

# PBPhys

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## Introduction

PBPhys is a C library providing structures and functions to simulate system of moving particles in any dimension.

Each particle is represented by a Shapoid, with a speed and acceleration vector, a mass and a drag coefficient. Particles can be fixed. The PBPhys is defined as GSet of particles. The system can emulate or ignore attraction between particles, downward gravity (applied to the second component of vectors, to simulate earth attraction for example), drag force on particle, elastic

collision between particles (considered as perfect spheres). The user can control the system's particle by position, speed or acceleration. The user can step the system by increment of time or until the next collision. The whole system and individual particles can be printed on a stream, saved/loaded in a file.

It uses the `PBErr`, `PBMath`, `Shapoid` and `GSet` libraries.

## 1 Definitions

### 1.1 Equation of movement

The movement of each particle is calculated as follow. Given  $drag$  the drag coefficient of the particle ( $drag \in \mathbb{R}^+$ , 0.0 means no drag),  $\vec{P}(t)$  the position of the particle at instant  $t$ ,  $\vec{S}(t)$  the speed of the particle at instant  $t$  and  $\vec{A}(t)$  the acceleration of the particle at instant  $t$ :

$$\vec{P}(t + \delta t) = \vec{P}(t) + \vec{S}(t)\delta t + 0.5 * (\vec{A}(t) - drag * \vec{S}(t))\delta t^2 \quad (1)$$

$$\vec{S}(t + \delta t) = \vec{S}(t) + (\vec{A}(t) - drag * \vec{S}(t))\delta t \quad (2)$$

If a "downward gravity" is applied, its value is substracted to the second component of the acceleration. If "gravity" is applied each particle  $P_i$ 's acceleration is added an attraction force toward others particles equals to:

$$\vec{F}_i(t) = \sum_j \left( G \cdot \frac{m_i \cdot m_j}{\|\vec{P}_j(t) - \vec{P}_i(t)\|^2} \cdot \frac{\vec{P}_j - \vec{P}_i}{\|\vec{P}_j(t) - \vec{P}_i(t)\|} \right) \quad (3)$$

where  $G$  is the gravity and  $m_i$  is the mass of the particle  $P_i$ .

### 1.2 Detection of collision

The detection of collision between particles is done while approximating particles to spheres.

The distance between two particles moving linearly is calculated as follow. Given  $\vec{P}_0(t)$  and  $\vec{S}_0(t)$  the position and speed of the first particle at time  $t$ , and  $\vec{P}_1(t)$  and  $\vec{S}_1(t)$  the position and speed of the second particle

at time  $t$ . The distance  $D(t)$  between the two particles is given by:

$$D(t_0 + dt) = \sqrt{\|\vec{V}(t_0)\|^2 + 2(\vec{V}(t_0) \cdot \vec{W}(t_0))dt + \|\vec{W}(t_0)\|^2 dt^2} \quad (4)$$

where  $\vec{V}(t) = \vec{P}_1(t) - \vec{P}_0(t)$  and  $\vec{W}(t) = \vec{S}_1(t) - \vec{S}_0(t)$ .

One can notice that the square of the distance between particles is a polynomial function of order 2. The time to smallest distance between particles  $dt_n$  can then simply be calculated by searching the solution of  $D'(t) = 0$ , which gives:

$$dt_n = \frac{-b}{2a} \quad (5)$$

where  $a, b, c$  represents the coefficients of the polynomial:  $D(t) = at^2 + bt + c$ .

Finally, given  $R_0$  and  $R_1$  the radius of the spheres approximating the particle, the time  $dt_h$  to hit can be calculated as follow:

$$dt_h = \frac{-b - \sqrt{b^2 - 4a(c - (R_0 + R_1)^2)}}{2a} \quad (6)$$

### 1.3 Elastic collision

The speed after collision of two colliding particles is calculated as follow. Given  $m_0$  and  $m_1$  the masses of the particles,  $\vec{P}_0$  and  $\vec{P}_1$  the position of the particles,  $\vec{S}_0$  and  $\vec{S}_1$  the speed of the particles before collision and  $\vec{S}'_0$  and  $\vec{S}'_1$  the speed of the particles after collision:

$$\vec{S}'_0 = \vec{S}_0 - \frac{2m_1}{m_0 + m_1} \cdot \frac{(\vec{S}_0 - \vec{S}_1) \cdot (\vec{P}_0 - \vec{P}_1)}{\|\vec{P}_0 - \vec{P}_1\|^2} (\vec{P}_0 - \vec{P}_1) \quad (7)$$

$$\vec{S}'_1 = \vec{S}_1 - \frac{2m_0}{m_0 + m_1} \cdot \frac{(\vec{S}_1 - \vec{S}_0) \cdot (\vec{P}_1 - \vec{P}_0)}{\|\vec{P}_1 - \vec{P}_0\|^2} (\vec{P}_1 - \vec{P}_0) \quad (8)$$

## 2 Interface

```
// ===== PBPHYS.H =====

#ifndef PBPHYS_H
#define PBPHYS_H

// ===== Include =====
```

```

#include <stdlib.h>
#include <stdio.h>
#include <math.h>
#include <string.h>
#include <stdbool.h>
#include "pberr.h"
#include "shapoid.h"

// ----- PBPhysParticle

// ===== Define =====

// ===== Data structure =====

typedef struct PBPhysParticle {
    // Shapoid
    Shapoid* _shape;
    // Speed
    VecFloat* _speed;
    // User acceleration
    VecFloat* _accel;
    // System acceleration (used internally for calculation)
    VecFloat* _sysAccel;
    // Mass
    float _mass;
    // Drag per time unit
    float _drag;
    // Flag for fixed particle
    bool _fixed;
    // User data
    void* _data;
} PBPhysParticle;

// ===== Functions declaration =====

// Create a new PBPhysParticle with dimension 'dim' and a 'shapeType'
// shapoid as shape
// Default values: _mass = 0.0, _drag = 0.0, _fixed = false
PBPhysParticle* PBPhysParticleCreate(int dim, ShapoidType shapeType);

// Free the memory used by the particle 'that'
void PBPhysParticleFree(PBPhysParticle** that);

// Return a clone of the particle 'that'
PBPhysParticle* PBPhysParticleClone(PBPhysParticle* that);

// Print the particle 'that' on the stream 'stream'
void PBPhysParticlePrintln(PBPhysParticle* that, FILE* stream);

// Save the particle 'that' on the stream 'stream'
// Return true if we could save the particle
// Return false else
// If user data is attached to the particle it must be saved by the user
bool PBPhysParticleSave(PBPhysParticle* that, FILE* stream);

// Load the particle 'that' from the stream 'stream'
// Return true if we could load the particle
// Return false else
// If user data is attached to the particle it must be loaded by the user
bool PBPhysParticleLoad(PBPhysParticle** that, FILE* stream);

// Return the dimension of the particle 'that'

```

```

#if BUILDMODE != 0
inline
#endif
int PBPhysParticleGetDim(PBPhysParticle* that);

// Return the shape type of the particle 'that'
#if BUILDMODE != 0
inline
#endif
ShapoidType PBPhysParticleGetShapeType(PBPhysParticle* that);

// Return the shape of the particle 'that'
#if BUILDMODE != 0
inline
#endif
Shapoid* PBPhysParticleShape(PBPhysParticle* that);

// Return the 'iAxis'-th axis of the shape of the particle 'that'
#if BUILDMODE != 0
inline
#endif
VecFloat* PBPhysParticleAxis(PBPhysParticle* that, int iAxis);

// Return the speed of the particle 'that'
#if BUILDMODE != 0
inline
#endif
VecFloat* PBPhysParticleSpeed(PBPhysParticle* that);

// Return the accel of the particle 'that'
#if BUILDMODE != 0
inline
#endif
VecFloat* PBPhysParticleAccel(PBPhysParticle* that);

// Return the sysAccel of the particle 'that'
#if BUILDMODE != 0
inline
#endif
VecFloat* PBPhysParticleSysAccel(PBPhysParticle* that);

// Return the position of the center of the particle 'that'
#if BUILDMODE != 0
inline
#endif
VecFloat* PBPhysParticleGetPos(PBPhysParticle* that);

// Set the speed of the particle 'that' to 'speed'
// If the particle is fixed do nothing
#if BUILDMODE != 0
inline
#endif
void _PBPhysParticleSetSpeed(PBPhysParticle* that, VecFloat* speed);

// Set the acceleration of the particle 'that' to 'accel'
// If the particle is fixed do nothing
#if BUILDMODE != 0
inline
#endif
void _PBPhysParticleSetAccel(PBPhysParticle* that, VecFloat* accel);

// Set the position of the center of the particle 'that' to 'pos'

