Lecture 30 of 41

Animation 3 of 3: Inverse Kinematics Control & Ragdoll Physics

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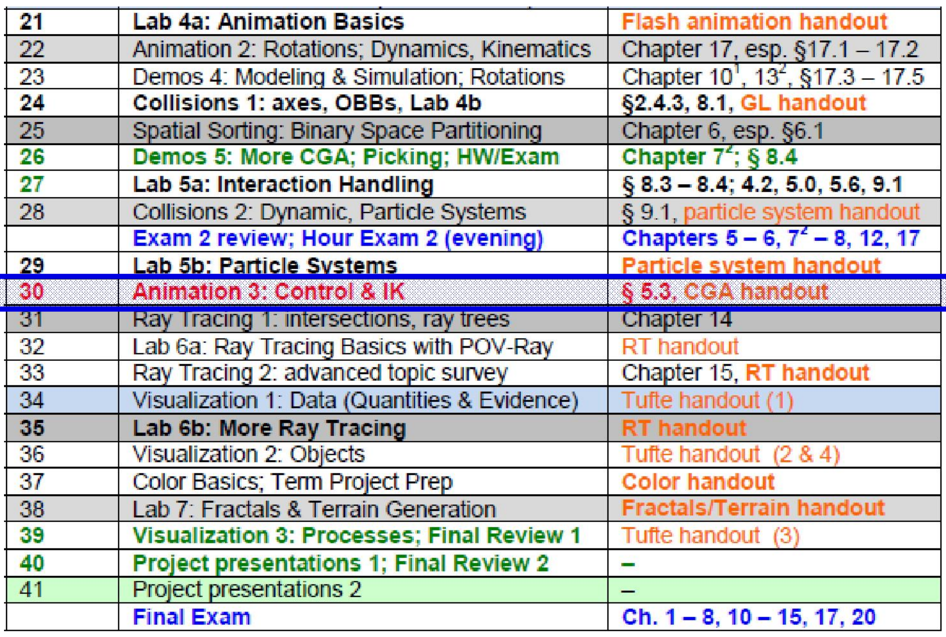
KSOL course pages: **http://bit.ly/hGvXlH** / **http://bit.ly/eVizrE**
Public mirror web site: **http://www.kddresearch.org/Courses/CIS636**
Instructor home page: **http://www.cis.ksu.edu/~bhsu**

Readings:
Last class: **Particle System Handout**
Today: §5.3, Eberly *2*^{e} – see **http://bit.ly/ieUq45**; **CGA Handout**
Next class: Chapter 14, Eberly *2*^{e}
Reference: Wikipedia, *Inverse Kinematics*, **http://bit.ly/hr8r2u**
Reference: Wikipedia, *Ragdoll Physics*, **http://bit.ly/3oggUZ**

Lecture Outline

- Reading for Last Class: Particle System Handout
- Reading for Today: §5.3, Eberly *2*^{e}; CGA Handout
- Reading for Next Class: Chapter 14, Eberly *2*^{e}
- Last Time: Lab on Particle Systems; Dissection of Working Program
- Today: Animation Part 3 of 3 – Inverse Kinematics
  - Autonomous agents (robots, swarms) *vs.* hand-animated movement
  - <u>F</u>orward <u>k</u>inematics and control
  - <u>I</u>nverse <u>k</u>inematics for autonomous movement in robotics
  - Jacobians and iterative minimization models
  - Rag doll physics
- End of Material on: Particle Systems, Collisions, CGA
- Also Conclusion of <u>P</u>hysically-<u>B</u>ased <u>M</u>odeling (PBM)
- Next Class: Ray Tracing, Part 1 of 2
  - Vectors: light/shadow (L), reflected (R), transmitted/refracted (T)
  - Basic recursive ray tracing: ray trees

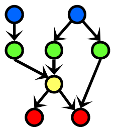
Where We Are



21	**Lab 4a: Animation Basics**	**Flash animation handout**
22	Animation 2: Rotations; Dynamics, Kinematics	Chapter 17, esp. §17.1 – 17.2
23	Demos 4: Modeling & Simulation; Rotations	Chapter 10^1, 13^2, §17.3 – 17.5
24	**Collisions 1: axes, OBBs, Lab 4b**	**§2.4.3, 8.1, GL handout**
25	Spatial Sorting: Binary Space Partitioning	Chapter 6, esp. §6.1
26	**Demos 5: More CGA; Picking; HW/Exam**	**Chapter 7^2; § 8.4**
27	**Lab 5a: Interaction Handling**	**§ 8.3 – 8.4; 4.2, 5.0, 5.6, 9.1**
28	Collisions 2: Dynamic, Particle Systems	§ 9.1, particle system handout
	Exam 2 review; Hour Exam 2 (evening)	**Chapters 5 – 6, 7^2 – 8, 12, 17**
29	**Lab 5b: Particle Systems**	**Particle system handout**
30	**Animation 3: Control & IK**	**§ 5.3, CGA handout**
31	Ray Tracing 1: intersections, ray trees	Chapter 14
32	Lab 6a: Ray Tracing Basics with POV-Ray	RT handout
33	Ray Tracing 2: advanced topic survey	Chapter 15, **RT handout**
34	Visualization 1: Data (Quantities & Evidence)	Tufte handout (1)
35	**Lab 6b: More Ray Tracing**	**RT handout**
36	Visualization 2: Objects	Tufte handout (2 & 4)
37	Color Basics; Term Project Prep	**Color handout**
38	Lab 7: Fractals & Terrain Generation	**Fractals/Terrain handout**
39	**Visualization 3: Processes; Final Review 1**	Tufte handout (3)
40	**Project presentations 1; Final Review 2**	**–**
41	Project presentations 2	–
	Final Exam	**Ch. 1 – 8, 10 – 15, 17, 20**

