Basic Game Physics

Technical Game Development II

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[some material provided by Mark Claypool]

Introduction

- *What is game physics and why is it important?*
  - 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)

- *What is game physics 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
  - pluggable, e.g.,
    - C4+PhysX
    - jME+ODE (via jME Physics)

Basic Game Physics Concepts

- Why?
  - 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
- Basic equations:

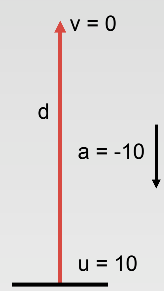
$$d = vt$$
$$v = u + at$$
$$d = ut + at^2/2$$
$$v^2 = u^2 + 2ad$$

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 (changing) ***frame rate***

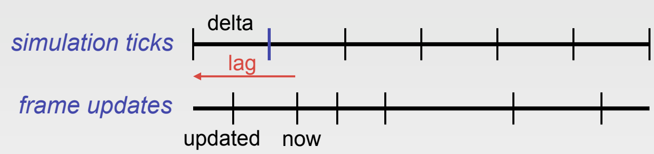
Frame Rate Independence

- 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 simulation interval separately

Frame Rate Independence

```
delta = 0.02   // physics simulation interval (sec)
lag = 0        // physics lag
updated = 0    // time of last update

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



Doing It In 3D

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

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

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

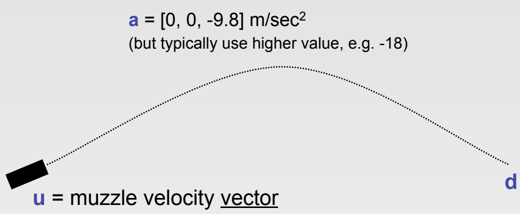
$$\mathbf{d} = \mathbf{u}t + \mathbf{a}t^2/2$$

(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



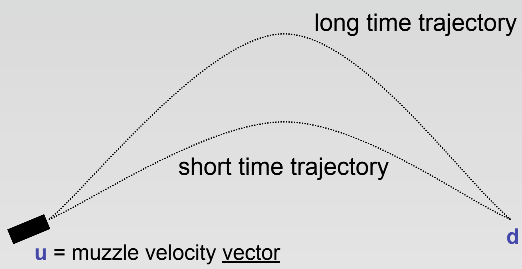
$$\mathbf{d} = \mathbf{u}t + \mathbf{a}t^2/2$$

Given d, solve for u.

The Firing Solution

- In most typical game situation, the *magnitude* of **u** is fixed 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:
  - 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



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

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

where x = max muzzle speed


