Physics engine

design and implementation
Physics Engine

• A component of the game engine.
• Separates reusable features and specific game logic.
  • basically software components (physics, graphics, input, network, etc.)
• Handles the simulation of the world
  • physical behavior, collisions, terrain changes, ragdoll and active characters, explosions, object breaking and destruction, liquids and soft bodies, ...
Physics engine

- Example SDKs:
  - Open Source
    - Bullet, Open Dynamics Engine (ODE), Tokamak, Newton Game Dynamics, PhysBam, Box2D
  - Closed source
    - Havok Physics
    - Nvidia PhysX
Case study: Bullet

• Bullet Physics Library is an open source game physics engine.
  • [http://bulletphysics.org](http://bulletphysics.org)
  • open source under ZLib license.
  • Provides collision detection, soft body and rigid body solvers.
  • Used by many movie and game companies in AAA titles on PC, consoles and mobile devices.
  • A modular extendible C++ design.
  • Used for the practical assignment.
  • User manual and numerous demos (e.g. CCD Physics, Collision and SoftBody Demo).
Features

• **Bullet Collision Detection** can be used on its own as a separate SDK without Bullet Dynamics
  • *Discrete* and *continuous* collision detection.
  • Swept collision queries.
  • Generic convex support (using GJK), capsule, cylinder, cone, sphere, box and non-convex triangle meshes.
  • Support for dynamic deformation of *nonconvex* triangle meshes.

• **Multi-physics Library** includes:
  • *Rigid-body dynamics* including constraint solvers.
  • Support for constraint limits and motors.
  • *Soft-body support* including cloth and rope.
Design

• The main components are organized as follows

  - **Soft Body Dynamics**
  - **Bullet Multi Threaded**
  - **Extras:** Maya Plugin, etc.
  - **Rigid Body Dynamics**
  - **Collision Detection**
  - **Linear Math, Memory, Containers**
Overview

• High level simulation manager:
  btDiscreteDynamicsWorld or btSoftRigidDynamicsWorld.
  • Manages the physics objects and constraints.
  • implements the update call to all objects at each frame.

• The objects:
  • btRigidBody

• Needing:
  • Mass (>0 for dynamic objects, 0 for static)
  • Collision shape (box, sphere, etc.)
  • Material properties (friction, restitution, etc.)

• Advancing simulation frames.
  • stepSimulation
// Collision configuration contains default setup for memory, collision setup
btDefaultCollisionConfiguration * collisionConfiguration = new
    btDefaultCollisionConfiguration();

// Set up the collision dispatcher
btCollisionDispatcher * dispatcher = new
    btCollisionDispatcher(collisionConfiguration);

// Set up broad phase method
btBroadphaseInterface * overlappingPairCache = new btDbvtBroadphase();

// Set up the constraint solver
btSequentialImpulseConstraintSolver * solver = new
    btSequentialImpulseConstraintSolver();

btDiscreteDynamicsWorld * dynamicsWorld = new btDiscreteDynamicsWorld(dispatcher,
    overlappingPairCache, solver, collisionConfiguration);

dynamicsWorld->setGravity(btVector3(0,-9.81,0));
Simulation

```cpp
for (int i=0; i<100; i++) {
    dynamicsWorld->stepSimulation(1.0f/60.f, 10);

    // print positions of all objects
    for (int j=dynamicsWorld->getNumCollisionObjects()-1; j>=0 ; j--) {
        btCollisionObject * obj = dynamicsWorld->getCollisionObjectArray()[j];
        btRigidBody * body = btRigidBody::upcast(obj);
        if (body && body->getMotionState()) {
            btTransform trans;
            body->getMotionState()->getWorldTransform(trans);
            printf("World pos = %f,%f,%f\n", float(trans.getOrigin().getX()), float(trans.getOrigin().getY()), float(trans.getOrigin().getZ()));
        }
    }
}
```
// remove the rigid bodies from the dynamics world and delete them
for (int i=dynamicsWorld->getNumCollisionObjects()-1; i>=0 ; i--) {
    btCollisionObject * obj = dynamicsWorld->getCollisionObjectArray()[i];
    btRigidBody * body = btRigidBody::upcast(obj);
    if (body && body->getMotionState()) delete body->getMotionState();
    dynamicsWorld->removeCollisionObject(obj);
    delete obj;
}