Lightly-shaded entries denote the due date of a written problem set; heavily-shaded entries, that of a machine problem (programming assignment); blue-shaded entries, that of a paper review; and the green-shaded entry, that of the term project.

Green, **blue** and **red** letters denote **exam review**, **exam**, and **exam solution review** dates.



Acknowledgements: Inverse Kinematics

David C. Brogan

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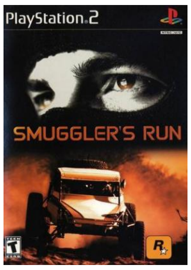
http://www.cs.virginia.edu/~dbrogan/

Susquehanna International Group (SIG)

http://www.sig.com



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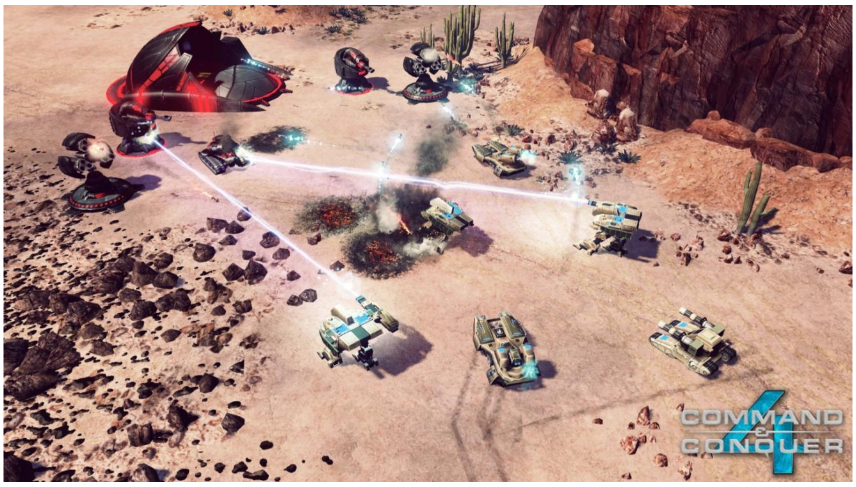
Review [1]: Uses of Particle Systems

- Explosions
  - Large
  - Fireworks
- Fire
- Vapor
  - Clouds
  - Dust
  - Fog
  - Smoke
  - Contrails
- Water
  - Waterfalls
  - Streams
- Plants



Command & Conquer 4: Tiberian Twilight
© 2010 Electronic Arts, Inc.
Wikipedia: http://bit.ly/gFGMjO

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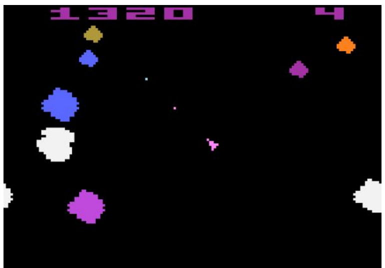
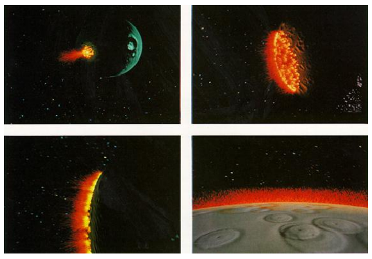
CS 536 Intro to 3-D Game Graphics, Spring 2008 – http://bit.ly/hNhUuE

Review [2]: History of Particle Systems

Spacewar! © 1962 S. Russell *et al.*
Wikipedia: http://bit.ly/eaiWUW


Asteroids © 1979 L. Rains & E. Logg
Wikipedia: http://bit.ly/hwfEQk


Star Trek II © 1983 Paramount
Wikipedia: http://bit.ly/eXwrhb

- *Spacewar!* (1962) Used Pixel Clouds as Explosions
- *Asteroids* (1979) First "Physically-Based" PS/Collision Model in Games
- *Star Trek II* (1983) Particle Fountain: http://youtu.be/Qe9qSLYK5q4
- *Hey, Hey, 16K* © 2000 M. J. Hibbett, Video © 2004 R. Manuel
  http://youtu.be/Ts96J7HhO28

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Review [3]: Definition & Physically-Based Model

- A particle system is a collection of a number of individual elements or *particles.*
- *Particle systems control a set of particles that act autonomously but share some common attributes.*

- Particle is a point in 3D space.
- Forces (e.g. gravity or wind) accelerate a particle.
- Acceleration changes velocity.
- Velocity changes position

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Review [4]: More Attributes of Particles

