IMDG 4000
Technical Game Development II
Basic Physics

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Introduction: What is Game Physics?

- Computing motion of objects in virtual scene
  - Including player avatars, NPCs, inanimate objects
- Computing mechanical interactions of objects
  - Interaction usually involves contact (collision)
- Simulation must be real-time (versus high-precision simulation for CAD/CAM, etc.)
- Simulation may be very realistic, approximate, or intentionally distorted (for effect)

Introduction: And Why is it Important?

- Can improve immersion
- Can support new gameplay elements
- Becoming increasingly prominent (expected) part of high-end games
- Like AI and graphics, facilitated by hardware developments (multi-core, GPU)
- Maturation of physics engine market

Physics Engines

- Similar *buy vs. build* analysis as game engines
  - ***Buy:***
    - Complete solution from day one
    - Proven, robust code base (hopefully)
    - Feature sets are pre-defined
    - Costs range from free to expensive
  - ***Build:***
    - Choose exact features you want
    - Opportunity for more game-specific optimizations
    - Greater opportunity to innovate
    - Cost guaranteed to be expensive (unless features extremely minimal)

Physics Engines (cont.)

- ***Open source***
  - Box2D, Bullet, Chipmunk, JigLib, ODE, OPAL, OpenTissue, PAL, Tokamak, Farseer, Physics2d, Glaze
- ***Closed source*** (limited free distribution)
  - Newton Game Dynamics, Simple Physics Engine, True Axis, PhysX
- ***Commercial***
  - Havok, nV Physics, Vortex
- ***Relation to Game Engines***
  - Integrated/native, e.g., C4
  - Integrated, e.g., Unity+PhysX
  - Pluggable, e.g., C4+PhysX, jME+ODE (via jME Physics)

Basic Game Physics Concepts

- *Why are we studying this?*
  - To use an engine effectively, you need to understand something about what it's doing
  - You may need to implement small features or extensions yourself
  - Cf. owning a car without understanding anything about how it works
- *Examples*
  - Kinematics and dynamics
  - Projectile motion
  - Collision detection and response

Kinematics

- Study of the motion of objects *without* taking into account mass or force
- Basic quantities: position, time
- ... and the derivatives: velocity, acceleration
- Basic equations:

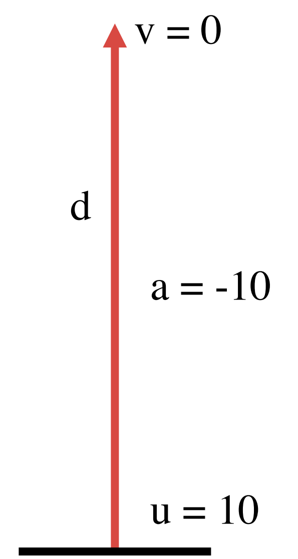
$$d = vt$$
$$v = u + at$$
$$d = ut + at^2/2$$
$$v^2 = u^2 + 2ad$$

where: *t - (elapsed) time*
d - distance (change in position)
v - (final) velocity (change in distance per unit time)
a - acceleration (change in velocity per unit time)
u - (initial) velocity

Kinematics (cont'd)

Prediction Example: If you throw a ball straight up into the air with an initial velocity of 10 m/sec, how high will it go?

$$v^2 = u^2 + 2ad$$



u = 10 m/sec

a = -10 m/sec^2 (approx due to gravity)

v = 0 m/sec (at top of flight)

$$0 = 10^2 + 2(-10)d$$

$$d = 5 \text{ m}$$

(note answer independent of mass of ball)

Computing Kinematics in Real Time

```
start = getTime( ) // start time
p = 0              // initial position
u = 10             // initial velocity
a = -10

function update ( ) { // in render loop
   now = getTime( )
   t = now - start
   simulate( t );
}

function simulate( t )  {
   d = ( u + ( 0.5 * a * t ) ) * t
   move object to p + d
}
```

