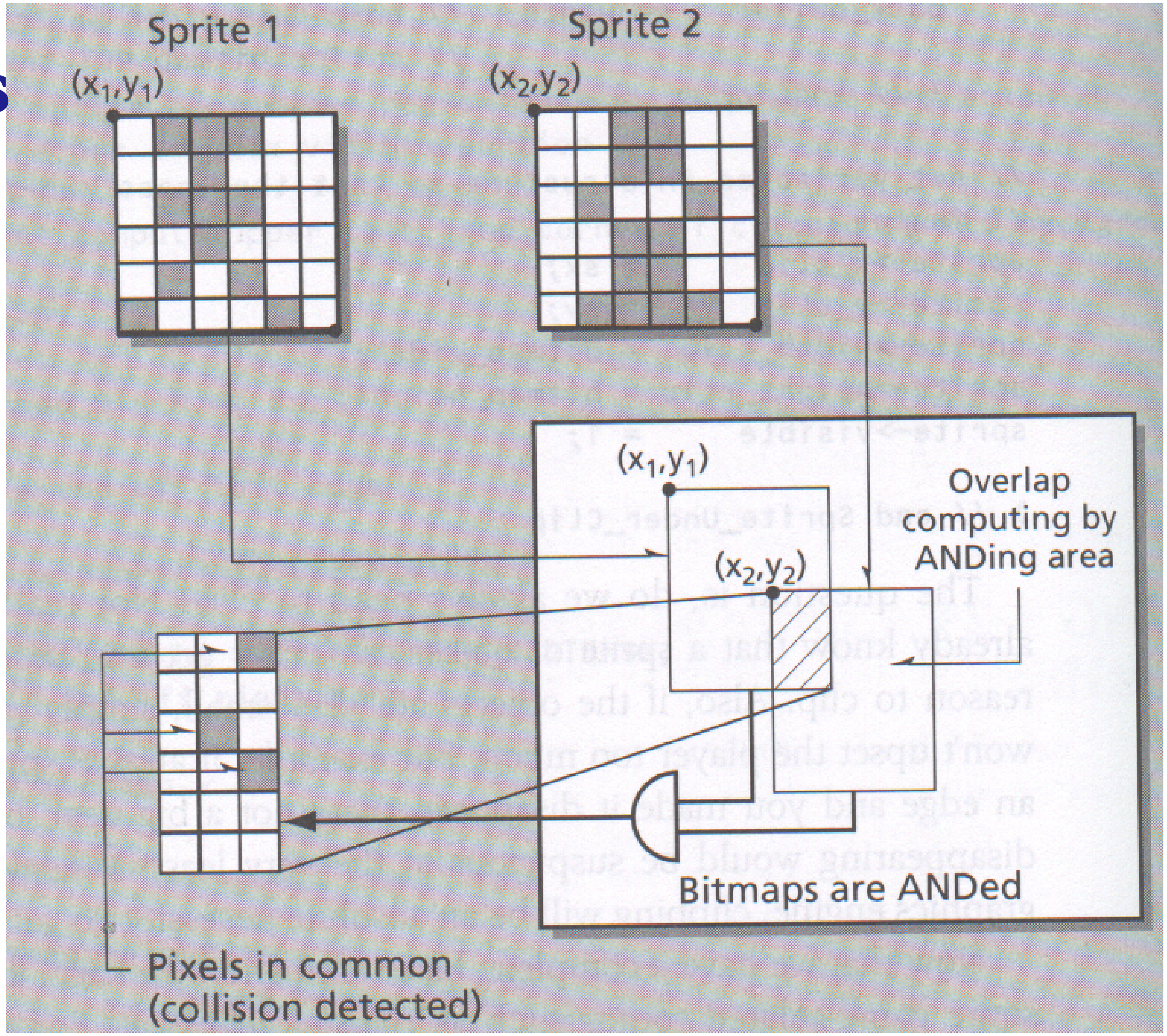
$d = \text{sqrt}\left(\left(x_1 - x_2\right)^2 - \left(y_1 - y_2\right)^2\right)$

cheaper distance calculation:

- compare against d^2
- approximate calculation:
  - $d' = \text{abs}(x_1 - x_2) + \text{abs}(y_1 - y_2)$
    $- \min(\text{abs}(x_1 - x_2), \text{abs}(y_1 - y_2))/2$
  - Manhattan distance – shortest side
    - $x=3, y=4 \Rightarrow d = 5$
    - $d' = 3 + 4 - 1.5 = 5.5$

Collision detection: sprites

AND for each pixel in sprites



Integration of Technologies

- layering
  - add hand/finger motion later
  - facial animation
- use keyframing to modify data
  - fix holes in data
- use motion capture data to drive
  - simulation

The Jacobian

$f(\theta) = x$

x is of dimension n (generally 6)

θ is of dimension m (# of dof)

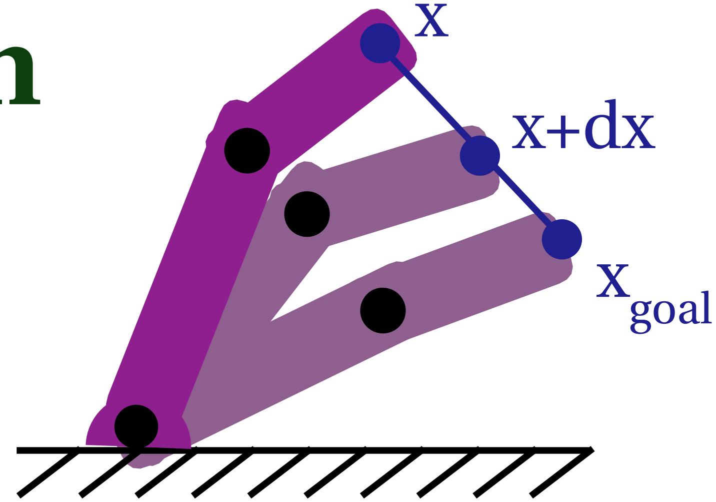
Jacobian is the n x m matrix relating differential changes of θ ($d\theta$) to differential changes of x (dx)

$J(\theta)\, d\theta = dx$ where the ijth element of J is

$$J_{ij} = \frac{\delta f_i}{\delta x_j}$$

Jacobian maps velocities in joint angle space to velocities in cartesian space

IK and the Jacobian



$$\theta = f^{-1}(x)$$
$$dx = J\, d\theta$$
$$d\theta = J^{-1}\, dx$$

Inverting the Jacobian

J is n x m–– not square in general
compute pseudo–inverse

Singularities cause the rank of the Jacobian to change

Damped Least Squares:
find solution that minimizes

$$||J - dx||^2 + \lambda^2 ||d\theta||^2$$