- Position
- Velocity
- Life Span
- Size
- Weight
- Representation
- Color
- Owner

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Review [5]: Four Ways to Represent Particles

- Points
- Lines
- Texture-mapped quads
- Point Sprites

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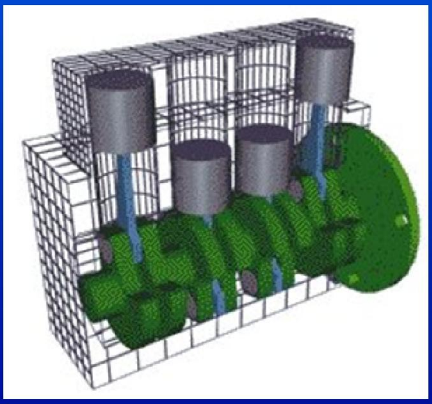
Kinematics

- The study of object movements irrespective of their speed or style of movement



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Degrees of Freedom (DOFs) [1]: Translational & Rotational

- The variables that affect an object's orientation
- How many degrees of freedom when flying?

- So the kinematics of this airplane permit movement anywhere in three dimensions

- Six
  - x, y, and z positions
  - roll, pitch, and yaw

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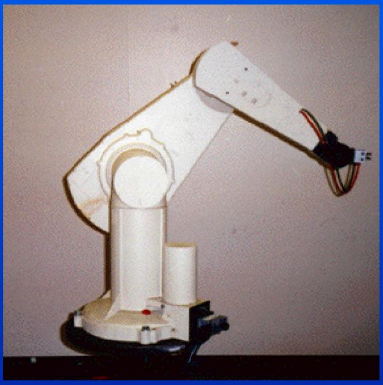
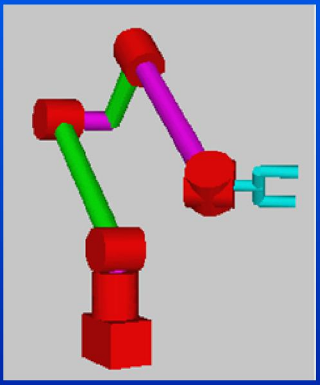
Degrees of Freedom (DOFs) [2]: Robot Arm

- How about this robot arm?

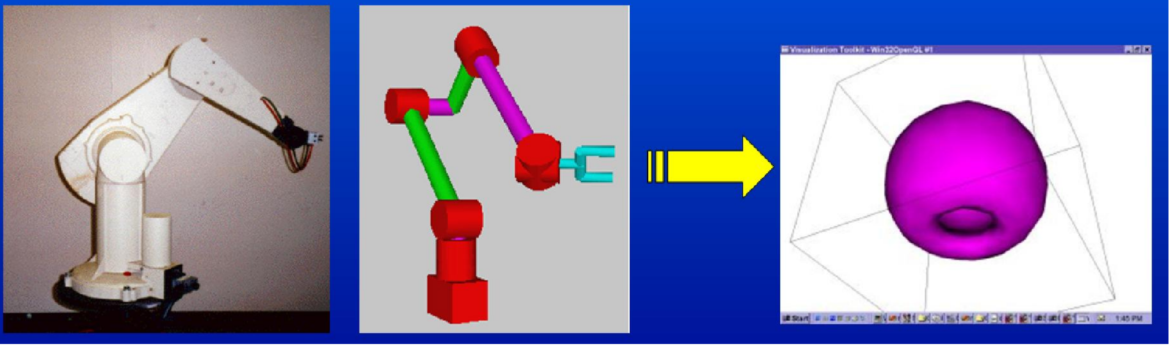




- Six again
  - 2-base, 1-shoulder, 1-elbow, 2-wrist

Configuration Space

- The set of all possible positions (defined by kinematics) an object can attain



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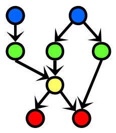

Work Space vs. Configuration Space

- Work space
  - The space in which the object exists
  - Dimensionality
    - R^3 for most things, R^2 for planar arms
- Configuration space
  - The space that defines the possible object configurations
  - Degrees of Freedom
    - The number of parameters that necessary and sufficient to define position in configuration

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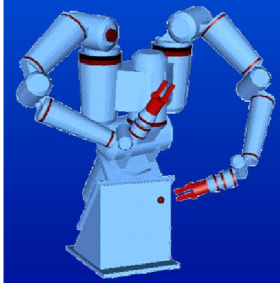
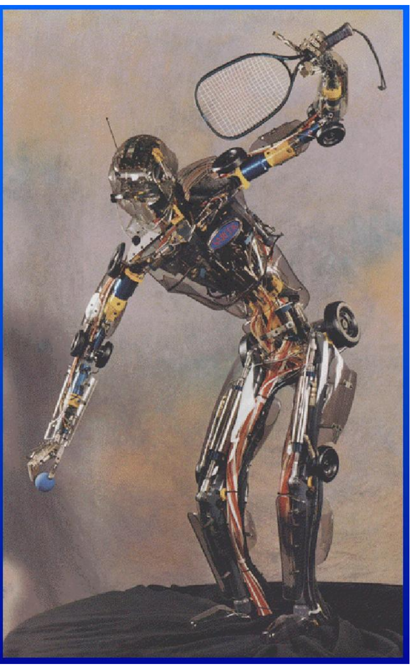
More Examples