```

```

#if BUILDMODE != 0
inline
#endif
void _PBPhysParticleSetPos(PBPhysParticle* that, VecFloat* pos);

// Return true if the particle 'that' is the same as the particle 'tho'
// Return false else
// User data is not compared
#if BUILDMODE != 0
inline
#endif
bool PBPhysParticleIsSame(PBPhysParticle* that, PBPhysParticle* tho);

// Set the shape size of the particle 'that' to 'size'
#if BUILDMODE != 0
inline
#endif
void _PBPhysParticleSetSizeVec(PBPhysParticle* that, VecFloat* size);
#if BUILDMODE != 0
inline
#endif
void _PBPhysParticleSetSizeScalar(PBPhysParticle* that, float size);

// Return the mass of the particle 'that'
#if BUILDMODE != 0
inline
#endif
float PBPhysParticleGetMass(PBPhysParticle* that);

// Set the mass of the particle 'that' to 'mass'
#if BUILDMODE != 0
inline
#endif
void PBPhysParticleSetMass(PBPhysParticle* that, float mass);

// Return the drag of the particle 'that'
#if BUILDMODE != 0
inline
#endif
float PBPhysParticleGetDrag(PBPhysParticle* that);

// Set the drag of the particle 'that' to 'drag'
#if BUILDMODE != 0
inline
#endif
void PBPhysParticleSetDrag(PBPhysParticle* that, float drag);

// Move the particle 'that' over a period of time 'dt'
//  $x(t+dt) = x(t) + v(t)*dt + 0.5*(a(t)-drag*v(t))*dt^2$ 
//  $v(t+dt) = v(t) + (a(t)-drag*v(t))*dt$ 
void PBPhysParticleMove(PBPhysParticle* that, float dt);

// Return true if the particle 'that' is fixed
// Return false else
#if BUILDMODE != 0
inline
#endif
bool PBPhysParticleIsFixed(PBPhysParticle* that);

// Set the fixed flag of the particle 'that' to 'fixed'
#if BUILDMODE != 0
inline

```

```

#endif
void PBPhysParticleSetFixed(PBPhysParticle* that, bool fixed);

// Set the user data of the particle 'that' to 'data'
#if BUILDMODE != 0
inline
#endif
void PBPhysParticleSetData(PBPhysParticle* that, void* data);

// Get the user data of the particle 'that'
#if BUILDMODE != 0
inline
#endif
void* PBPhysParticleData(PBPhysParticle* that);

// Correct the current speed of the two colliding particles 'that' and
// 'tho' under the hypothesis of elastic collision
// If at least one of the particle as a null mass, do nothing
void PBPhysParticleApplyElasticCollision(PBPhysParticle* that,
    PBPhysParticle* tho);

// Return the coefficients of the polynom describing the square of the
// distance between particles 'that' and 'tho'
// Return a vector such as  $\text{dist}^2(t) = v[0] + v[1]t + v[2]t^2$ 
VecFloat3D PBPhysParticleGetDistPoly(PBPhysParticle* that,
    PBPhysParticle* tho);

// ----- PBPhys

// ===== Define =====

// units : meter, second, kilogram
#define PBPHYS_Gn 9.80665
#define PBPHYS_G 6.6740831e-11
#define PBPHYS_DELTAT 0.01

// ===== Data structure =====

typedef struct PBPhys {
    // Dimension of space
    int _dim;
    // Set of particles
    GSetPBPhysParticle _particles;
    // Delta time used in Step()
    float _deltaT;
    // Downward gravity
    float _downGravity;
    // Gravity between particles
    float _gravity;
    // Current time
    float _curTime;
} PBPhys;

// ===== Functions declaration =====

// Create a new PBPhys for space dimension 'dim'
// Default values: _deltaT = PBPHYS_DELTAT, _downGravity = 0.0,
// _gravity = 0.0, _curTime = 0.0
PBPhys* PBPhysCreate(int dim);

// Free memory used by the PBPhys 'that'
void PBPhysFree(PBPhys** that);

```

```

// Return a clone of the PBPhys 'that'
PBPhys* PBPhysClone(PBPhys* that);

// Print the PBPhys 'that' on the stream 'stream'
void PBPhysPrintln(PBPhys* that, FILE* stream);

// Save the PBPhys 'that' on the stream 'stream'
// Return true if we could save the PBPhys
// Return false else
bool PBPhysSave(PBPhys* that, FILE* stream);

// Load the PBPhys 'that' from the stream 'stream'
// Return true if we could load the PBPhys
// Return false else
bool PBPhysLoad(PBPhys** that, FILE* stream);

// Return the space dimension of the PBPhys 'that'
#if BUILDMODE != 0
inline
#endif
int PBPhysGetDim(PBPhys* that);

// Return the set of particles of the PBPhys 'that'
#if BUILDMODE != 0
inline
#endif
GSetPBPhysParticle* PBPhysParticles(PBPhys* that);

// Return the delta t of the PBPhys 'that'
#if BUILDMODE != 0
inline
#endif
float PBPhysGetDeltaT(PBPhys* that);

// Return the current time of the PBPhys 'that'
#if BUILDMODE != 0
inline
#endif
float PBPhysGetCurTime(PBPhys* that);

// Return the downward gravity of the PBPhys 'that'
#if BUILDMODE != 0
inline
#endif
float PBPhysGetDownGravity(PBPhys* that);

// Return the gravity coefficient between particles of the PBPhys 'that'
#if BUILDMODE != 0
inline
#endif
float PBPhysGetGravity(PBPhys* that);

// Return true if the PBPhys 'that' is the same as PBPhys 'tho'
bool PBPhysIsSame(PBPhys* that, PBPhys* tho);

// Set the delta t of the PBPhys 'that' to 'deltaT'
#if BUILDMODE != 0
inline
#endif
void PBPhysSetDeltaT(PBPhys* that, float deltaT);

```



```

// Set the current time of the PBPhys 'that' to 't'
#if BUILDMODE != 0
inline
#endif
void PBPhysSetCurTime(PBPhys* that, float t);

// Set the downward gravity of the PBPhys 'that' to 'gravity'
#if BUILDMODE != 0
inline
#endif
void PBPhysSetDownGravity(PBPhys* that, float gravity);

// Set the gravity coefficient between particles of the PBPhys 'that'
// to 'gravity'
#if BUILDMODE != 0
inline
#endif
void PBPhysSetGravity(PBPhys* that, float gravity);

// Step the PBPhys 'that' by that->_deltaT ignoring collision
void PBPhysNext(PBPhys* that);

// Step the PBPhys 'that' by that->_deltaT managing collision(s)
void PBPhysStep(PBPhys* that);

// Step the PBPhys 'that' by that->_deltaT or until a collision occurred
// If no collision occurred return NULL
// If a collision occurred one can check the collision time with the
// current time that->_curTime, and the returned GSet contains the
// particles wich have collided
GSetPBPhysParticle* PBPhysStepToCollision(PBPhys* that);

// Return the 'iParticle'-th particle of the PBPhys 'that'
#if BUILDMODE != 0
inline
#endif
PBPhysParticle* PBPhysPart(PBPhys* that, int iParticle);

// Get the number of particles of the PBPhys 'that'
#if BUILDMODE != 0
inline
#endif
int PBPhysGetNbParticle(PBPhys* that);

// Add 'nb' particles of shape 'shape' into the PBPhys 'that'
#if BUILDMODE != 0
inline
#endif
void PBPhysAddParticles(PBPhys* that, int nb, ShapoidType shape);

// ===== Polymorphism =====

#define PBPhysParticleSetAccel(Particle, Accel) _Generic(Accel, \
    VecFloat*: _PBPhysParticleSetAccel, \
    VecFloat2D*: _PBPhysParticleSetAccel, \
    VecFloat3D*: _PBPhysParticleSetAccel, \
    default: PBErrInvalidPolymorphism)(Particle, (VecFloat*)(Accel))

#define PBPhysParticleSetSpeed(Particle, Speed) _Generic(Speed, \
    VecFloat*: _PBPhysParticleSetSpeed, \
    VecFloat2D*: _PBPhysParticleSetSpeed, \
    VecFloat3D*: _PBPhysParticleSetSpeed, \

```

```

    default: PBErrInvalidPolymorphism)(Particle, (VecFloat*)(Speed))

#define PBPhysParticleSetPos(Particle, Pos) _Generic(Pos, \
    VecFloat*: _PBPhysParticleSetPos, \
    VecFloat2D*: _PBPhysParticleSetPos, \
    VecFloat3D*: _PBPhysParticleSetPos, \
    default: PBErrInvalidPolymorphism)(Particle, (VecFloat*)(Pos))

#define PBPhysParticleSetSize(Particle, Size) _Generic(Size, \
    VecFloat*: _PBPhysParticleSetSizeVec, \
    float: _PBPhysParticleSetSizeScalar, \
    default: PBErrInvalidPolymorphism)(Particle, Size)

// ===== Inliner =====

#if BUILDMODE != 0
#include "pbphys-inline.c"
#endif

#endif