```
function firingSolution (d, x, gravity) {

   // real-valued coefficents of quadratic
   a = gravity * gravity
   b = -4 * (gravity * d + x*x)
   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*x*x)
}
```

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

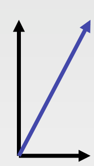
*[a,b,c] * [d,e,f] = a*d + b*e + c*f*

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

F = ma

at each moment in time:

F = force vector, Newton's

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
- 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 (later in term)

Collision Detection

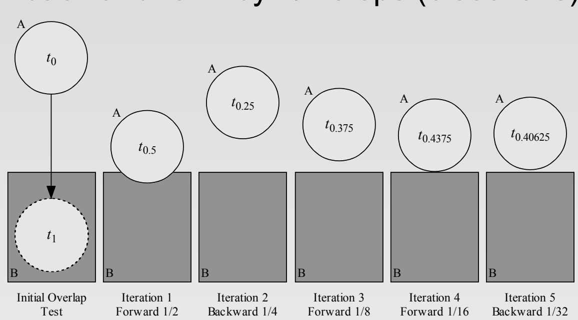
- Determining when objects collide is not as easy as it seems
  - geometry can be complex
  - objects can be moving quickly
  - there can be *many* objects
    - naive algorithms are $O(n^2)$
- Two basic approaches:
  - overlap testing
    - detects whether collision has already occurred
  - intersection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

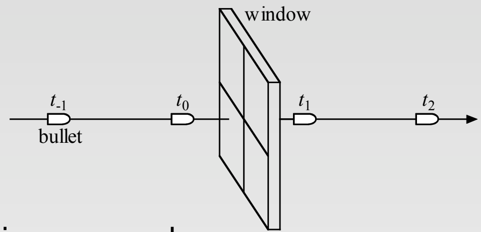
- Calculated by doing “binary search” in time, moving object back and forth by 1/2 steps (bisections)



- In practice, five iterations usually enough

Limitations of Overlap Testing

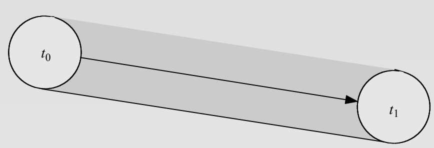
- Fails with objects that move too fast (no overlap during simulation time slice)



- Solution approach:
  - constrain game design so that *fastest object* moves smaller distance in one tick 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



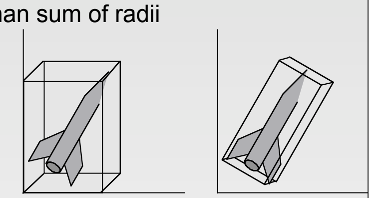
- Then, see if extruded shape overlaps objects
- When collision found (predicted)
  - move simulation to time of collision (no searching)
  - resolve collision
  - simulate remaining time step(s)
  - works for bullet/window example

Speeding Up Collision Detection

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

Bounding Volumes

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



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) in jME

Oriented Bounding Box Tree

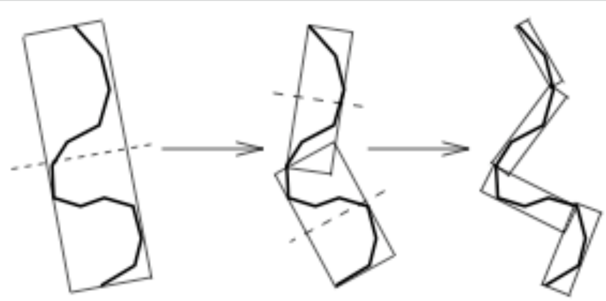
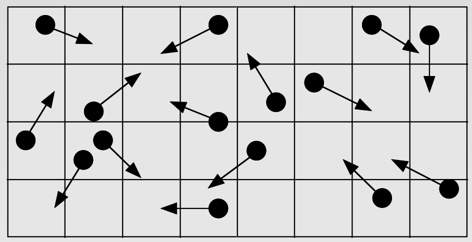


Figure 1: Building the OBBTree: recursively partition the bounded polygons and bound the resulting groups.

[Gottschalk, Lin, Minocha, SIGGRAPH '96]

Partitioning for Collision Testing

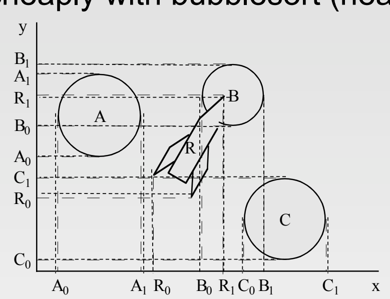
- To address the n^2 problem...
- Partition space so only test objects in same cell



- 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 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)



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
  - spring-mass-damper dynamics

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