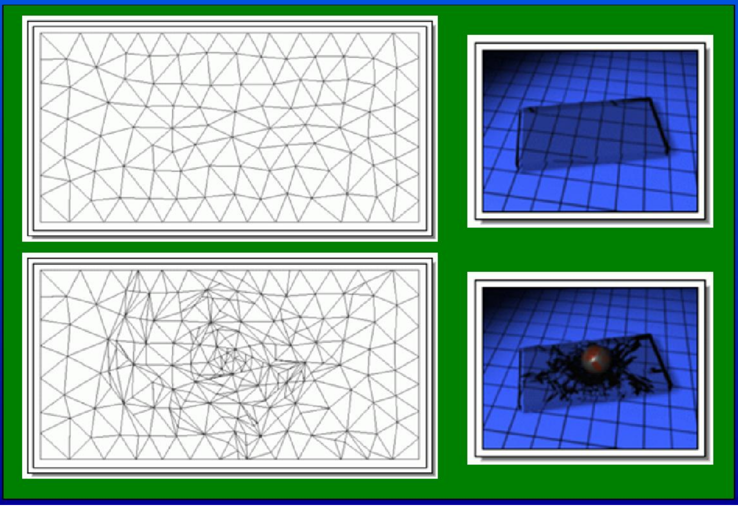
- A point on a plane
- A point in space
- A point moving on a line in space





Controlled DOFs

- DOFs that you can actually control (position explicitly)



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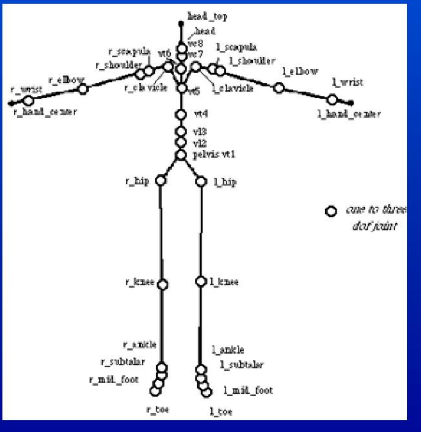
Hierarchical Kinetic Modeling

- A family of parent-child spatial relationships are functionally defined
  - Moon/Earth/Sun movements
  - Articulations of a humanoid
- Limb connectivity is built into model (joints) and animation is easier



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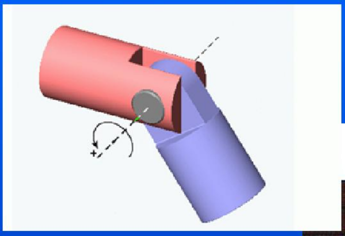
Robot Parts & Terms

- Links
- End effector
- Frame
- Revolute Joint
- Prismatic Joint



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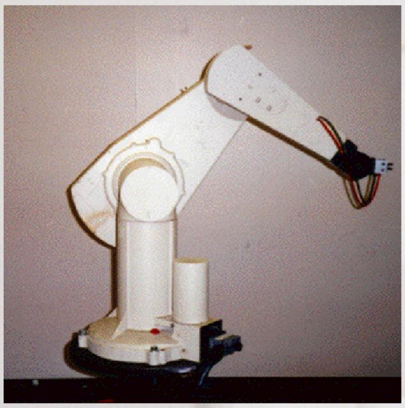
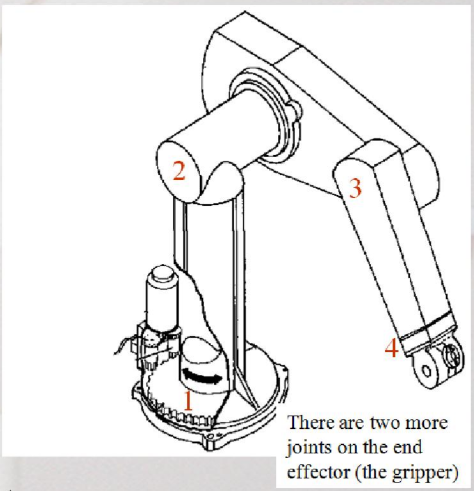
Example: Puma 560 Robot





The PUMA 560 has SIX revolute joints

A revolute joint has ONE degree of freedom (1 DOF) that is defined by its angle

Wikipedia, *Programmable Universal Machine for Assembly (PUMA)*: http://bit.ly/fBMRaM

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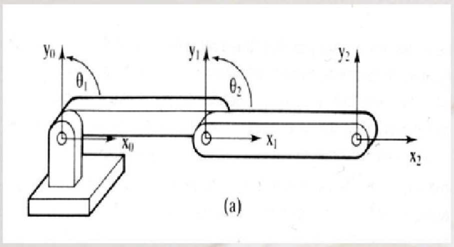
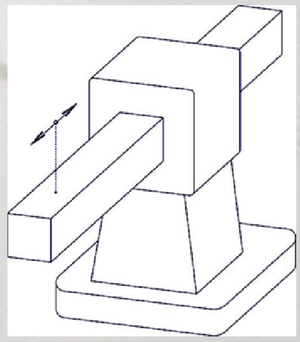
Mirrored at CMU 16-311 Introduction to Robotics, http://generalrobotics.org