// delete collision shapes
for (int j=0; j<collisionShapes.size(); j++) {
    btCollisionShape * shape = collisionShapes[j];
    collisionShapes[j] = 0;
    delete shape;
}

delete dynamicsWorld;
delete solver;
delete overlappingPairCache;
delete dispatcher;
delete collisionConfiguration;
Rigid Body Physics Pipeline

- Data structures used and computation stages performed by a call to `stepSimulation`

**Collision Data**
- Collision shapes
- Object AABBs
- Overlapping pairs
- Contact points

**Dynamics Data**
- Transform velocity
- Mass and inertia
- Constraint contacts joints

**Forward Dynamics Pipeline**
- Apply forces
- Predict transforms
- Compute AABBs
- Detect pairs
- Compute contacts
- Solve constraints
- Integrate positions

**Broadphase Collision Detection**
- Compute AABBs
- Detect pairs

**Narrowphase Collision Detection**
- Compute contacts
- Solve constraints

**Integrate positions**
- Integrate positions
Simulation Step

• The simulation stepper updates the world transformation for active objects by calling `btMotionState::setWorldTransform`

• It uses an internal fixed time step of 60 Hertz
  • Game frame frequency smaller (game faster) => interpolating the world transformation of the objects without further simulation.
  • Game frame frequency larger (game slower) => performing multiple simulations
    • Maximum number of iterations can be specified.
Collision detection

• Bullet provides algorithms and structures for collision detection:
  • Object with world transformation and collision shape
    • btCollisionObject
  • Collision shape (box, sphere etc.) usually centered around the origin of their local coordinate frame
    • btCollisionShape
  • Interface for queries
    • btCollisionWorld

• The **broad phase** quickly rejects pairs of objects that do not collide using a dynamic bounding volume tree based on the AABBs.
  • Can be changed to another algorithm.
Collision dispatcher

• Iterates over each pair of possibly colliding objects, and calls the collision algorithm corresponding to each configuration.

• These algorithms return:
  • Time of impact
  • Closest points on each object
  • Penetration depth / Distance vector.
## Collision dispatcher

<table>
<thead>
<tr>
<th></th>
<th>BOX</th>
<th>SPHERE</th>
<th>CONVEX, CYLINDER, CONE, CAPSULE</th>
<th>COMPOUND</th>
<th>TRIANGLE MESH</th>
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<tr>
<td>BOX</td>
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<td>concaveconvex</td>
<td>compound</td>
<td>gimpact</td>
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</table>
Collision detection

• Bullet uses a small collision margin for collision shapes to improve performance and reliability
  • set to a factor of 0.04 (i.e. expand the shape by 4 cm if unit is meter)
  • to still look correct, the margin is usually subtracted from the original shape.

• It is always highly recommended to use SI units everywhere.
User collision filtering

• Bullet provides three ways to filter colliding objects
  – Masks
    • user defined IDs (could be seen as layers in 2D) grouping possibly colliding objects together.
  – Broadphase filter callbacks
    • user defined callbacks called at the early broad phase of the collision detection pipeline.
  – Nearcallbacks
    • user defined callbacks called at the late narrow phase of the collision detection pipeline.
Rigid body dynamics

- The rigid body dynamics is implemented on top of the collision detection.
- It adds force, mass, inertia, velocity and constraint.
- **Main rigid body object is** `btRigidBody`
  - Moving objects have non-zero mass and inertia.
  - Inherits world transform, friction and restitution from `btCollisionObject`.
  - Adds linear and angular velocity.
Rigid body dynamics

• Bullet has 3 types of rigid bodies
  • Dynamic (moving) bodies
    • have positive mass, position updated at each frame
  • Static (non moving) bodies
    • have zero mass, cannot move but can collide
  • Kinematic bodies
    • have zero mass, can be animated by the user (can push dynamic bodies but cannot react to them).
Rigid body dynamics