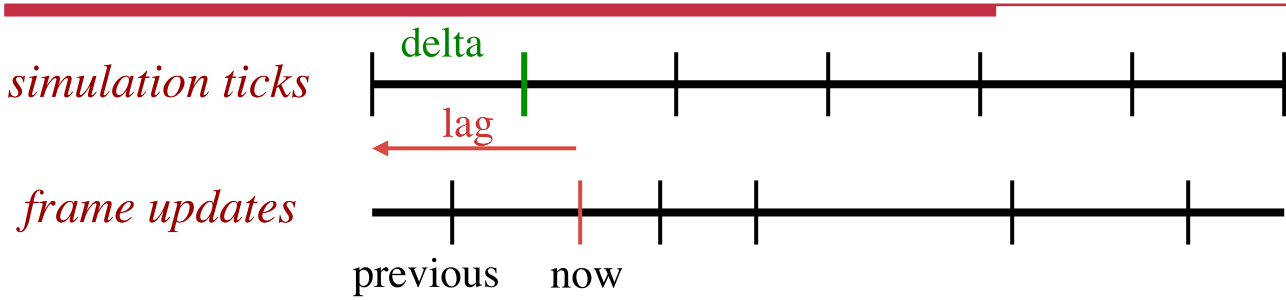
$$d = ut + at^2/2$$

Problem: Number of calls and time values to `simulate` depend on ***frame rate***, which is variable!

Frame Rate Independence

- Complex numerical simulations are very sensitive to time steps (due to truncation error and other numerical effects)
- But results need to be repeatable regardless of CPU/GPU performance
  - For debugging
  - For game play
- ***Solution:*** control simulation interval independently of frame rate

Frame Rate Independence




```
start = ...    // Initialized one time at start of simulation
delta = 0.02   // physics simulation interval (sec)
lag = 0        // time since last simulated
previous = 0   // time of previous call to update

function update( ) { // in render loop
   now = getTime( )
   t = ( previous - start ) - lag  // previous simulate( t )
   lag = lag + ( now - previous )  // new lag
   while( lag > delta )
     t = t + delta
     simulate( t )
     lag = lag - delta
   previous = now
}
```

Doing It In 3D

- Mathematically, consider all quantities involving position to be **vectors**:

$$\mathbf{d} = \mathbf{v}t$$

$$\mathbf{v} = \mathbf{u} + \mathbf{a}t$$

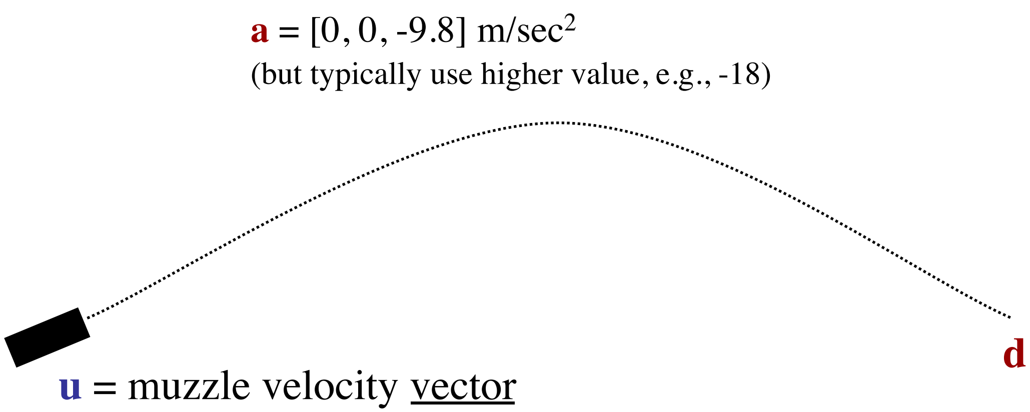
$$\mathbf{d} = \mathbf{u}t + \mathbf{a}t^2/2$$

 (Note these are all scalar products, so essentially calculations are performed independently in each dimension)