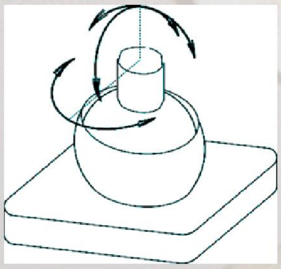
Joint Types: Revolute, Prismatic, Spherical



Revolute Joint
1 DOF (Variable - Y)



Prismatic Joint
1 DOF (linear) (Variables - d)



Spherical Joint
3 DOF (Variables - Y_1, Y_2, Y_3)

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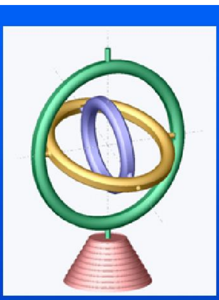
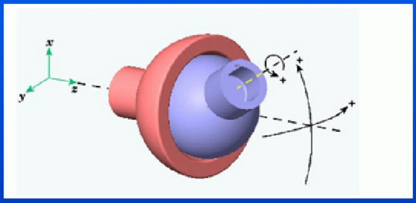
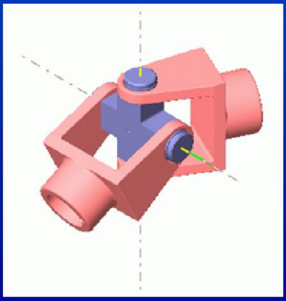
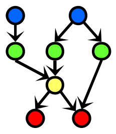
More Complex Joints

- 3 DOF joints
  - Gimbal
  - Spherical (doesn't possess singularity)
- 2 DOF joints
  - Universal









Hierarchical Representation

- Model bodies (links) as nodes of a tree
- All body frames are local (relative to parent)
  - Transformations affecting root affect all children
  - Transformations affecting any node affect all its children

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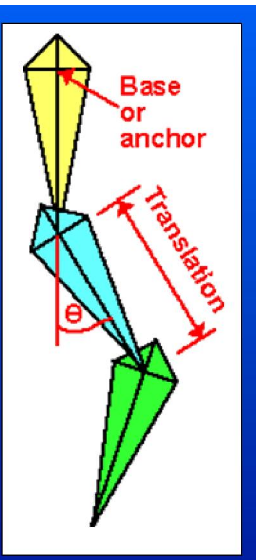
Forward vs. Inverse Kinematics

- Forward Kinematics
  - Compute configuration (pose) given individual DOF values
- Inverse Kinematics
  - Compute individual DOF values that result in specified end effector position

Forward Kinematics [1]: Definition & General Approach

- Traverse kinematic tree and propagate transformations downward
  - Use stack
  - Compose parent transformation with child's
  - Pop stack when leaf is reached
- High DOF models are tedious to control this way



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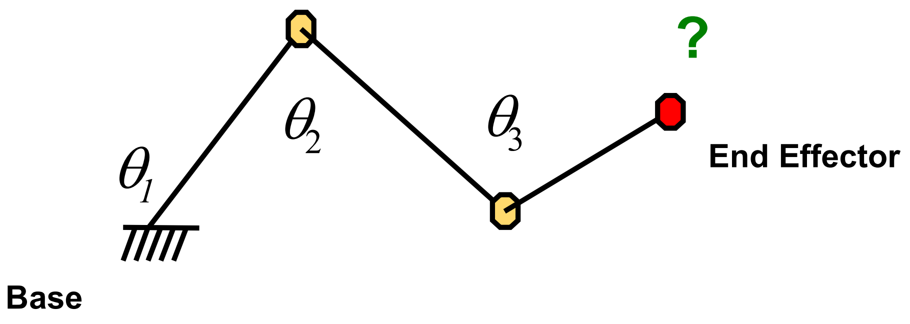
Forward Kinematics [2]: Illustration



$$\vec{\mathbf{x}} = \mathrm{f}(\vec{\boldsymbol{\theta}}) \qquad \mathbf{e} = f\left(\boldsymbol{\Phi}\right)$$

