

Basic Game Physics

Technical Game Development II

Professor Charles Rich
Computer Science Department
rich@wpi.edu

[some material provided by Mark Claypool]

Introduction

- *What is game physics?*
 - computing *motion* of objects in virtual scene
 - including player avatars, NPC's, 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 (cont'd)

- *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 exactly features you want
 - opportunity for more game-specification optimizations
 - greater opportunity to innovate
 - cost guaranteed to be expensive (unless features extremely minimal)

Physics Engines

- **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 their derivatives: **velocity, acceleration**
- Basic equations:

- 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

$$d = vt$$

$$v = u + at$$

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

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

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?

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

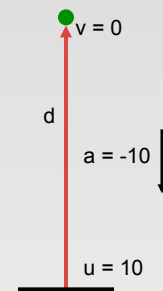
$$u = 10 \text{ m/sec}$$

$$a = -10 \text{ m/sec}^2 \text{ (approx due to gravity)}$$

$$v = 0 \text{ m/sec (at top of flight)}$$

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

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



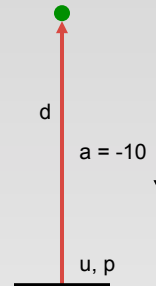
(note answer independent of mass of ball)

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 (changing) **frame rate**

Frame Rate Independence

- Complex numerical simulations used in physics engines 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 physics *simulation* interval independently of *frame rate*

Frame Rate Independence



```
start = ...
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.)

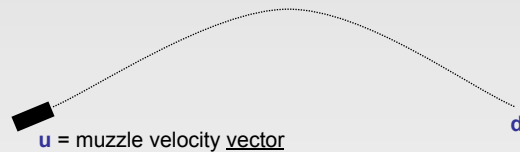
- Computationally, using appropriate 3-element vector datatype

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 straight line
 - projectile travels in a parabolic arc

$\mathbf{a} = [0, 0, -9.8] \text{ m/sec}^2$
(but typically use higher value, e.g. -18)

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



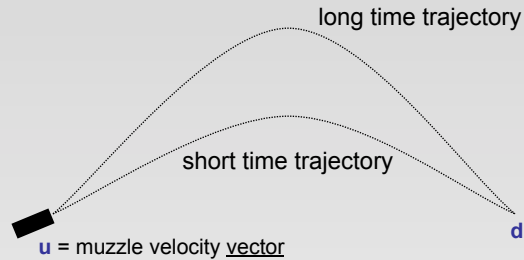
Given \mathbf{d} , solve for \mathbf{u} .

The Firing Solution



- In most typical game situations, the *magnitude* of \mathbf{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



5% Optional Extra Credit
HW to implement this in
Unity! (due end of term)

$$u = (2d - at^2) / 2st$$

where s = max muzzle speed

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

```
function firingSolution (d, s, gravity) {  
    // real-valued coefficients 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 (esp. with appropriate animations)

Newton's Second Law

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

at each moment in time:

\mathbf{F} = force vector, Newton's

m = mass (intrinsic property of matter), kg

\mathbf{a} = acceleration vector, m/sec²

This equation is the fundamental driver of all physics simulations:

- force causes acceleration ($\mathbf{a} = \mathbf{F}/m$)
- acceleration causes change in velocity
- velocity causes change in position

How Are Forces Applied?

- Usually involves contact
 - collision (rebound)
 - friction (rolling, sliding)
- Without contact
 - gravity
 - wind (if not modeling air particles)
 - magic
- Dynamic (force) modeling also used for autonomous **steering behaviors**

Collision Detection

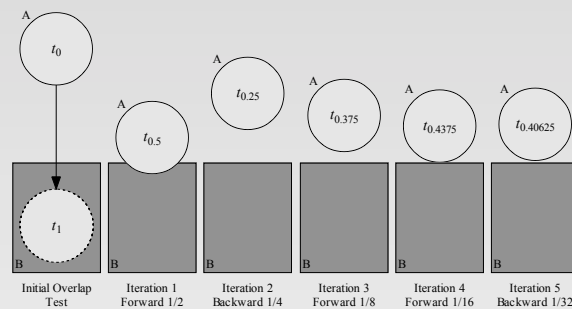
- Determining when objects collide is not as easy as it seems
 - geometry can be complex
 - objects can be moving quickly
 - there can be *many* objects
 - naive algorithms are $O(n^2)$
- Two basic approaches:
 - **overlap testing**
 - detects whether collision has already occurred
 - **intersection 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 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

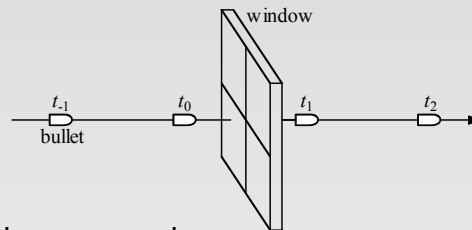
- Calculated by doing “binary search” in time, moving object back and forth by 1/2 steps (bisections)