- Computationally, use appropriate 3-element vector data type

The Firing Solution

- How to hit a target
  - With a grenade, spear, catapult, etc.
  - A beam weapon or high-velocity bullet over short ranges can be viewed as traveling in a straight line
  - Projectile travels in a parabolic arc



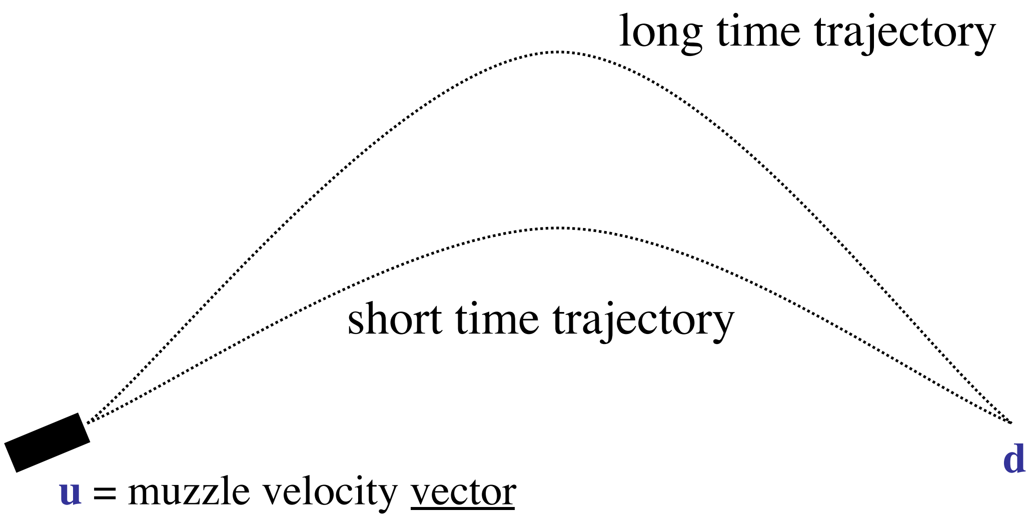
$$\mathbf{d} = \mathbf{u}t + \mathbf{a}t^2/2$$

Given u, solve for d.

The Firing Solution

- In most game situations, the *magnitude* of **u** is fixed (why?) and we only need to know its relative components (orientation)
- After a lot of hairy math [see Millington 3.5.3], it turns out there are *three* relevant cases (why?):
  - Target is out of range (no solutions)
  - Target is at exact maximum range (single solution)
  - Target is closer than maximum range (two possible solutions)

The Firing Solution (cont.)



$$\mathbf{u} = (2\mathbf{d} - \mathbf{a}t^2) / 2st$$

where s = max muzzle speed

- Usually choose short time trajectory
  - Gives target less time to escape
  - Unless shooting over wall, etc.

The Firing Solution (cont.)

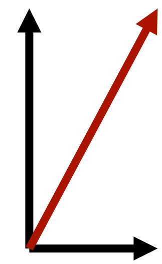
```
function firingSolution( d, s, gravity ) {
   // real-valued coefficents of quadratic
   a = gravity * gravity
   b = -4 * ( ( gravity * d ) + ( s * s ) )
   c = 4 * d * d

   // check for no real solutions
   if ( ( 4 * a * c ) > ( b * b ) ) return null

   // find short and long times
   disc = sqrt( ( b * b ) - ( 4 * a * c ) )
   t1 = sqrt( ( -b + disc ) / ( 2 * a ) )
   t2 = sqrt( ( -b - disc ) / ( 2 * a ) )
   if ( t1 < 0 )
      if ( t2 < 0 ) return null
      else t = t2
   else if ( t2 < 0 ) t = t1
   else t = min( t1, t2 )

   // return firing vector
   return ( ( 2 * d ) - ( gravity * t * t ) ) / ( ( 2 * s * t ) )
}
```

*Note scalar product of two vectors using *, e.g.,*

$$[a,b,c] * [d,e,f] = a*d + b*e + c*f$$

Dynamics

- Notice that the preceding kinematic descriptions say nothing about *why* an object accelerates (or why its acceleration might change)
- To get a full "modern" physical simulation, you need to add two more basic concepts:
  - ***force***
  - ***mass***
- Discovered by Sir Isaac Newton
- Around 1700 ☺



Newton's Laws

1. A body will remain at rest or continue to move in a straight line at a constant speed unless acted upon by a *force*.
2. The acceleration of a body is *proportional* to the resultant force acting on the body and is in the same direction as the resultant force.
3. For every action, there is an equal and opposite reaction.