Choi   Rotenberg

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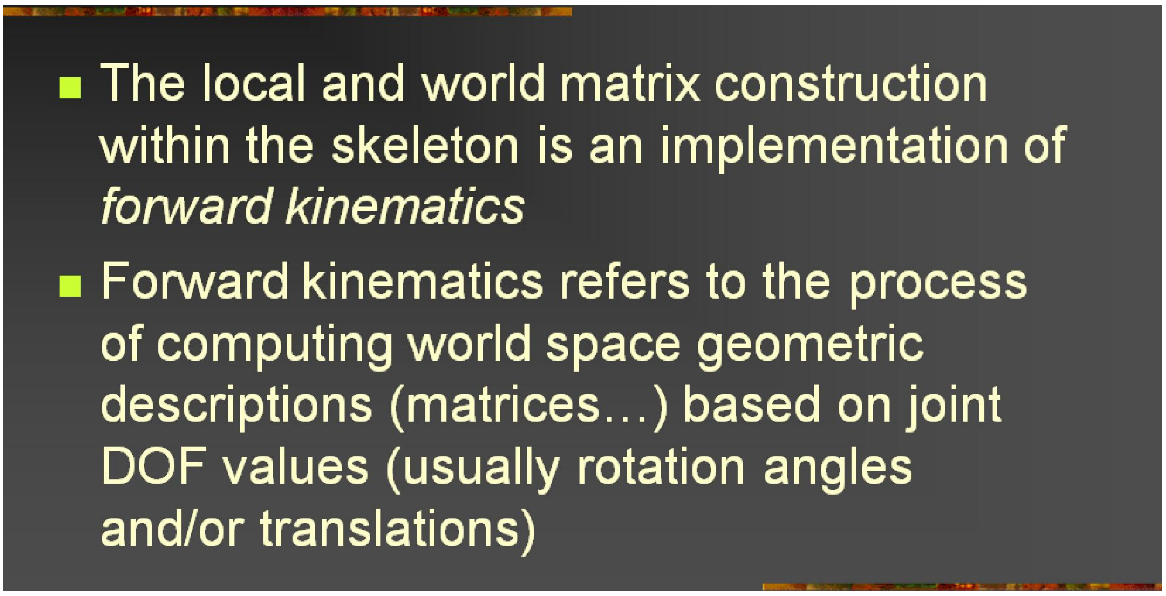
Forward Kinematics [3]: Joint Angles to Bone Coordinates



- The local and world matrix construction within the skeleton is an implementation of *forward kinematics*
- Forward kinematics refers to the process of computing world space geometric descriptions (matrices…) based on joint DOF values (usually rotation angles and/or translations)

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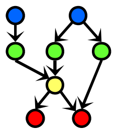
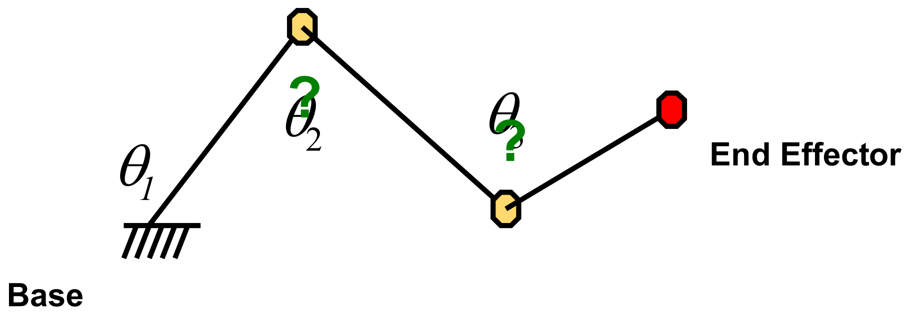


Inverse Kinematics [1]: Definition & General Approach

- Given end effector position, compute required joint angles
- In simple case, analytic solution exists
  - Use trig, geometry, and algebra to solve

Inverse Kinematics [2]: Illustration

For more on characters & IK, see: Advanced Topics in CG Lecture 05



$$\vec{\theta} = f^{-1}(\vec{x}) \qquad \Phi = f^{-1}(\mathbf{e})$$

Choi Rotenberg

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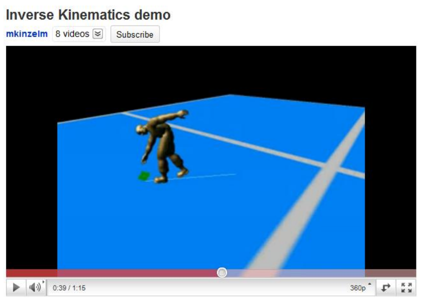
Inverse Kinematics [3]: Demos



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http://youtu.be/I52yZ491kPo

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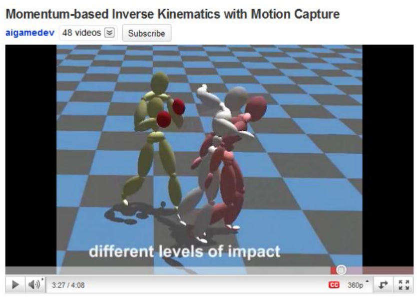
http://youtu.be/6JdLOLazJJ0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different levels of impact
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360p

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http://youtu.be/FJTBMnP6oCM

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Inverse Kinematics [4]: Analytic Solution for 2-Link Case