```

## 3 Code

### 3.1 pbphys.c

```

// ===== PBPHYS.C =====

// ===== Include =====

#include "pbphys.h"
#if BUILDMODE == 0
#include "pbphys-inline.c"
#endif

// ----- PBPhysParticle

// ===== Functions declaration =====

// Return the displacement of the particle from current position to
// the position after dt
VecFloat* PBPhysParticleGetNextDisplacement(PBPhysParticle* that,
    float dt);

// Return the coefficients of the polynom describing the square of the
// distance between two lines passing through 'posA' and 'posB' and
// colinear to 'dirA' and 'dirB' respectively
// Return a vector such as  $\text{dist}^2(t) = v[0] + v[1]t + v[2]t^2$ 
VecFloat3D PBPhysGetDistPoly(VecFloat* posA, VecFloat* dirA,
    VecFloat* posB, VecFloat* dirB);

// ===== Functions implementation =====

// Create a new PBPhysParticle with dimension 'dim' and a 'shapeType'
// shapoid as shape
// Default values: _mass = 0.0, _drag = 0.0, _fixed = false
PBPhysParticle* PBPhysParticleCreate(int dim, ShapoidType shapeType) {
#if BUILDMODE == 0

```

```

    if (dim <= 0) {
        PBPhysErr->_type = PBErrTypeInvalidArg;
        sprintf(PBPhysErr->_msg, "'dim' is invalid (0<%d)", dim);
        PBErrCatch(PBPhysErr);
    }
#endif
    // Allocate memory
    PBPhysParticle *that = PBErrMalloc(PBPhysErr, sizeof(PBPhysParticle));
    // Set properties
    that->_shape = ShapoidCreate(dim, shapeType);
    that->_speed = VecFloatCreate(dim);
    that->_accel = VecFloatCreate(dim);
    that->_sysAccel = VecFloatCreate(dim);
    that->_mass = 0.0;
    that->_drag = 0.0;
    that->_fixed = false;
    that->_data = NULL;
    // Return the new PBPhysParticle
    return that;
}

// Free the memory used by the particle 'that'
void PBPhysParticleFree(PBPhysParticle** that) {
    // Check arguments
    if (that == NULL || *that == NULL)
        // Nothing to do
        return;
    // Free memory
    ShapoidFree(&((*that)->_shape));
    VecFree(&((*that)->_speed));
    VecFree(&((*that)->_accel));
    VecFree(&((*that)->_sysAccel));
    free(*that);
    *that = NULL;
}

// Return a clone of the particle 'that'
PBPhysParticle* PBPhysParticleClone(PBPhysParticle* that) {
    #if BUILDMODE == 0
        if (that == NULL) {
            PBPhysErr->_type = PBErrTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'that' is null");
            PBErrCatch(PBPhysErr);
        }
    #endif
    // Declare the clone
    PBPhysParticle* clone = PBPhysParticleCreate(
        PBPhysParticleGetDim(that), PBPhysParticleGetShapeType(that));
    // Copy properties
    PBPhysParticleSetSpeed(clone, PBPhysParticleSpeed(that));
    PBPhysParticleSetAccel(clone, PBPhysParticleAccel(that));
    PBPhysParticleSetMass(clone, PBPhysParticleGetMass(that));
    PBPhysParticleSetFixed(clone, PBPhysParticleIsFixed(that));
    PBPhysParticleSetDrag(clone,
        PBPhysParticleGetDrag(that));
    VecFloat* center = PBPhysParticleGetPos(that);
    PBPhysParticleSetPos(clone, center);
    VecFree(&center);
    // Return the clone
    return clone;
}

```

```

// Print the particle 'that' on the stream 'stream'
void PBPhysParticlePrintln(PBPhysParticle* that, FILE* stream) {
    #if BUILDMODE == 0
        if (that == NULL) {
            PBPhysErr->_type = PBErrTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'that' is null");
            PBErrCatch(PBPhysErr);
        }
        if (stream == NULL) {
            PBPhysErr->_type = PBErrTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'stream' is null");
            PBErrCatch(PBPhysErr);
        }
    #endif
    ShapoidPrintln(PBPhysParticleShape(that), stream);
    fprintf(stream, "speed: ");
    VecPrint(PBPhysParticleSpeed(that), stream);
    fprintf(stream, "\n");
    fprintf(stream, "accel: ");
    VecPrint(PBPhysParticleAccel(that), stream);
    fprintf(stream, "\n");
    fprintf(stream, "mass: %.3f\n", PBPhysParticleGetMass(that));
    fprintf(stream, "drag: %.3f\n",
        PBPhysParticleGetDrag(that));
    if (PBPhysParticleIsFixed(that))
        fprintf(stream, "fixed\n");
    else
        fprintf(stream, "unfixed\n");
}

// Save the particle 'that' on the stream 'stream'
// Return true if we could save the particle
// Return false else
// If user data is attached to the particle it must be saved by the user
bool PBPhysParticleSave(PBPhysParticle* that, FILE* stream) {
    #if BUILDMODE == 0
        if (that == NULL) {
            PBPhysErr->_type = PBErrTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'that' is null");
            PBErrCatch(PBPhysErr);
        }
        if (stream == NULL) {
            PBPhysErr->_type = PBErrTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'stream' is null");
            PBErrCatch(PBPhysErr);
        }
    #endif
    // Save the shape
    if (!ShapoidSave(PBPhysParticleShape(that), stream))
        return false;
    // Save the speed
    if (!VecSave(PBPhysParticleSpeed(that), stream))
        return false;
    // Save the acceleration
    if (!VecSave(PBPhysParticleAccel(that), stream))
        return false;
    // Save the mass and drag and fixed
    int ret = fprintf(stream, "%f %f %d\n", that->_mass, that->_drag,
        that->_fixed);
    // If we couldn't fprintf
    if (ret < 0)
        return false;
}

```

```

    // Return the success code
    return true;
}

// Load the particle 'that' from the stream 'stream'
// Return true if we could load the particle
// Return false else
// If user data is attached to the particle it must be loaded by the user
bool PBPhysParticleLoad(PBPhysParticle** that, FILE* stream) {
#ifdef BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
    if (stream == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'stream' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    // If the particle is allocated
    if (*that != NULL)
        // Free the memory
        PBPhysParticleFree(that);
    // Allocate memory for a new particle
    *that = PBErrMalloc(PBPhysErr, sizeof(PBPhysParticle));
    (*that)->_shape = NULL;
    (*that)->_speed = NULL;
    (*that)->_accel = NULL;
    // Load the shape
    if (!ShapoidLoad(&((*that)->_shape), stream)) {
        PBPhysParticleFree(that);
        return false;
    }
    // Load the speed
    if (!VecLoad(&((*that)->_speed), stream) ||
        VecGetDim((*that)->_speed) != ShapoidGetDim((*that)->_shape)) {
        PBPhysParticleFree(that);
        return false;
    }
    // Load the accel
    if (!VecLoad(&((*that)->_accel), stream) ||
        VecGetDim((*that)->_accel) != ShapoidGetDim((*that)->_shape)) {
        PBPhysParticleFree(that);
        return false;
    }
    (*that)->_sysAccel = VecFloatCreate(VecGetDim((*that)->_accel));
    // Load the mass and drag and fixed
    int fixed;
    int ret = fscanf(stream, "%f %f %d", &((*that)->_mass),
        &((*that)->_drag), &fixed);
    // If we couldn't fscanf
    if (ret == EOF) {
        PBPhysParticleFree(that);
        return false;
    }
    if (fixed)
        (*that)->_fixed = true;
    else
        (*that)->_fixed = false;
    // Return the success code

```

```

    return true;
}

// Move the particle 'that' over a period of time 'dt'
//  $x(t+dt) = x(t) + v(t)*dt + 0.5*(a(t)-drag*v(t))*dt^2$ 
//  $v(t+dt) = v(t) + (a(t)-drag*v(t))*dt$ 
void PBPhysParticleMove(PBPhysParticle* that, float dt) {
    #if BUILDMODE == 0
        if (that == NULL) {
            PBPhysErr->_type = PBErrTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'that' is null");
            PBErrCatch(PBPhysErr);
        }
    #endif
    if (!PBPhysParticleIsFixed(that)) {
        // Get the displacement
        VecFloat* disp = PBPhysParticleGetNextDisplacement(that, dt);
        // Update the position
        VecOp(ShapoidPos(PBPhysParticleShape(that)), 1.0, disp, 1.0);
        // Update the speed
        VecOp(PBPhysParticleSpeed(that), 1.0,
            PBPhysParticleSpeed(that), -dt * PBPhysParticleGetDrag(that));
        VecOp(PBPhysParticleSpeed(that), 1.0,
            PBPhysParticleAccel(that), dt);
        VecOp(PBPhysParticleSpeed(that), 1.0,
            PBPhysParticleSysAccel(that), dt);
        // Free memory
        VecFree(&disp);
    }
}

// Return the displacement of the particle from current position to
// the position after dt
VecFloat* PBPhysParticleGetNextDisplacement(PBPhysParticle* that,
    float dt) {
    #if BUILDMODE == 0
        if (that == NULL) {
            PBPhysErr->_type = PBErrTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'that' is null");
            PBErrCatch(PBPhysErr);
        }
    #endif
    VecFloat* v = VecGetOp(PBPhysParticleAccel(that), 1.0,
        PBPhysParticleSpeed(that), -1.0 * PBPhysParticleGetDrag(that));
    VecOp(v, 1.0, PBPhysParticleSysAccel(that), 1.0);
    VecOp(v, 0.5 * fsquare(dt), PBPhysParticleSpeed(that), dt);
    return v;
}

// Correct the current speed of the two colliding particles 'that' and
// 'tho' under the hypothesis of elastic collision
// Particles' mass must not be null
void PBPhysParticleApplyElasticCollision(PBPhysParticle* that,
    PBPhysParticle* tho) {
    #if BUILDMODE == 0
        if (that == NULL) {
            PBPhysErr->_type = PBErrTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'that' is null");
            PBErrCatch(PBPhysErr);
        }
        if (tho == NULL) {
            PBPhysErr->_type = PBErrTypeNullPointer;