Motion Without Newton's Laws

- Pac-Man or early Mario style
  - Follow path with *instantaneous changes* in speed and direction (velocity)

  - Not physically possible
  - Fine for some casual games (especially with appropriate animations)

Newton's Second Law

$$\mathbf{F} = m\mathbf{a}$$

At each moment in time:

F = force vector, in Newtons

m = mass (intrinsic property of matter), kg

a = acceleration vector, m/sec^2

This equation is the fundamental driver of all physics simulations:

- Force causes acceleration (**a** = **F**/m)
- Acceleration causes change in velocity
- Velocity causes change in position

How Are Forces Applied?

- Without contact
  - Gravity
  - Wind (if not modeling air particles)
  - Magic
- Usually involves contact
  - Collision (rebound)
  - Friction (rolling, sliding)
- Dynamic (force) modeling also used for autonomous steering behaviors

Collision Detection

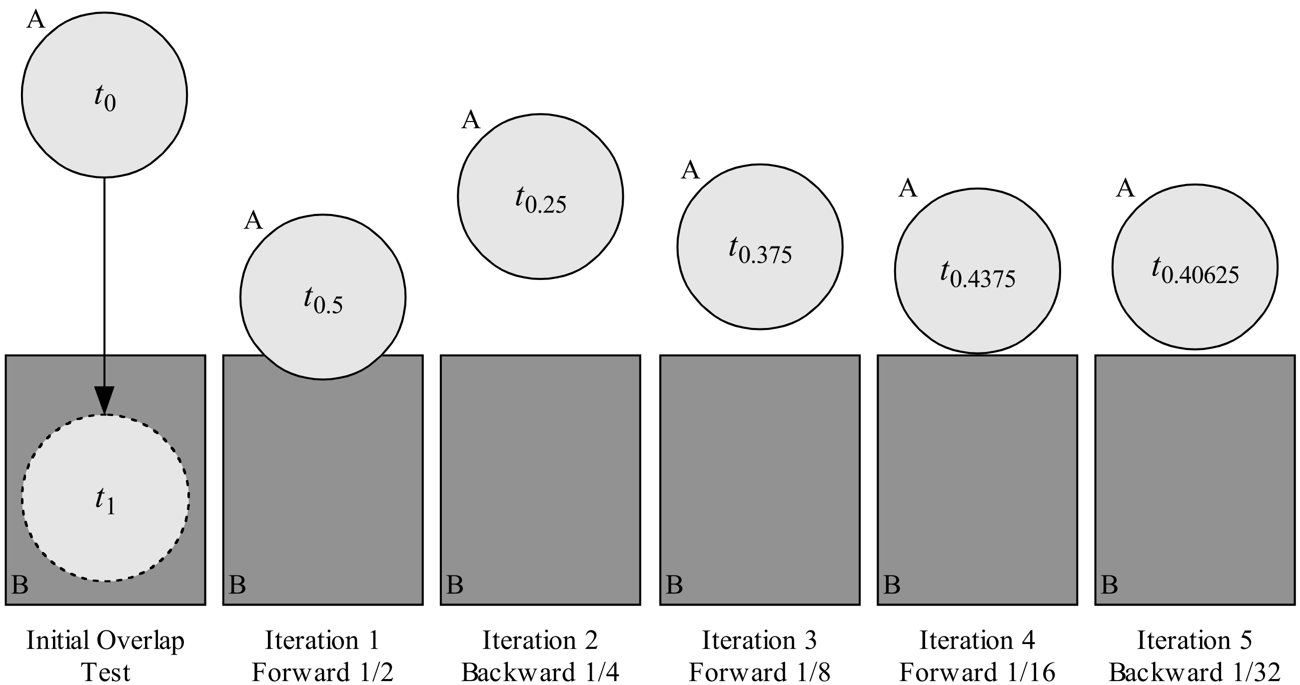
- Determining when objects collide is not as easy as it seems
  - Geometry can be complex
  - Objects can be moving quickly
  - There can be *many* objects
    - Naive algorithms are $O(n^2)$
- Two basic approaches
  - Overlap testing
    - Detects whether collision has already occurred
  - Intersection testing
    - Predicts whether a collision will occur in the future