$$x^2 + y^2 = a_1^2 + a_2^2 - 2a_1a_2\cos(\pi - \theta_2)$$

$$\cos\theta_2 = \frac{x^2 + y^2 - a_1^2 - a_2^2}{2a_1a_2}$$

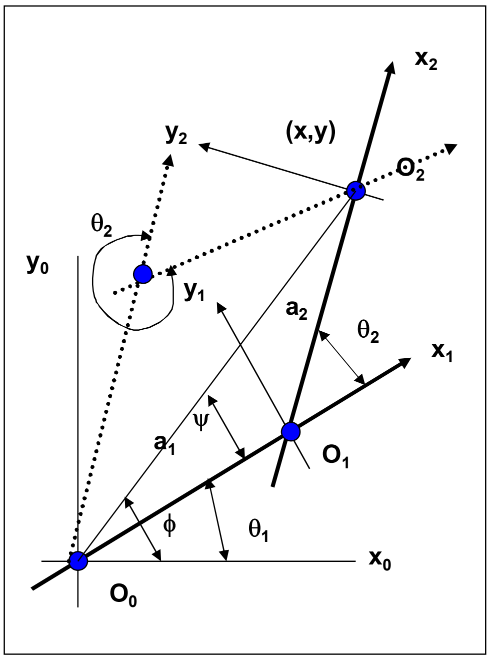
for greater accuracy

$$\tan^2\frac{\theta_2}{2} = \frac{1-\cos\theta}{1+\cos\theta} = \frac{2a_1a_2 - x^2 - y^2 + a_1^2 + a_2^2}{2a_1a_2 + x^2 + y^2 - a_1^2 - a_2^2}$$

$$= \frac{\left(a_1^2 + a_2^2\right)^2 - \left(x^2 + y^2\right)}{\left(x^2 + y^2\right) - \left(a_1^2 - a_2^2\right)^2}$$

$$\theta_2 = \pm 2\tan^{-1}\sqrt{\frac{\left(a_1^2 + a_2^2\right)^2 - \left(x^2 + y^2\right)}{\left(x^2 + y^2\right) - \left(a_1^2 - a_2^2\right)^2}}$$

Two solutions: elbow up & elbow down



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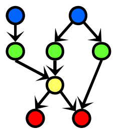

Inverse Kinematics [5]: Iterative IK Solutions

- Frequently analytic solution is infeasible
- Use Jacobian
- Derivative of function output relative to each of its inputs
- If y is function of three inputs and one output

$$y = f(x_1, x_2, x_3)$$

$$\delta y = \frac{\delta f}{\partial x_1} \cdot \delta x_1 + \frac{\delta f}{\partial x_2} \cdot \delta x_2 + \frac{\delta f}{\partial x_3} \cdot \delta x_3$$

- Represent Jacobian J(X) as a 1x3 matrix of partial derivatives

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Jacobian [1]: 6x6 DOF Case

- In another situation, end effector has 6 DOFs and robotic arm has 6 DOFs
- $f(x_1, \ldots, x_6) = (x, y, z, r, p, y)$
- Therefore $J(X)$ = 6x6 matrix

$$\begin{bmatrix} \frac{\partial f_x}{\partial x_1} & \frac{\partial f_y}{\partial x_1} & \frac{\partial f_z}{\partial x_1} & \frac{\partial f_r}{\partial x_1} & \frac{\partial f_p}{\partial x_1} & \frac{\partial f_y}{\partial x_1} \\ \frac{\partial f_x}{\partial x_2} & & & & & \\ \frac{\partial f_x}{\partial x_3} & & & & & \\ \frac{\partial f_x}{\partial x_4} & & & & & \\ \frac{\partial f_x}{\partial x_5} & & & & & \\ \frac{\partial f_x}{\partial x_6} & & & & & \end{bmatrix}$$

Adapted from slides ♥ 2000 – 2005 D. Brogan, University of Virginia
CS 551, Advanced CG & Animation – http://bit.ly/hUXrqd

Computer Science at the University of Virginia

Jacobian [2]: Solution

- Relates velocities in parameter space to velocities of outputs

$$\dot{Y} = J(X) \cdot \dot{X}$$

- If we know $Y_{current}$ and $Y_{desired}$, then we subtract to compute Y_{dot}
- Invert Jacobian and solve for X_{dot}

Adapted from slides ♥ 2000 – 2005 D. Brogan, University of Virginia
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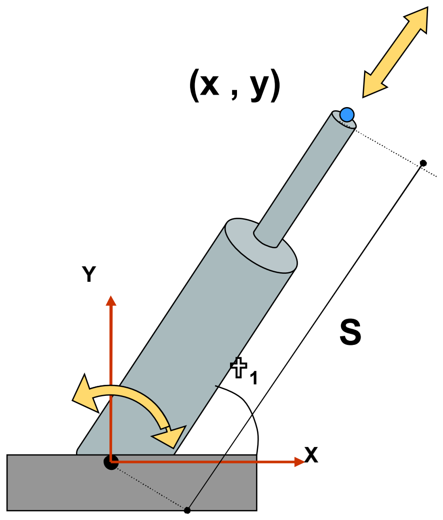
Another IK Problem: Revolute & Prismatic Joints Combined



Finding θ:

$$\theta = \arctan(\frac{y}{x})$$

More Specifically:

$$\theta = \arctan 2(\frac{y}{x})$$

arctan2() specifies that it's in the first quadrant

Finding S:

$$S = \sqrt{(x^2 + y^2)}$$

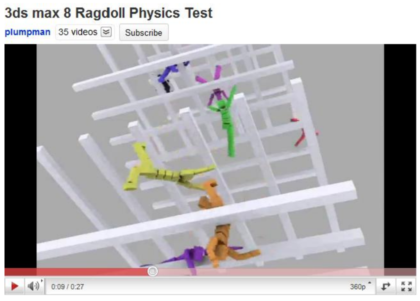
Adapted from slides © 2002 R. Melamud, Stanford University
Mirrored at CMU 16-311 Introduction to Robotics, http://generalrobotics.org