Open Dynamics Engine

- Brief case study of a complete physics engine
- Overview from author (Russell Smith)
- jME Physics interface

Dynamics Simulation

A whirlwind tour.
(Current State, and New Frontiers)

Russell Smith

Dec 2004

What is Dynamics?

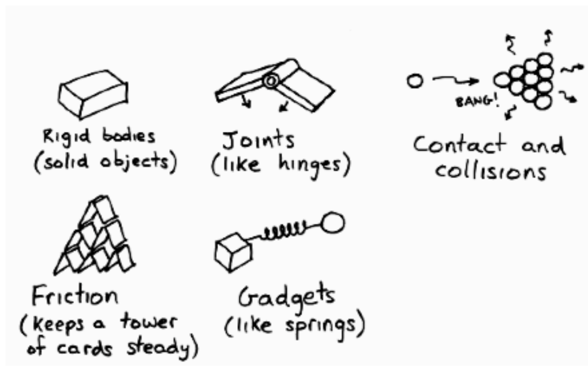
- Classical physics: Newton's law[s].

High school → $f = ma$ $\mathbf{M}\frac{d^2\mathbf{p}}{dt^2} = -\frac{\partial V}{\partial \mathbf{p}}^T$ ← Grad school

- In this talk "dynamics" is mostly "articulated rigid body dynamics".
- But also:
  - Particle dynamics, cloth dynamics, wave dynamics, fluid dynamics, flexible body dynamics, fracture dynamics…

Dynamics Simulation Libraries

- API primitives: rigid or flexible bodies, joints, contact with friction, collision detection, etc…
- Many techniques, many libraries, lots of research.

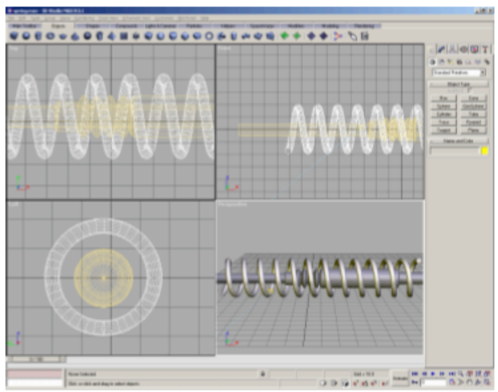


Applications: Games

- Interactive 3D worlds – typically FPS games.
- Limited uses: stacks of boxes, rag-dolls, collapsing buildings. But: need fast, stable and predictable simulation.

Applications: 3D animation tools

- The big three (Maya, SoftImage, 3DS Max), many others.
- Simulate dead things, or in combination with motion capture.
- Many custom tools, e.g. Massive ("Lord of the Rings").



Applications: Industrial

- Robot prototyping / modeling / research (e.g. Honda ASIMO, NASA mars rover).
- Biomechanics.
- Vehicle operator training, prototyping.

Open Dynamics Engine™

- My rigid body simulation library.
  - Many others: Havok, PhysX (Novodex, Meqon), SD/Fast…
- A platform for research.
  - Simulation algorithms, simulation applications.
- Open source (BSD license).
  - Dynamics should be ubiquitous: encourage innovation.
  - Closed source libraries constrain users: endless customization and integration hassles.
  - Why customization: ODE → SoftImage XSI → ILM
    - Used in "Eternal Sunshine of the Spotless Mind".

Open Dynamics Engine™

- Over 1000 users: widely used in games, game engines, robot simulation, 3D animation.

Why Simulation is Hard

- Modeling real-world mechanisms is hard.
- Unexpected behavior.
  - Hard-to-debug numerical explosions, jitter, poor contact behavior and general unexpected weirdness.
- APIs force the user to learn arcane concepts.
  - Many simulation primitives not intuitive – angular velocity, inertia tensors.
- Too slow for big models.
- Force-based modeling is tricky.
- Too many numerical parameters to tune.
  - Many modeling / numerical approximations used, all with their own tradeoff parameters. Little guidance available, need to experiment.

API Issues

- In the old days it was harder:
  - MDH parameters, weird reference frames, text file configuration, poor documentation, implementation exposed.
- Now we think about the user experience.
  - Absolute positions, utility functions (e.g. for rotation), interactive setup (3D tools), documentation, API consistency, only essential concepts in the API.
- Still lots of room for improvement.
  - Constructive modeling: glue, split, clone, deform, etc.
  - Dynamics debuggers – identify model physical / numerical errors.
  - Standardized data formats.

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Speed

- Higher speed → real time simulation of more complex worlds.
- Big-matrix methods need lots of Optimization.
  - Coding tricks: minimize memory traffic, cache-friendly algorithms, pipelining, SIMD.
    - Parameterized code, search for efficient parameters (ATLAS).
- CPU budgeting.
  - Iterative methods allow us to cap effort per frame.
  - But accuracy is an issue.
- Parallelization.
  - Problem is not coarse grained – so clusters don't work well.
  - Parallel direct factorization – only for *large* problems.
  - Iterative techniques the easiest to parallelize.
  - ODE QuickStep inner loop: 3x speedup using 6 CPUs – [SGI Altix].

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Constraint Based Modeling (good!)

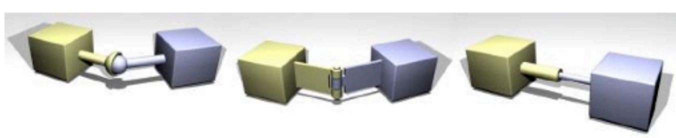
- Velocity / acceleration [in]equality constraints (LCP):

$$f_u(\mathbf{v}) = 0,\ f_v(\mathbf{v}) \geq 0 \quad \text{or} \quad f_a(\mathbf{a}) = 0,\ f_b(\mathbf{a}) \geq 0$$

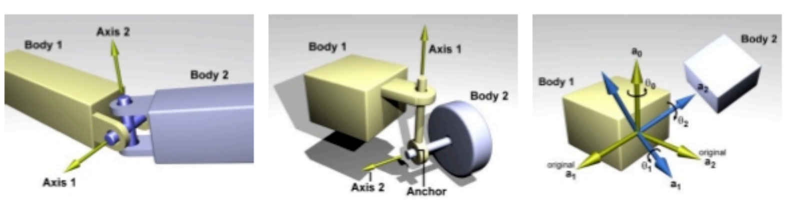
- Contacts and friction.
  - Relative velocity & force normal to contact surface ≥ 0.
  - Tangential forces limited by Coulomb friction (various models).
  - Constraint modeling is now commonplace for contacts.
- Actuators and brakes.
  - Joint velocity = v, but don't apply too much force.
- Simulator enforces constraints automatically
  - No parameters to tune.
  - Integration problems hidden away.
- Can also model stiff springs, e.g. suspensions.

Joints are Constraint

ODE's "robot" joints:



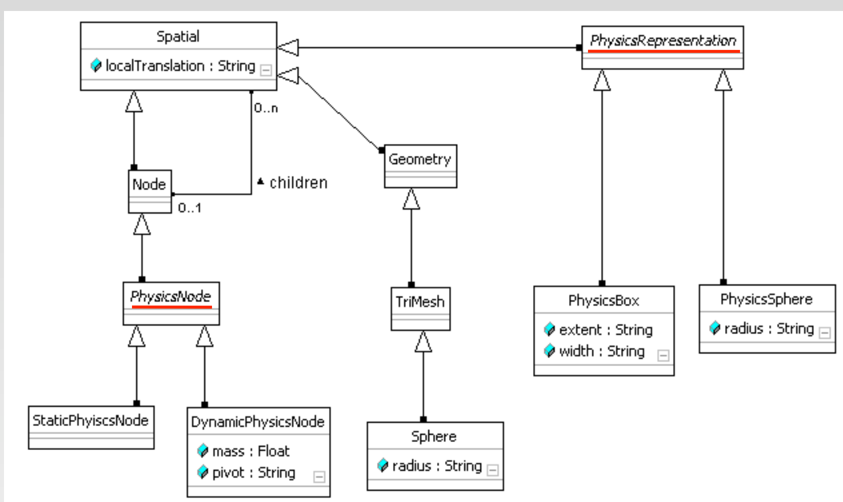
ODE's special purpose joints:



Constraint Also Good For:

- Mechanisms
  - Gears, linked platforms, steering geometry, suspensions, roller coasters, weird joints (e.g. screw joints), etc.
- Modeling
  - Contact geometry, various kinds of friction, various actuators, spongy / flexible joints, etc.
- Disadvantages:
  - More expensive than forces.
    - Must factor a matrix of constraint information.
  - More mathematically difficult to formulate.
    - But "intuitive" guidance available, see Game Gems IV ch3.4.

jME/ODE Integration (jME Physics 2.1)



https://jmephysics.dev.java.net

jME Physics (2.1)