Overlap Testing

- Most common technique used in games
- Exhibits more error than intersection testing
- Basic idea:
  - At every simulation step, test every pair of objects to see if they overlap
- Easy for simple volumes (e.g., spheres), harder for polygonal models
- Results of test
  - Collision normal vector (useful for reaction)
  - Time that collision took place

Overlap Testing: Finding Collision Time

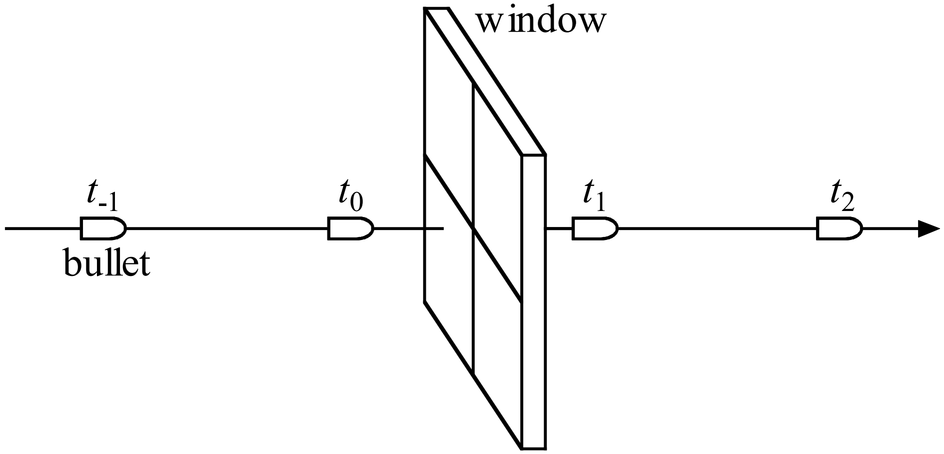
- Calculated by doing "binary search" in time, moving object back and forth by 1/2 steps (bisections)



- In practice, five iterations usually enough

Limitations of Overlap Testing

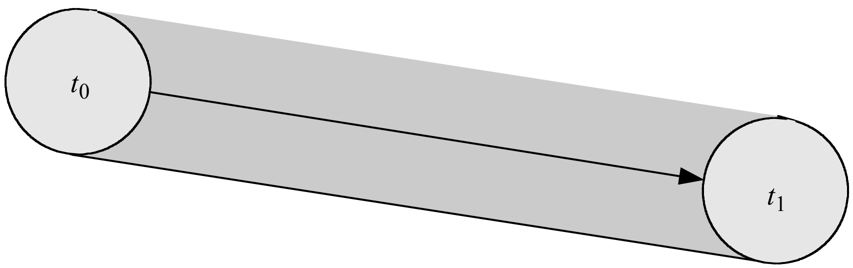
- Fails with objects that move too fast (no overlap during simulation time slice)



- Solution approach:
  - Constrain game design so that *fastest object* moves smaller distance in one physics "tick" (delta) than *thinnest object*
  - May require reducing simulation step size (adds computation overhead)

Intersection Testing: Swept-volume Collisions

- Predict future collisions
- Extrude geometry in direction of movement
  - e.g., “swept” sphere turns into capsule shape