Ragdoll Physics [1]: Definition

- Type of Procedural Animation
  - Automatically generates CGA directives (rotations)
  - Based on simulation
  - Rigid-body dynamics
- Articulated Figure
  - Gravity
  - No autonomous movement
  - Used for inert body
    - Usually: character death (car impact, falling body, *etc.*)
    - Less often: unconscious, paralyzed character
- Collisions with Multiple Bodies
  - Inter-character
  - Character-object

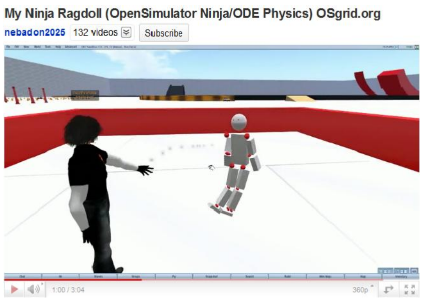
Falling Bodies © 1997 – 2001 Animats
http://www.animats.com

Ragdoll Physics [2]: Demos



© 2007 N. Picouet
http://youtu.be/ohNqCb--aSs

© 2006 P. Pelt
http://youtu.be/6JdLOLazJJ0
See also: http://youtu.be/5_QIsl0fyaU


My Ninja Ragdoll (OpenSimulator Ninja/ODE Physics) OSgrid.org
nebadon2025 132 videos
Subscribe
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360p

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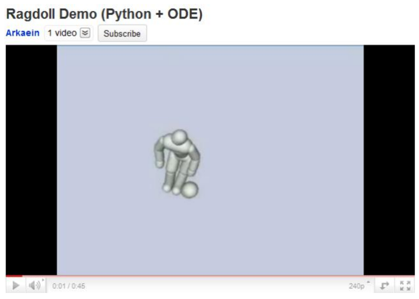
http://youtu.be/uW_DK2qvKv8



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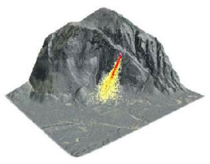
http://bit.ly/gUj9Su / http://youtu.be/FJTBMnP6oCM

Physically-Based Modeling (PBM) [1]: Looking Back

- Particle Dynamics
  - Emitters
    - 0-D (points), 1-D (lines), 2-D (planes, discs, cross-sections)
    - *e.g.*, fireworks (0-D); fountains (0/1/2-D); smokestacks, jets (2-D)
  - Simulation: birth-death process, functions of particle age/trajectory
- Rigid-Body Dynamics
  - Constrained systems of connected parts
  - Examples: falling rocks, colliding vehicles, rag dolls
- Articulated Figures
- More References
  - ACM, *Intro to Physically-Based Modeling*: http://bit.ly/hhQvXd
  - Wikipedia, *Physics Engine*: http://bit.ly/h4PIRt
  - Wikipedia, *N-Body Problem*: http://bit.ly/1ayWwe


Rocks fall
Everyone dies

Physically-Based Modeling (PBM) [2]: Applications in Movies & Games

Star Wars Episode I: The Phantom Menace **© 1999 Lucasfilm, Inc. http://youtu.be/d4PSMXUCi-0**

Summary

- Reading for Today: §5.3, Eberly *2^e*; CGA Handout
- Reading for Next Class: Chapter 14, Eberly *2^e*
- Last Class: Lab on Particle Systems; Dissection of Working Program
- Today: Computer-Generated Animation Concluded
  - CGA of autonomous agents (robots, swarms) *vs.* animation by hand
  - Degrees of freedom (DOFs) and kinds of joints
  - Forward kinematics (FK)
    - Forward problem illustrated
    - Control problem
  - Inverse kinematics (IK)
    - IK (finding angles) *vs.* mechanical problem of finding forces
    - Analytical models
    - Iterative models (Jacobian-based)
  - Ragdoll physics
- Next Class: Ray Tracing, Part 1 of 2

Terminology

- Emitter – Point, Line, Plane or Region from which Particles Originate
- Particle Fountain – Particle System with Directional Emitter
- Sprite (Wikipedia: http://bit.ly/gyInPg)
  - Definition: 2-D image or animation made part of larger scene
  - Point sprite (Saar & Rotzler, 2008): http://bit.ly/fkjBPY
- Joints: Parts of Robot / Articulated Figure That Turn, Slide
  - Revolute: able to turn (rotate), forming angle between bones
  - Prismatic (*aka* slider): "bone" slides through – http://bit.ly/hScjoe
  - Spherical (*aka* ball joint): "bone" rotates around socket
  - Cylindrical (*aka* hinge): flaps wrap around joint, joined to surfaces
- Effectors: Parts of Robot / Articulated Figure That Act (*e.g.*, Hand, Foot)
- Bones: Effectors, Other Parts That Rotate about, Slide through Joints
- Procedural Animation: Automatic Generation of Motion *via* Simulation
  - Ragdoll physics: procedural animation for inert characters
  - Other types: particle systems, *N*-body dynamics