- In practice, five iterations usually enough

Limitations of Overlap Testing

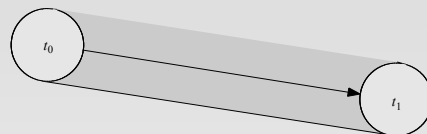
- Fails with objects that move too fast (no overlap during simulation time slice)



- Solution approach:
 - constrain game design so that *fastest object* moves smaller distance in one physics “tick” (δ) than *thinnest object*
 - may require reducing simulation step size (adds computation overhead)

Intersection Testing

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



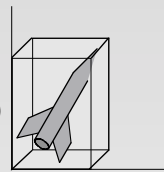
- Then, see if extruded shape overlaps objects
- When collision found (predicted)
 - move simulation to time of collision (no searching)
 - resolve collision
 - simulate remaining time step(s)
 - works for bullet/window example

Speeding Up Collision Detection

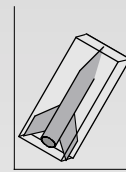
- Bounding Volumes
 - Oriented
 - Hierarchical
- Partitioning
- Plane Sweep

Bounding Volumes

- Commonly used volumes
 - sphere - distance between centers less than sum of radii
 - boxes
 - axis aligned (loose fit, easier math)
 - oriented (tighter fit, more expensive)
- 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



Axis-Aligned Bounding Box



Oriented Bounding Box

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

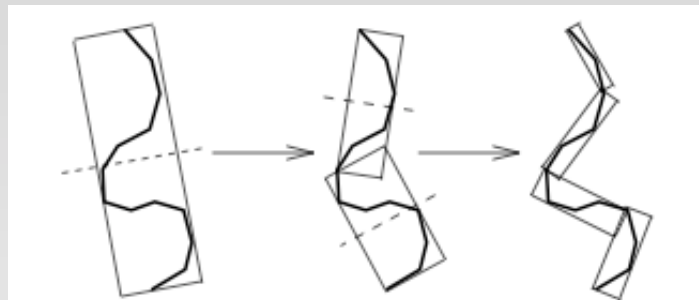
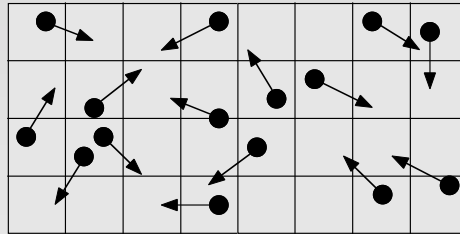


Figure 1: Building the OBBTree: recursively partition the bounded polygons and bound the resulting groups.

[Gottschalk, Lin, Minocha, SIGGRAPH '96]

Partitioning for Collision Testing

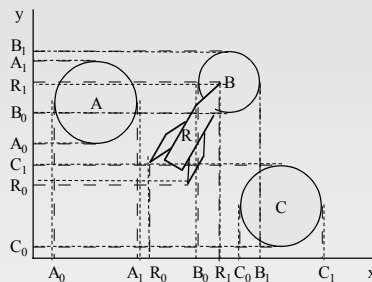
- To address the n^2 problem...
- Partition space so only test objects in same cell



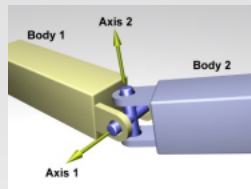
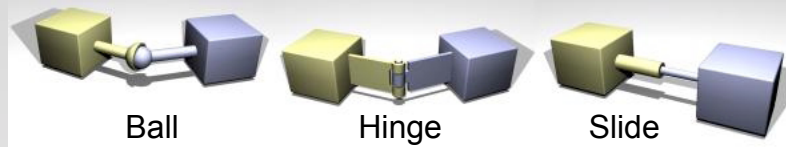
- In **best case** (uniform distribution) reduces n^2 to linear
- In **worst case** (all objects in same cell) no improvement

Plane Sweep for Collision Testing

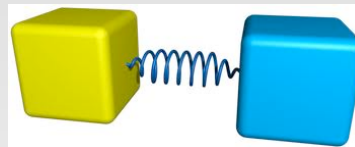
- **Observation:** a lot of moveable objects stay in one place most of the time
- **Sort** bounds along axes (expensive to do once!)
- Only **adjacent** sorted objects which overlap on all axes need to be checked further
- Since many objects don't move, can keep sort up to date very cheaply with bubblesort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



Joins as Constraints on Motion



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 (IP)
- 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.
 - and 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 (GPU's)
- 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

The “Cutting Edge” in Physics Engines

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

Videos from:

- Havok (PhysX competitor bought by Intel)
- Unity