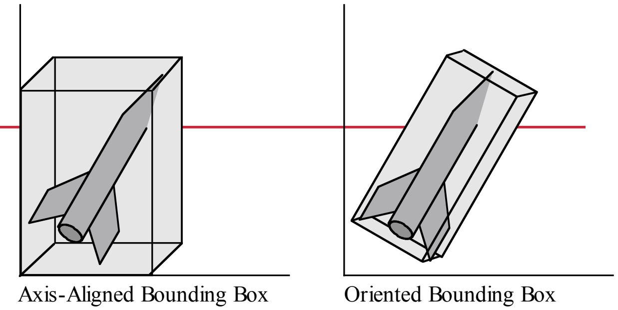


- Then, see if extruded shape overlaps objects
- When a collision is found (predicted)
  - Move simulation to time of collision (no searching)
  - Resolve collision
  - Simulate remaining time step(s)
  - Works for bullet/window example

Speeding Up Collision Detection

- Bounding Volumes
  - Oriented
  - Hierarchical
- Space Partitioning
- Plane Sweep

Bounding Volumes



- Commonly used volumes
  - Sphere
    - Distance between centers less than sum of radii
  - Box
    - Axis aligned (loose fit, easier math) (ABB)
    - Oriented (tighter fit, more expensive) (OBB)
- If bounding volumes don't overlap, then no more testing is required
  - If overlap, more refined testing required
  - Bounding volume alone may be good enough for some games

Complex Bounding Volumes

- Multiple volumes per object
  - e.g., separate volumes for head, torso and limbs of avatar object
- Hierarchical volumes
  - e.g., boxes inside of boxes
- Techniques can be combined
  - e.g., hierarchical oriented bounding boxes (OBBTree)

Oriented Bounding Box Tree

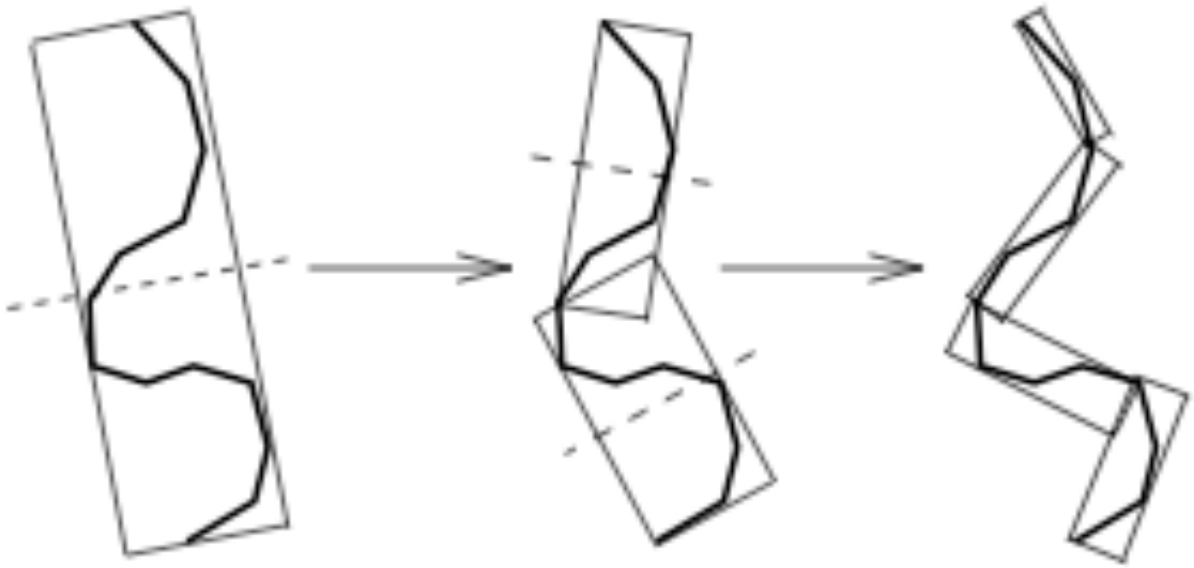
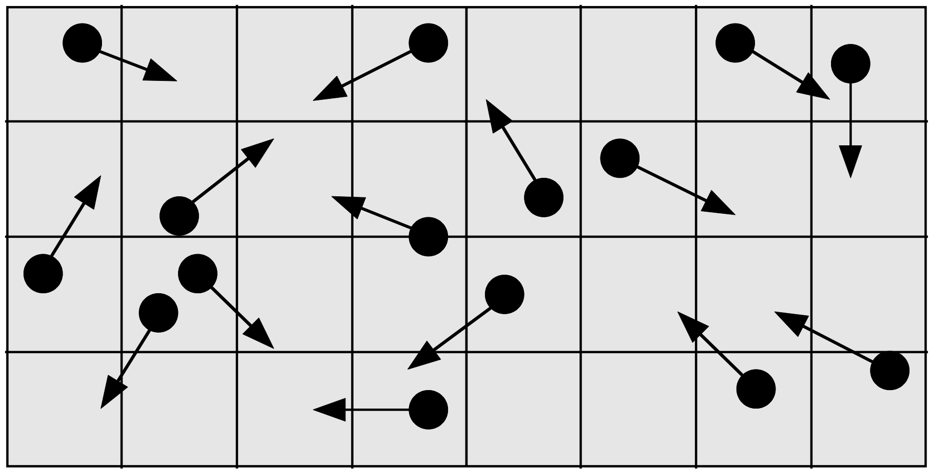