```

```

        sprintf(PBPhysErr->_msg, "'tho' is null");
        PBErCatch(PBPhysErr);
    }
    if (fabs(PBPhysParticleGetMass(that)) < PBMath_EPSILON) {
        PBPhysErr->_type = PBErrTypeInvalidArg;
        sprintf(PBPhysErr->_msg, "mass of 'that' is null");
        PBErCatch(PBPhysErr);
    }
    if (fabs(PBPhysParticleGetMass(tho)) < PBMath_EPSILON) {
        PBPhysErr->_type = PBErrTypeInvalidArg;
        sprintf(PBPhysErr->_msg, "mass of 'tho' is null");
        PBErCatch(PBPhysErr);
    }
}
#endif

// Get the center of particles
VecFloat* posA = PBPhysParticleGetPos(that);
VecFloat* posB = PBPhysParticleGetPos(tho);
// Get the difference in pos
VecFloat* v = VecGetOp(posA, 1.0, posB, -1.0);
// Get the difference in speed
VecFloat* w = VecGetOp(PBPhysParticleSpeed(that), 1.0,
    PBPhysParticleSpeed(tho), -1.0);
// Get the prod of differences
float prod = VecDotProd(v, w);
// Get the norm of difference in pos
float norm = VecNorm(v);
// Calculate a temporary value for following calculation
float c = 2.0 * prod /
    ((PBPhysParticleGetMass(that) + PBPhysParticleGetMass(tho)) *
    fsquare(norm));
// Update the speed of 'that' if it's not fixed
if (!PBPhysParticleIsFixed(that))
    VecOp(PBPhysParticleSpeed(that), 1.0, v,
        -1.0 * c * PBPhysParticleGetMass(tho));
// Update the speed of 'tho' if it's not fixed
if (!PBPhysParticleIsFixed(tho))
    VecOp(PBPhysParticleSpeed(tho), 1.0, v,
        c * PBPhysParticleGetMass(that));
// Free memory
VecFree(&posA);
VecFree(&posB);
VecFree(&v);
VecFree(&w);
}

// Return the coefficients of the polynom describing the square of the
// distance between particles 'that' and 'tho'
// Return a vector such as dist^2(t)=v[0]+v[1]t+v[2]t^2
VecFloat3D PBPhysParticleGetDistPoly(PBPhysParticle* that,
    PBPhysParticle* tho) {
    #if BUILDMODE == 0
        if (that == NULL) {
            PBPhysErr->_type = PBErrTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'that' is null");
            PBErCatch(PBPhysErr);
        }
        if (tho == NULL) {
            PBPhysErr->_type = PBErrTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'tho' is null");
            PBErCatch(PBPhysErr);
        }
    }
}
#endif

```

```

    VecFloat* posA = PBPhysParticleGetPos(that);
    VecFloat* posB = PBPhysParticleGetPos(tho);
    VecFloat3D ret = PBPhysGetDistPoly(posA, PBPhysParticleSpeed(that),
        posB, PBPhysParticleSpeed(tho));
    VecFree(&posA);
    VecFree(&posB);
    return ret;
}

// ----- PBPhys

// ===== Functions declaration =====

// Calculate the system acceleration of the particle 'part' in the
// PBPhys 'that'
void PBPhysUpdateSysAccel(PBPhys* that, PBPhysParticle* part);

// Return the time to collision between two particles of radius 'rA'
// and 'rB' and the polynom of the square distance between particles
// over time 'distPoly'
float PBPhysGetTimeToHit(float rA, float rB, VecFloat3D* distPoly);

// ===== Functions implementation =====

// Create a new PBPhys for space dimension 'dim'
// Default values: _deltaT = 0.01, _downGravity = 0.0, _gravity = 0.0,
// _curTime = 0.0
PBPhys* PBPhysCreate(int dim) {
#ifdef BUILDMODE == 0
    if (dim <= 0) {
        PBPhysErr->_type = PBErrTypeInvalidArg;
        sprintf(PBPhysErr->_msg, "'dim' is invalid (0<%d)", dim);
        PBErrCatch(PBPhysErr);
    }
#endif
    // Allocate memory
    PBPhys* that = PBErrMalloc(PBPhysErr, sizeof(PBPhys));
    // Set properties
    that->_dim = dim;
    that->_particles = GSetPBPhysParticleCreateStatic();
    that->_deltaT = PBPHYS_DELTAT;
    that->_downGravity = 0.0;
    that->_gravity = false;
    that->_curTime = 0.0;
    // Return the new PBPhys
    return that;
}

// Free memory used by the PBPhys 'that'
void PBPhysFree(PBPhys** that) {
    // Check argument
    if (that == NULL || *that == NULL)
        // Nothing to do
        return;
    // Free memory
    while (PBPhysGetNbParticle(*that) > 0) {
        PBPhysParticle* particle = GSetPop(PBPhysParticles(*that));
        PBPhysParticleFree(&particle);
    }
    free(*that);
    *that = NULL;
}

```



```

// Return a clone of the PBPhys 'that'
PBPhys* PBPhysClone(PBPhys* that) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    // Declare the clone
    PBPhys* clone = PBPhysCreate(PBPhysGetDim(that));
    // Copy the properties
    PBPhysSetGravity(clone, PBPhysGetGravity(that));
    PBPhysSetCurTime(clone, PBPhysGetCurTime(that));
    PBPhysSetDeltaT(clone, PBPhysGetDeltaT(that));
    PBPhysSetDownGravity(clone, PBPhysGetDownGravity(that));
    // Copy the particles
    if (PBPhysGetNbParticle(that) > 0) {
        GSetIterForward iter =
            GSetIterForwardCreateStatic(PBPhysParticles(that));
        do {
            PBPhysParticle* part = GSetIterGet(&iter);
            PBPhysParticle* clonePart = PBPhysParticleClone(part);
            GSetAppend(PBPhysParticles(clone), clonePart);
        } while (GSetIterStep(&iter));
    }
    // Return the clone
    return clone;
}

// Print the PBPhys 'that' on the stream 'stream'
void PBPhysPrintln(PBPhys* that, FILE* stream) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
    if (stream == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'stream' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    fprintf(stream, "dimension: %d\n", PBPhysGetDim(that));
    fprintf(stream, "t: %f\n", PBPhysGetCurTime(that));
    fprintf(stream, "dt: %f\n", PBPhysGetDeltaT(that));
    fprintf(stream, "down gravity: %f\n", PBPhysGetDownGravity(that));
    fprintf(stream, "gravity: %f\n", PBPhysGetGravity(that));
    fprintf(stream, "nb particles: %d\n", PBPhysGetNbParticle(that));
    if (PBPhysGetNbParticle(that) > 0) {
        GSetIterForward iter =
            GSetIterForwardCreateStatic(PBPhysParticles(that));
        int iPart = 0;
        do {
            fprintf(stream, "particle #%d:\n", iPart);
            PBPhysParticle* part = GSetIterGet(&iter);
            PBPhysParticlePrintln(part, stream);
            ++iPart;
        } while (GSetIterStep(&iter));
    }
}

```

```

}

// Save the PBPhys 'that' on the stream 'stream'
// Return true if we could save the PBPhys
// Return false else
bool PBPhysSave(PBPhys* that, FILE* stream) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
    if (stream == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'stream' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    // Save the properties
    int ret = fprintf(stream, "%d %f %f %f %f %d\n",
        that->_dim, that->_curTime, that->_deltaT, that->_downGravity,
        that->_gravity, PBPhysGetNbParticle(that));
    // If we couldn't fprintf
    if (ret < 0)
        return false;
    // Save the particles
    if (PBPhysGetNbParticle(that) > 0) {
        GSetIterForward iter =
            GSetIterForwardCreateStatic(PBPhysParticles(that));
        do {
            PBPhysParticle* part = GSetIterGet(&iter);
            if (!PBPhysParticleSave(part, stream))
                return false;
        } while (GSetIterStep(&iter));
    }
    // Return the success code
    return true;
}

// Load the PBPhys 'that' from the stream 'stream'
// Return true if we could load the PBPhys
// Return false else
bool PBPhysLoad(PBPhys** that, FILE* stream) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
    if (stream == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'stream' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    if (*that != NULL)
        PBPhysFree(that);
    // Load the dimension
    int dim = 0;
    int ret = fscanf(stream, "%d", &dim);
    // If we couldn't fscanf
    if (ret == EOF) {