- The world transform of a body is given for its center of mass.
  - if the collision shape is not aligned with COM, it can be shifted in a compound shape
- Its basis defines the local frame for inertia.
- The `btCollisionShape` class provides a method to automatically calculate the local inertia according to the shape and the mass.
  - the inertia can be edited if the collision shape is different from the inertia shape.
Rigid body dynamics

• Rigid body constraints are defined as \texttt{btTypedConstraint}
  • Bullet includes different constraints such as hinge joint (1 rot. DOF) and ball-and-socket joint (3 rot. DOF)

• Constraint limits are given for each DOF
  • \textit{Lower limit} and \textit{upper limit}.
  • 3 configurations
    • \texttt{Lower = upper}: the DOF is locked
    • \texttt{Lower > upper}: the DOF is unlimited
    • \texttt{Lower < upper}: the DOF is limited in that range
Soft body dynamics

• Bullet provides dynamics for rope, cloth and soft body.

• The main soft body object is `btSoftBody` that also inherits from `btCollisionObject`.
  • each node has a dedicated world transform.

• The container for soft bodies, rigid bodies and collision objects is `btSoftRigidDynamicsWorld`
Soft body dynamics

- Bullet offers the function `btSoftBodyHelpers::CreateFromTriMesh` to automatically create a soft body from a triangle mesh.
- Can use either direct `nodes/triangles collision` detection or a more efficient decomposition into convex deformable clusters.
Soft body dynamics

• Forces can be applied either on every node of a body or on an individual node

```cpp
softBody->addForce(const btVector3& forceVector);
softBody->addForce(const btVector3& forceVector, int node);
```

• It is possible to make nodes immovable

```cpp
softBody->setMass(int node, 0.0f);
```

• Or attach nodes to a rigid body

```cpp
softBody->appendAnchor(int node, btRigidBody* rigidbody, bool disableCollisionBetweenLinkedBodies=false);
```

• Or attach two soft bodies using constraints
Demos

- Convex collision
- Concave collision
- Convex hull distance
- Joint
- Fracture
- Soft
Assignment

• You will use Bullet in your assignment to control the motion of a creature.
• The default configuration of the physics world uses:
  • A 3D axis sweep and prune broad phase.
  • A sequential impulse constraint solver.
  • A fixed collision object for the ground.
• The Application creates and manages a Creature, a Scene and the simulation time stepping.
• The Application takes care of the simulation loop (update and render) and manages the user inputs.
• The Scene manages the rotation of the mobile platform and the throwing of the balls.
Assignment

• To control the motion of the creature you have to use **PD controllers** at the joints.
  • Create a class **PDController** and add a container for them in the **Creature** (1 per DOF)
  • Angular motors have to be enabled for the joints you want to control (**Creature.cpp**, line 69 and 82)
  • PD controller gains have to be tuned to produce natural behavior.
• At each simulation step:
  • **Balance corrections** are fed to the PD controllers.
  • PD controllers give back the **torques** to apply to correct the pose according to the current pose, velocity and gains.
  • The torques are given to the joint motors (function **setMotorTarget**).
Assignment

• The function `btCollisionObject::getWorldTransform` returns a `btTransform` describing the 3D transformation from the local reference frame of an object to the global world reference frame (common to every object).
• Use `btTransform::inverse` for the inverse transformation.
• The functions `getCenterOfMassPosition` and `getInvMass` return respectively the COM and the inverse of the mass of a `btRigidBody`. 
Assignment

- **UPPER_LEG**
  - Mass: 3 kg

- **LOWER_LEG**
  - Mass: 3 kg

- **FOOT**
  - Mass: 5 kg

The diagram illustrates a mechanical model with labeled joints and segments, including the knee (KNEE) and ankle (ANKLE) locations along with their respective masses. The dimensions and positions are indicated with numerical values.
Efficiency

• Do not waste time with more processing power than needed.
  – Graphics, AI, and so on need it as well.
• Simplify the equations depending on the number of dimensions of the simulated world.
• Use primitive shapes as much as possible for collision detection
  • use low number of vertices in convex hulls (performance and stability).
Efficiency

• Be careful about the ratios
  • sometimes difficult to manage both very small and very big objects, need to reduce internal time step.
  • same for very different masses.
• Combine multiple static triangle meshes into one to reduce computations in broad phase.
Efficiency

• Neglect unwanted or not important effects
  • e.g., you can assume that the sum of the gravity, reaction force and static friction is 0.
  • Neglect or simulate air resistance by a drag coefficient multiplied by the velocity.
• Run full physics simulation only on relevant objects
  • only visible or near player objects.
  • only currently active objects.
  • but be careful about the discontinuities when they are simulated again.
Object (de)activation

• To save up many useless calculations, we do not want to simulate an object which does not move
  • Sitting on the ground or a spring at rest.
  • Because of drag and friction, only objects on which a consistent net force is applied keep moving.