Figure 1: Building the OBBTree: recursively partition the bounded polygons and bound the resulting groups.

[Gottschalk, Lin, Minocha, SIGGRAPH '96]

Space Partitioning for Collision Testing

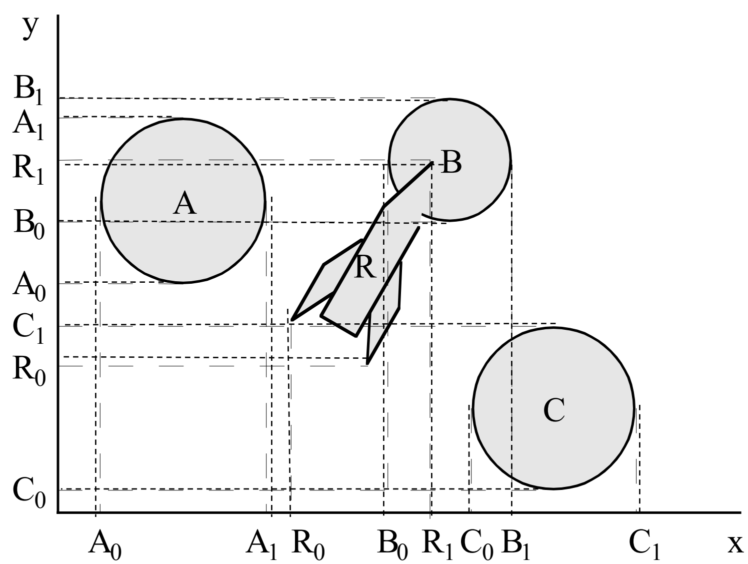
- To address the n^2 problem...
- Partition space so only test objects in same cell