```

```

        PBPhysFree(that);
        return false;
    }
    // Create the loaded PBPhys
    *that = PBPhysCreate(dim);
    // Load the properties
    int nbPart = 0;
    ret = fscanf(stream, "%f %f %f %f %d",
        &((*that)->_curTime), &((*that)->_deltaT), &((*that)->_downGravity),
        &((*that)->_gravity), &nbPart);
    // If we couldn't fscanf
    if (ret == EOF) {
        PBPhysFree(that);
        return false;
    }
    // Load the particles
    for (int iPart = nbPart; iPart--;) {
        PBPhysParticle* part = NULL;
        if (!PBPhysParticleLoad(&part, stream)) {
            PBPhysFree(that);
            return false;
        }
        GSetAppend(PBPhysParticles(*that), part);
    }
    // Return the success code
    return true;
}

// Step the PBPhys 'that' by that->_deltaT ignoring collision
void PBPhysNext(PBPhys* that) {
    #if BUILDMODE == 0
        if (that == NULL) {
            PBPhysErr->_type = PBErrTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'that' is null");
            PBErrCatch(PBPhysErr);
        }
    #endif
    // If there is particle
    if (PBPhysGetNbParticle(that) > 0) {
        // Loop on particles
        GSetIterForward iter =
            GSetIterForwardCreateStatic(PBPhysParticles(that));
        do {
            PBPhysParticle* part = GSetIterGet(&iter);
            // Calculate the system acceleration of the particle
            PBPhysUpdateSysAccel(that, part);
            // Move the particle
            PBPhysParticleMove(part, PBPhysGetDeltaT(that));
        } while (GSetIterStep(&iter));
    }
    // Update current time
    PBPhysSetCurTime(that, PBPhysGetCurTime(that) + PBPhysGetDeltaT(that));
}

// Calculate the system acceleration of the particle 'part' in the
// PBPhys 'that'
void PBPhysUpdateSysAccel(PBPhys* that, PBPhysParticle* particle) {
    #if BUILDMODE == 0
        if (that == NULL) {
            PBPhysErr->_type = PBErrTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'that' is null");
            PBErrCatch(PBPhysErr);
        }
    #endif
}

```

```

    }
    if (particle == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'particle' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    // If the particle is fixed there is nothing to do
    if (PBPhysParticleIsFixed(particle))
        return;
    // Reset the system acceleration
    VecSetNull(PBPhysParticleSysAccel(particle));
    // If the down gravity is active
    if (fabs(PBPhysGetDownGravity(that)) > PBMath_EPSILON) {
        // Subtract the down gravity to the y axis of the system
        // acceleration
        VecSet(PBPhysParticleSysAccel(particle), 1,
            -1.0 * PBPhysGetDownGravity(that));
    }
    // If the gravity is active
    if (fabs(PBPhysGetGravity(that)) > PBMath_EPSILON) {
        // Get the center pos of the particle
        VecFloat* centerParticle = PBPhysParticleGetPos(particle);
        // Loop on particles
        GSetIterForward iter =
            GSetIterForwardCreateStatic(PBPhysParticles(that));
        do {
            PBPhysParticle* part = GSetIterGet(&iter);
            // If the current particle is not the particle in argument
            if (particle != part) {
                // Get the distance between the two particles
                VecFloat* centerPart = PBPhysParticleGetPos(part);
                float dist = VecDist(centerParticle, centerPart);
                if (fabs(dist) > PBMath_EPSILON) {
                    // Get the magnitude of the attraction
                    float mag = PBPhysGetGravity(that) *
                        PBPhysParticleGetMass(particle) *
                        PBPhysParticleGetMass(part) / fsquare(dist);
                    // Apply the attraction toward the other particle
                    VecOp(centerPart, 1.0, centerParticle, -1.0);
                    VecNormalise(centerPart);
                    VecOp(PBPhysParticleSysAccel(particle), 1.0, centerPart, mag);
                }
                // Free memory
                VecFree(&centerPart);
            }
        } while (GSetIterStep(&iter));
        // Free memory
        VecFree(&centerParticle);
    }
}

// Step the PBPhys 'that' by that->_deltaT managing collision(s)
void PBPhysStep(PBPhys* that) {
    #if BUILDMODE == 0
        if (that == NULL) {
            PBPhysErr->_type = PBErrTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'that' is null");
            PBErrCatch(PBPhysErr);
        }
    #endif
    // Declare a variable to memorize the goal time

```

```

float goalT = PBPhysGetCurTime(that) + PBPhysGetDeltaT(that);
// Declare a variable to memorize the initial deltat
float origDeltaT = PBPhysGetDeltaT(that);
// Loop until we reach the goal time
while (PBPhysGetCurTime(that) < goalT) {
//printf("curt %f goalt %f\n", PBPhysGetCurTime(that), goalT);
// Step until next collision
GSetPBPhysParticle* set = PBPhysStepToCollision(that);
//printf("curt %f goalt %f\n", PBPhysGetCurTime(that), goalT);
// If there has been collision
if (set != NULL) {
//printf("hit\n");
// Manage the collision
PBPhysParticleApplyElasticCollision(
GSetGet(set, 0), GSetGet(set, 1));
// Correct the deltat to reach the initial goal time
PBPhysSetDeltaT(that, goalT - PBPhysGetCurTime(that));
//printf("deltat %f\n", PBPhysGetDeltaT(that));
// Free the set
GSetFree(&set);
}
}
// Reset the initial deltat
PBPhysSetDeltaT(that, origDeltaT);
}

// Step the PBPhys 'that' for that->_deltat or until a collision occurred
// If no collision occurred return NULL
// If a collision occurred one can check the collision time with the
// current time that->_curTime, and the returned GSet contains the
// particles wich have collided
GSetPBPhysParticle* PBPhysStepToCollision(PBPhys* that) {
#ifdef BUILDMODE == 0
if (that == NULL) {
PBPhysErr->_type = PBErrTypeNullPointer;
sprintf(PBPhysErr->_msg, "'that' is null");
PBErrCatch(PBPhysErr);
}
#endif
// Declare a variable to memorize the deltat until next collision
float deltat = PBPhysGetDeltaT(that);
// Declare a set to memorize the colliding particle
GSetPBPhysParticle* setCollision = GSetPBPhysParticleCreate();
// If there is particle
if (PBPhysGetNbParticle(that) > 0) {
// Loop on particles
GSetIterForward iter =
GSetIterForwardCreateStatic(PBPhysParticles(that));
do {
PBPhysParticle* part = GSetIterGet(&iter);
// Calculate the system acceleration of the particle
PBPhysUpdateSysAccel(that, part);
} while (GSetIterStep(&iter));
// If there is at least two particles
if (PBPhysGetNbParticle(that) > 1) {
// Declare a variabe to memorize the inverse of deltat
float invDeltaT = 1.0 / PBPhysGetDeltaT(that);
// Loop on particles once again from the beginning
GSetIterReset(&iter);
do {
PBPhysParticle* part = GSetIterGet(&iter);
// Get the pos of the center of the particle

```

```

VecFloat* posPart = PBPhysParticleGetPos(part);
// Get the displacement vector for the current particle
VecFloat* vPart = PBPhysParticleGetNextDisplacement(part,
    PBPhysGetDeltaT(that));
// Scale to have the displacement per time unit
VecScale(vPart, invDeltaT);
// Get the bounding radius of the particle
float radPart =
    ShapoidGetBoundingRadius(PBPhysParticleShape(part));
// Create a new iterator to loop through following particles
GSetIterForward iterPair = iter;
GSetIterStep(&iterPair);
do {
    PBPhysParticle* pair = GSetIterGet(&iterPair);
    // Get the pos of the center of the particle
    VecFloat* posPair = PBPhysParticleGetPos(pair);
    // Get the displacement vector for the current pair
    VecFloat* vPair = PBPhysParticleGetNextDisplacement(pair,
        PBPhysGetDeltaT(that));
    // Scale to have the displacement per time unit
    VecScale(vPair, invDeltaT);
    // Get the bounding radius of the pair
    float radPair =
        ShapoidGetBoundingRadius(PBPhysParticleShape(pair));
    // Check the pair trajectory to determine at what time they
    // are at the closest and what is this closest distance
    VecFloat3D distPoly = PBPhysGetDistPoly(posPart, vPart,
        posPair, vPair);
    float tNearest = deltata;
    if (fabs(VecGet(&distPoly, 2)) > PBMath_EPSILON)
        tNearest = -0.5 * VecGet(&distPoly, 1) /
            VecGet(&distPoly, 2);
    float distNearest = sqrt(VecGet(&distPoly, 0) +
        tNearest * VecGet(&distPoly, 1) +
        fsquare(tNearest) * VecGet(&distPoly, 2));
    // If there is an impact in future
    if (tNearest > 0.0 && distNearest < radPart + radPair) {
        // Get the exact time at which particles hit
        float tHit = PBPhysGetTimeToHit(radPart, radPair, &distPoly);
        // If the time at hit is sooner than current delta
        if (tHit < deltata) {
            // Remove the eventual previous colliding particles
            GSetFlush(setCollision);
            // Add the colliding particles
            GSetAppend(setCollision, part);
            GSetAppend(setCollision, pair);
            // Update the time at hit
            deltata = tHit;
        }
    }
    // Free memory
    VecFree(&vPair);
    VecFree(&posPair);
} while (GSetIterStep(&iterPair));
// Free memory
VecFree(&posPart);
VecFree(&vPart);
} while (GSetIterStep(&iter) && !GSetIterIsLast(&iter));
}
// Move the particles
GSetIterReset(&iter);
do {