• Two functionalities needed:
  • One for deactivating an object.
  • And one for activating an object back.
Object (de)activation

• Collision detector still returns contacts with deactivated objects but omitted in velocity resolution algorithm
  • Numerical integration is skipped for deactivated objects, saving computation time.

• The object is deactivated when both linear and angular velocities are below a threshold (body specific values).
  • Deactivated objects are therefore more stable.
Object (de)activation

- The object is activated:
  - when it collides with another active object.
    - Threshold used for the minimal severity of the collision needed for activation.
  - When non-constant external forces are applied to the object.
  - Initially, every object is initialized in its rest configuration and deactivated.
    - Very fast startup, even with many objects.
    - Object is activated only when interactions occur.
Optimization techniques

• Precompute as much as possible
  • Tabulate mathematical functions, random numbering \textit{etc.} as much as possible.
  • Perform only \textbf{array access} in the physics update.
• Example:
  • sine call takes 5 times longer to be evaluated than to access an array

```c
float acc = 0;
for (int i = 0; i < 1000; i++)
    acc = acc + i * sin(x * i); // instead use: sinTable[x*i]
```

• \textbf{Not always!} Check empirically.
Optimization techniques

• Simplify your math
  • Mathematical operators are not equivalently fast.
  • Complex function >> divide >> multiply >> addition/subtraction.
  • Simplify equations (and/or tabulate them)
  • Reduce type conversion.
  • Examples:

```c
double acc = 1000000;
for (int i = 0; i < 10000; i++) acc = acc / 2.0;
acc = 1000000;
for (int i = 0; i < 10000; i++) acc = acc * 0.5; // takes 60% of
  the execution time of the previous version

a*b + a*c = a*(b+c); // gets rid of one multiply
b/a + c/a = (1/a)*(b+c); // changes one divide for one multiply
= (b+c)/a; // gets rid of one divide
```
Optimization techniques

- Store data efficiently
  - chose the data type with the right precision.
  - both code execution and memory footprint are proportional to the number of bytes used.

<table>
<thead>
<tr>
<th>Type</th>
<th>Size (B)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
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<td>[-128, 127]</td>
</tr>
<tr>
<td>unsigned char</td>
<td>1</td>
<td>[0, 255]</td>
</tr>
<tr>
<td>int</td>
<td>4</td>
<td>[-2 147 483 648, 2 147 483 647]</td>
</tr>
<tr>
<td>unsigned int</td>
<td>4</td>
<td>[0, 4 294 967 295]</td>
</tr>
<tr>
<td>float</td>
<td>4</td>
<td>[-3.4<em>10^{38}, 3.4</em>10^{38}] (7 decimal)</td>
</tr>
<tr>
<td>double</td>
<td>8</td>
<td>[-1.7<em>10^{308}, 1.7</em>10^{308}] (15 decimal)</td>
</tr>
<tr>
<td>bool</td>
<td>1</td>
<td>true / false</td>
</tr>
</tbody>
</table>
Optimization techniques

• Be linear
  • CPUs come with memory caches loaded when accessing data.
  • Access continuous data in memory (e.g. traversing an array from begin to end) produces less cache misses.
    • Less loading time.
    • Pre-allocated vectors are faster to traverse than dynamic lists.
Optimization techniques

• Size does matter
  • To compile arrays of structures, the compiler performs a multiplication by the size to create the array indexing.
    • if the structure size is a power of 2, the multiplication is replaced by a shift operation (much faster).
    • you can round array sizes aligned to a power of 2 even if you do not use all of it.
  
• Example:

```c
int softBodyNodes [38];
int softBodyNodes [64]; // faster allocation
```