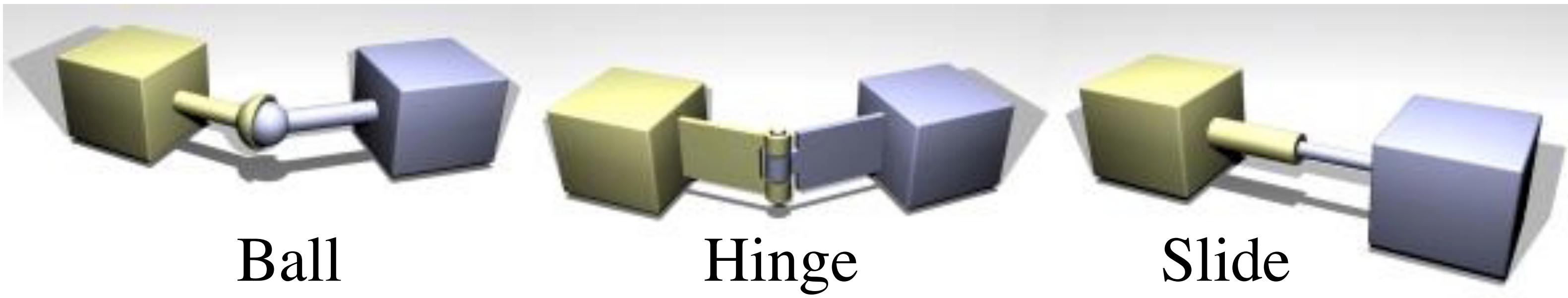
- In best case (uniform distribution) reduces n^2 to linear
- In worst case (all objects in same cell) no improvement
- What is the cost of this?

Plane Sweep for Collision Testing

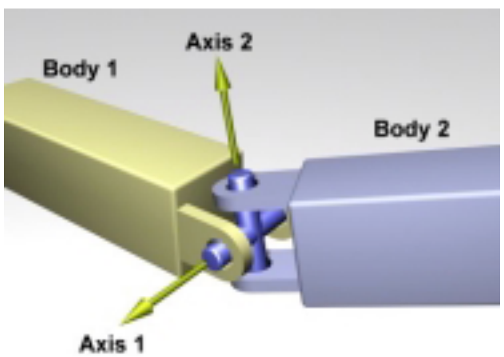
- *Observation:* a lot of objects stay in one place
- *Sort* bounds along axes (expensive to do once!)
- Only adjacent sorted objects which overlap on all axes need to be checked further
- Since many objects don't move, can keep sort up to date very cheaply with bubblesort (nearly linear)



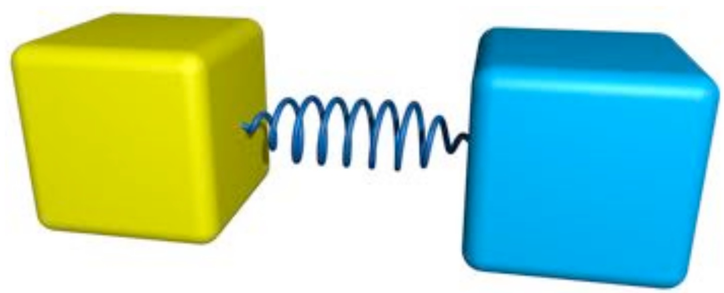
Joints as Constraints on Motion



Ball Hinge Slide



Universal



Spring

Some More Physics we are not Covering

- Collision response
  - Conservation of momentum
  - Elastic collisions
  - Non-elastic collisions - coefficient of restitution
- Rigid body simulation (vs. point masses)
- Soft body simulation

[see excellent recent book by Millington, “Game Physics Engine Development”, MK, 2007]

What Algorithms Does PhysX Use?

- Hard to know exactly, because algorithm details are nVidia's intellectual property
- However from various forums and clues, it is clear PhysX uses:
  - Both sweep and overlap collision detection
  - OBBT and ABB (both axis-aligned and oriented bounding bounding box trees)
  - Constraints: hinges, springs, etc.
  - Lots of other hairy stuff, see http://developer.nvidia.com/forums/index.php?showtopic=5758

Why Does nVidia Make Physics Software?

- nVidia is mainly known as a developer and manufacturer of graphics hardware (GPUs)
- So they are taking advantage of the GPU for hardware acceleration of their physics engine
  - Algorithms can be tuned to their hardware
  - Giving a competitive advantage over other GPU manufacturers
  - Before nVidia bought it, PhysX used to use proprietary hardware anyway (I have one)

The “Cutting Edge” in Physics Engines

- **Cloth Simulation**
- **Destruction**

Videos from:

- Havok (PhysX competitor bought by Intel)
- Unity