```

```

        PBPhysParticle* part = GSetIterGet(&iter);
        // Move the particle
        PBPhysParticleMove(part, deltat);
    } while (GSetIterStep(&iter));
}
// Update current time
PBPhysSetCurTime(that, PBPhysGetCurTime(that) + deltat);
// If the set of collision is empty free it
if (GSetNbElem(setCollision) == 0)
    GSetFree(&setCollision);
// Return the set of colliding particles
return setCollision;
}

// Return the time to collision between two particles of radius 'rA'
// and 'rB' and the polynom of the square distance between particles
// over time 'distPoly'
float PBPhysGetTimeToHit(float rA, float rB, VecFloat3D* distPoly) {
    float dist = fsquare(rA + rB);
    float tHit = (-1.0 * VecGet(distPoly, 1) -
        sqrt(fsquare(VecGet(distPoly, 1)) - 4.0 * VecGet(distPoly, 2) *
            (VecGet(distPoly, 0) - dist))) / (2.0 * VecGet(distPoly, 2));
    return tHit;
}

// Return the coefficients of the polynom describing the square of the
// distance between two lines passing through 'posA' and 'posB' and
// colinear to 'dirA' and 'dirB' respectively
// Return a vector such as  $\text{dist}^2(t) = v[0] + v[1]t + v[2]t^2$ 
VecFloat3D PBPhysGetDistPoly(VecFloat* posA, VecFloat* dirA,
    VecFloat* posB, VecFloat* dirB) {
    #if BUILDMODE == 0
        if (posA == NULL) {
            PBPhysErr->_type = PBErrTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'posA' is null");
            PBErrCatch(PBPhysErr);
        }
        if (posB == NULL) {
            PBPhysErr->_type = PBErrTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'posB' is null");
            PBErrCatch(PBPhysErr);
        }
        if (dirA == NULL) {
            PBPhysErr->_type = PBErrTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'dirA' is null");
            PBErrCatch(PBPhysErr);
        }
        if (dirB == NULL) {
            PBPhysErr->_type = PBErrTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'dirB' is null");
            PBErrCatch(PBPhysErr);
        }
    #endif
    // Declare the vector result
    VecFloat3D res = VecFloatCreateStatic3D();
    // Loop on dimensions
    for (int iDim = VecGetDim(posA); iDim--;) {
        VecSetAdd(&res, 0,
            fsquare(VecGet(posA, iDim) - VecGet(posB, iDim)));
        VecSetAdd(&res, 1,
            (VecGet(posA, iDim) - VecGet(posB, iDim)) *
            (VecGet(dirA, iDim) - VecGet(dirB, iDim)));
    }
}

```

```

        VecSetAdd(&res, 2,
            fsquare(VecGet(dirA, iDim) - VecGet(dirB, iDim)));
    }
    VecSet(&res, 1, VecGet(&res, 1) * 2.0);
    // Return the result
    return res;
}

// Return true if the PBPhys 'that' is the same as PBPhys 'tho'
bool PBPhysIsSame(PBPhys* that, PBPhys* tho) {
    #if BUILDMODE == 0
        if (that == NULL) {
            PBPhysErr->_type = PBErrTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'that' is null");
            PBErrCatch(PBPhysErr);
        }
    #endif
    if (that->_dim != tho->_dim ||
        !ISEQUALF(that->_deltaT, tho->_deltaT) ||
        !ISEQUALF(that->_curTime, tho->_curTime) ||
        !ISEQUALF(that->_downGravity, tho->_downGravity) ||
        that->_gravity != tho->_gravity ||
        PBPhysGetNbParticle(that) != PBPhysGetNbParticle(tho))
        return false;
    if (PBPhysGetNbParticle(that) > 0) {
        GSetIterForward iterA =
            GSetIterForwardCreateStatic(PBPhysParticles(that));
        GSetIterForward iterB =
            GSetIterForwardCreateStatic(PBPhysParticles(tho));
        do {
            PBPhysParticle* partA = GSetIterGet(&iterA);
            PBPhysParticle* partB = GSetIterGet(&iterB);
            if (!PBPhysParticleIsSame(partA, partB))
                return false;
        } while (GSetIterStep(&iterA) && GSetIterStep(&iterB));
    }
    return true;
}

```

## 3.2 pbphys-inline.c

```

// ===== PBPHYS-INLINE.C =====

// ----- PBPhysParticle

// ===== Functions implementation =====

// Return the dimension of the particle 'that'
#if BUILDMODE != 0
inline
#endif
int PBPhysParticleGetDim(PBPhysParticle* that) {
    #if BUILDMODE == 0
        if (that == NULL) {
            PBPhysErr->_type = PBErrTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'that' is null");
            PBErrCatch(PBPhysErr);
        }
    #endif
}

```



```

    return ShapoidGetDim(that->_shape);
}

// Return the shape type of the particle 'that'
#if BUILDMODE != 0
inline
#endif
ShapoidType PBPhysParticleGetShapeType(PBPhysParticle* that) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    return ShapoidGetType(that->_shape);
}

// Return the shape of the particle 'that'
#if BUILDMODE != 0
inline
#endif
Shapoid* PBPhysParticleShape(PBPhysParticle* that) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    return that->_shape;
}

// Return the 'iAxis'-th axis of the shape of the particle 'that'
#if BUILDMODE != 0
inline
#endif
VecFloat* PBPhysParticleAxis(PBPhysParticle* that, int iAxis) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
    if (iAxis < 0 || iAxis >= PBPhysParticleGetDim(that)) {
        PBPhysErr->_type = PBErrTypeInvalidArg;
        sprintf(PBPhysErr->_msg, "'iAxis' is invalid (0<=%d<%d)",
            iAxis, PBPhysParticleGetDim(that));
        PBErrCatch(PBPhysErr);
    }
#endif
    return ShapoidAxis(PBPhysParticleShape(that), iAxis);
}

// Return the speed of the particle 'that'
#if BUILDMODE != 0
inline
#endif
VecFloat* PBPhysParticleSpeed(PBPhysParticle* that) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;

```

```

        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErCatch(PBPhysErr);
    }
#endif
    return that->_speed;
}

// Return the acceleration of the particle 'that'
#if BUILDMODE != 0
inline
#endif
VecFloat* PBPhysParticleAccel(PBPhysParticle* that) {
    if BUILDMODE == 0
        if (that == NULL) {
            PBPhysErr->_type = PBErTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'that' is null");
            PBErCatch(PBPhysErr);
        }
    #endif
    return that->_accel;
}

// Return the sysAccel of the particle 'that'
#if BUILDMODE != 0
inline
#endif
VecFloat* PBPhysParticleSysAccel(PBPhysParticle* that) {
    if BUILDMODE == 0
        if (that == NULL) {
            PBPhysErr->_type = PBErTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'that' is null");
            PBErCatch(PBPhysErr);
        }
    #endif
    return that->_sysAccel;
}

// Return the position of the center of the particle 'that'
#if BUILDMODE != 0
inline
#endif
VecFloat* PBPhysParticleGetPos(PBPhysParticle* that) {
    if BUILDMODE == 0
        if (that == NULL) {
            PBPhysErr->_type = PBErTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'that' is null");
            PBErCatch(PBPhysErr);
        }
    #endif
    return ShapoidGetCenter(that->_shape);
}

// Set the speed of the particle 'that' to 'speed'
// If the particle is fixed do nothing
#if BUILDMODE != 0
inline
#endif
void _PBPhysParticleSetSpeed(PBPhysParticle* that, VecFloat* speed) {
    if BUILDMODE == 0
        if (that == NULL) {
            PBPhysErr->_type = PBErTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'that' is null");
        }
    #endif
}

```

```

        PBErCatch(PBPhysErr);
    }
    if (speed == NULL) {
        PBPhysErr->_type = PBErTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'speed' is null");
        PBErCatch(PBPhysErr);
    }
    if (VecGetDim(speed) != PBPhysParticleGetDim(that)) {
        PBPhysErr->_type = PBErTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'speed' 's dimension is invalid (%d=%d)",
            VecGetDim(speed), PBPhysParticleGetDim(that));
        PBErCatch(PBPhysErr);
    }
#endif
    if (!PBPhysParticleIsFixed(that))
        VecCopy(that->_speed, speed);
}

// Set the acceleration of the particle 'that' to 'accel'
// If the particle is fixed do nothing
#if BUILDMODE != 0
inline
#endif
void _PBPhysParticleSetAccel(PBPhysParticle* that, VecFloat* accel) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErCatch(PBPhysErr);
    }
    if (accel == NULL) {
        PBPhysErr->_type = PBErTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'accel' is null");
        PBErCatch(PBPhysErr);
    }
    if (VecGetDim(accel) != PBPhysParticleGetDim(that)) {
        PBPhysErr->_type = PBErTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'accel' 's dimension is invalid (%d=%d)",
            VecGetDim(accel), PBPhysParticleGetDim(that));
        PBErCatch(PBPhysErr);
    }
#endif
    if (!PBPhysParticleIsFixed(that))
        VecCopy(that->_accel, accel);
}

// Set the position of the center of the particle 'that' to 'pos'
#if BUILDMODE != 0
inline
#endif
void _PBPhysParticleSetPos(PBPhysParticle* that, VecFloat* pos) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErCatch(PBPhysErr);
    }
    if (pos == NULL) {
        PBPhysErr->_type = PBErTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'pos' is null");
        PBErCatch(PBPhysErr);
    }
}

```

```

    if (VecGetDim(pos) != PBPhysParticleGetDim(that)) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'pos' 's dimension is invalid (%d=%d)",
            VecGetDim(pos), PBPhysParticleGetDim(that));
        PBErrCatch(PBPhysErr);
    }
#endif
    ShapoidSetCenterPos(PBPhysParticleShape(that), pos);
}

// Return true if the particle 'that' is the same is the particle 'tho'
// Return false else
// User data is not compared
#if BUILDMODE != 0
inline
#endif
bool PBPhysParticleIsSame(PBPhysParticle* that, PBPhysParticle* tho) {
    #if BUILDMODE == 0
        if (that == NULL) {
            PBPhysErr->_type = PBErrTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'that' is null");
            PBErrCatch(PBPhysErr);
        }
        if (tho == NULL) {
            PBPhysErr->_type = PBErrTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'tho' is null");
            PBErrCatch(PBPhysErr);
        }
    #endif
    if (!ShapoidIsEqual(PBPhysParticleShape(that),
        PBPhysParticleShape(tho)) ||
        !VecIsEqual(PBPhysParticleSpeed(that), PBPhysParticleSpeed(tho)) ||
        !VecIsEqual(PBPhysParticleAccel(that), PBPhysParticleAccel(tho)) ||
        !ISEQUALF(PBPhysParticleGetMass(that), PBPhysParticleGetMass(tho)) ||
        PBPhysParticleIsFixed(that) != PBPhysParticleIsFixed(tho))
        return false;
    return true;
}

// Set the shape size of the particle 'that' to 'size'
#if BUILDMODE != 0
inline
#endif
void _PBPhysParticleSetSizeVec(PBPhysParticle* that, VecFloat* size) {
    #if BUILDMODE == 0
        if (that == NULL) {
            PBPhysErr->_type = PBErrTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'that' is null");
            PBErrCatch(PBPhysErr);
        }
        if (size == NULL) {
            PBPhysErr->_type = PBErrTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'size' is null");
            PBErrCatch(PBPhysErr);
        }
        if (VecGetDim(size) != PBPhysParticleGetDim(that)) {
            PBPhysErr->_type = PBErrTypeNullPointer;
            sprintf(PBPhysErr->_msg, "'size' 's dimension is invalid (%d=%d)",
                VecGetDim(size), PBPhysParticleGetDim(that));
            PBErrCatch(PBPhysErr);
        }
    #endif
}

```

```

    for (int iAxis = PBPhysParticleGetDim(that); iAxis--;) {
        VecFloat* axis = ShapoidAxis(PBPhysParticleShape(that), iAxis);
        VecScale(axis, VecGet(size, iAxis) / VecNorm(axis));
    }
}

#if BUILDMODE != 0
inline
#endif
void _PBPhysParticleSetSizeScalar(PBPhysParticle* that, float size) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    for (int iAxis = PBPhysParticleGetDim(that); iAxis--;) {
        VecFloat* axis = ShapoidAxis(PBPhysParticleShape(that), iAxis);
        VecScale(axis, size / VecNorm(axis));
    }
}

// Return the mass of the particle 'that'
#if BUILDMODE != 0
inline
#endif
float PBPhysParticleGetMass(PBPhysParticle* that) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    return that->_mass;
}

// Set the mass of the particle 'that' to 'mass'
#if BUILDMODE != 0
inline
#endif
void PBPhysParticleSetMass(PBPhysParticle* that, float mass) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    that->_mass = mass;
}

// Return the drag of the particle 'that'
#if BUILDMODE != 0
inline
#endif
float PBPhysParticleGetDrag(PBPhysParticle* that) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
    }
#endif
}

```

```

        PBErrCatch(PBPhysErr);
    }
#endif
    return that->_drag;
}

// Set the drag of the particle 'that' to 'drag'
#if BUILDMODE != 0
inline
#endif
void PBPhysParticleSetDrag(PBPhysParticle* that, float drag) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    that->_drag = drag;
}

// Return true if the particle 'that' is fixed
// Return false else
#if BUILDMODE != 0
inline
#endif
bool PBPhysParticleIsFixed(PBPhysParticle* that) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    return that->_fixed;
}

// Set the fixed flag of the particle 'that' to 'fixed'
#if BUILDMODE != 0
inline
#endif
void PBPhysParticleSetFixed(PBPhysParticle* that, bool fixed) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    that->_fixed = fixed;
    if (fixed) {
        VecSetNull(that->_speed);
        VecSetNull(that->_accel);
    }
}

// Set the user data of the particle 'that' to 'data'
#if BUILDMODE != 0
inline
#endif
void PBPhysParticleSetData(PBPhysParticle* that, void* data) {
#if BUILDMODE == 0

```

```

    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    that->_data = data;
}

// Get the user data of the particle 'that'
#if BUILDMODE != 0
inline
#endif
void* PBPhysParticleData(PBPhysParticle* that) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    return that->_data;
}

// ----- PBPhys

// ===== Functions implementation =====

// Return the space dimension of the PBPhys 'that'
#if BUILDMODE != 0
inline
#endif
int PBPhysGetDim(PBPhys* that) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    return that->_dim;
}

// Return the set of particles of the PBPhys 'that'
#if BUILDMODE != 0
inline
#endif
GSetPBPhysParticle* PBPhysParticles(PBPhys* that) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    return &(that->_particles);
}

// Return the delta t of the PBPhys 'that'
#if BUILDMODE != 0
inline
#endif

```

```

float PBPhysGetDeltaT(PBPhys* that) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    return that->_deltaT;
}

// Return the current time of the PBPhys 'that'
#if BUILDMODE != 0
inline
#endif
float PBPhysGetCurTime(PBPhys* that) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    return that->_curTime;
}

// Return the downward gravity of the PBPhys 'that'
#if BUILDMODE != 0
inline
#endif
float PBPhysGetDownGravity(PBPhys* that) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    return that->_downGravity;
}

// Return the gravity coefficient between particles of the PBPhys 'that'
#if BUILDMODE != 0
inline
#endif
float PBPhysGetGravity(PBPhys* that) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    return that->_gravity;
}

// Set the delta t of the PBPhys 'that' to 'deltaT'
#if BUILDMODE != 0
inline
#endif
void PBPhysSetDeltaT(PBPhys* that, float deltaT) {
#if BUILDMODE == 0

```



```

    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    that->_deltaT = deltaT;
}

// Set the current time of the PBPhys 'that' to 't'
#if BUILDMODE != 0
inline
#endif
void PBPhysSetCurTime(PBPhys* that, float t) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    that->_curTime = t;
}

// Set the downward gravity of the PBPhys 'that' to 'gravity'
#if BUILDMODE != 0
inline
#endif
void PBPhysSetDownGravity(PBPhys* that, float gravity) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    that->_downGravity = gravity;
}

// Set the gravity coefficient between particles of the PBPhys 'that'
// to 'gravity'
#if BUILDMODE != 0
inline
#endif
void PBPhysSetGravity(PBPhys* that, float gravity) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErrTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErrCatch(PBPhysErr);
    }
#endif
    that->_gravity = gravity;
}

// Return the 'iParticle'-th particle of the PBPhys 'that'
#if BUILDMODE != 0
inline
#endif
PBPhysParticle* PBPhysPart(PBPhys* that, int iParticle) {
#if BUILDMODE == 0
    if (that == NULL) {

```

```

    PBPhysErr->_type = PBErTypeNullPointer;
    sprintf(PBPhysErr->_msg, "'that' is null");
    PBErCatch(PBPhysErr);
}
if (iParticle < 0 || iParticle >= PBPhysGetNbParticle(that)) {
    PBPhysErr->_type = PBErTypeInvalidArg;
    sprintf(PBPhysErr->_msg, "'iParticle' is invalid (0<=%d<%d)",
        iParticle, PBPhysGetNbParticle(that));
    PBErCatch(PBPhysErr);
}
#endif
return GSetGet(&(that->_particles), iParticle);
}

// Get the number of particles of the PBPhys 'that'
#if BUILDMODE != 0
inline
#endif
int PBPhysGetNbParticle(PBPhys* that) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErCatch(PBPhysErr);
    }
#endif
    return GSetNbElem(&(that->_particles));
}

// Add 'nb' particles of shape 'shape' into the PBPhys 'that'
#if BUILDMODE != 0
inline
#endif
void PBPhysAddParticles(PBPhys* that, int nb, ShapoidType shape) {
#if BUILDMODE == 0
    if (that == NULL) {
        PBPhysErr->_type = PBErTypeNullPointer;
        sprintf(PBPhysErr->_msg, "'that' is null");
        PBErCatch(PBPhysErr);
    }
    if (nb <= 0) {
        PBPhysErr->_type = PBErTypeInvalidArg;
        sprintf(PBPhysErr->_msg, "'nb' is invalid (0<%d)", nb);
        PBErCatch(PBPhysErr);
    }
#endif
    for (int iParticle = nb; iParticle--;) {
        PBPhysParticle* particle =
            PBPhysParticleCreate(PBPhysGetDim(that), shape);
        GSetAppend(&(that->_particles), particle);
    }
}

```

## 4 Makefile

```

#directory
PBERRDIR=../PBEr
SHAPOIDDIR=../Shapoid
PBMATHDIR=../PBMath

```

```

GSETDIR=../GSet

# Build mode
# 0: development (max safety, no optimisation)
# 1: release (min safety, optimisation)
# 2: fast and furious (no safety, optimisation)
BUILDMODE=0

include $(PBERRDIR)/Makefile.inc

INCPATH=-I./ -I$(PBERRDIR)/ -I$(PBATHDIR)/ -I$(GSETDIR)/ -I$(SHAPOIDDIR)/
BUILDOPTIONS=$(BUILDPARAM) $(INCPATH)

# compiler
COMPILER=gcc

#rules
all : main

main: main.o pberr.o pbphys.o shapoid.o pbmath.o gset.o Makefile
$(COMPILER) main.o pberr.o shapoid.o pbmath.o gset.o pbphys.o $(LINKOPTIONS) -o main

main.o : main.c $(PBERRDIR)/pberr.h pbphys.h pbphys-inline.c Makefile
$(COMPILER) $(BUILDOPTIONS) -c main.c

pbphys.o : pbphys.c pbphys.h pbphys-inline.c Makefile $(SHAPOIDDIR)/shapoid.h $(SHAPOIDDIR)/shapoid-inline.c
$(COMPILER) $(BUILDOPTIONS) -c pbphys.c

pberr.o : $(PBERRDIR)/pberr.c $(PBERRDIR)/pberr.h Makefile
$(COMPILER) $(BUILDOPTIONS) -c $(PBERRDIR)/pberr.c

shapoid.o : $(SHAPOIDDIR)/shapoid.c $(SHAPOIDDIR)/shapoid.h $(SHAPOIDDIR)/shapoid-inline.c $(PBATHDIR)/pbmath.h $(PBATHDIR)/pbmath-inline.c
$(COMPILER) $(BUILDOPTIONS) -c $(SHAPOIDDIR)/shapoid.c

pbmath.o : $(PBATHDIR)/pbmath.c $(PBATHDIR)/pbmath-inline.c $(PBATHDIR)/pbmath.h Makefile $(PBERRDIR)/pberr.h
$(COMPILER) $(BUILDOPTIONS) -c $(PBATHDIR)/pbmath.c

gset.o : $(GSETDIR)/gset.c $(GSETDIR)/gset-inline.c $(GSETDIR)/gset.h Makefile $(PBERRDIR)/pberr.h
$(COMPILER) $(BUILDOPTIONS) -c $(GSETDIR)/gset.c

clean :
rm -rf *.o main

valgrind :
valgrind -v --track-origins=yes --leak-check=full --gen-suppressions=yes --show-leak-kinds=all ./main

unitTest :
main > unitTest.txt; diff unitTest.txt unitTestRef.txt

```

## 5 Unit tests

```

#include <stdlib.h>
#include <stdio.h>
#include <time.h>
#include <string.h>
#include <time.h>
#include <unistd.h>
#include <sys/time.h>
#include "pberr.h"

```

```

#include "pbphys.h"

#define RANDOMSEED 0

void UnitTestPBPhysParticleCreateFreePrint() {
    PBPhysParticle* particle = PBPhysParticleCreate(2,
        ShapoidTypeSpheroid);
    if (particle == NULL ||
        particle->_shape == NULL ||
        particle->_speed == NULL ||
        particle->_accel == NULL ||
        particle->_fixed == true ||
        ISEQUALF(particle->_mass, 0.0) == false ||
        ISEQUALF(particle->_drag, 0.0) == false ||
        VecGetDim(particle->_speed) != 2 ||
        VecGetDim(particle->_accel) != 2 ||
        ShapoidGetDim(particle->_shape) != 2 ||
        ShapoidGetType(particle->_shape) != ShapoidTypeSpheroid) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysParticleCreate failed");
        PBErrCatch(PBPhysErr);
    }
    PBPhysParticlePrintln(particle, stdout);
    PBPhysParticleFree(&particle);
    if (particle != NULL) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysParticleFree failed");
        PBErrCatch(PBPhysErr);
    }
    printf("UnitTestPBPhysParticleCreateFreePrint OK\n");
}

void UnitTestPBPhysParticleGetSet() {
    int dim = 2;
    ShapoidType type = ShapoidTypeSpheroid;
    PBPhysParticle* particle = PBPhysParticleCreate(dim, type);
    if (PBPhysParticleGetDim(particle) != dim) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysParticleGetDim failed");
        PBErrCatch(PBPhysErr);
    }
    if (PBPhysParticleGetShapeType(particle) != type) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysParticleGetShapeType failed");
        PBErrCatch(PBPhysErr);
    }
    if (PBPhysParticleShape(particle) != particle->_shape) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysParticleShape failed");
        PBErrCatch(PBPhysErr);
    }
    if (PBPhysParticleSpeed(particle) != particle->_speed) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysParticleSpeed failed");
        PBErrCatch(PBPhysErr);
    }
    if (PBPhysParticleAccel(particle) != particle->_accel) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysParticleAccel failed");
        PBErrCatch(PBPhysErr);
    }
    if (PBPhysParticleIsFixed(particle) != particle->_fixed) {

```

```

    PBPhysErr->_type = PBErrTypeUnitTestFailed;
    sprintf(PBPhysErr->_msg, "PBPhysParticleIsFixed failed");
    PBErrCatch(PBPhysErr);
}
VecFloat2D v = VecFloatCreateStatic2D();
VecSet(&v, 0, 2.0); VecSet(&v, 1, 3.0);
PBPhysParticleSetSpeed(particle, &v);
if (VecIsEqual(PBPhysParticleSpeed(particle), &v) == false) {
    PBPhysErr->_type = PBErrTypeUnitTestFailed;
    sprintf(PBPhysErr->_msg, "PBPhysParticleSetSpeed failed");
    PBErrCatch(PBPhysErr);
}
VecSet(&v, 0, 4.0); VecSet(&v, 1, 5.0);
PBPhysParticleSetPos(particle, &v);
VecFloat* pos = PBPhysParticleGetPos(particle);
if (VecIsEqual(pos, &v) == false) {
    PBPhysErr->_type = PBErrTypeUnitTestFailed;
    sprintf(PBPhysErr->_msg, "PBPhysParticleSetPos failed");
    PBErrCatch(PBPhysErr);
}
VecFree(&pos);
VecSet(&v, 0, 6.0); VecSet(&v, 1, 7.0);
PBPhysParticleSetAccel(particle, &v);
if (VecIsEqual(PBPhysParticleAccel(particle), &v) == false) {
    PBPhysErr->_type = PBErrTypeUnitTestFailed;
    sprintf(PBPhysErr->_msg, "PBPhysParticleSetAccel failed");
    PBErrCatch(PBPhysErr);
}
for (int iAxis = dim; iAxis--;)
    if (PBPhysParticleAxis(particle, iAxis) !=
        ShapoidAxis(PBPhysParticleShape(particle), iAxis)) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysParticleAxis failed");
        PBErrCatch(PBPhysErr);
    }
PBPhysParticleSetSize(particle, (VecFloat*)&v);
for (int iAxis = dim; iAxis--;)
    if (!ISEQUALF(VecNorm(PBPhysParticleAxis(particle, iAxis)),
        VecGet(&v, iAxis))) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysParticleSetSize failed");
        PBErrCatch(PBPhysErr);
    }
float size = 0.5;
PBPhysParticleSetSize(particle, size);
for (int iAxis = dim; iAxis--;)
    if (!ISEQUALF(VecNorm(PBPhysParticleAxis(particle, iAxis)), size)) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysParticleSetSize failed");
        PBErrCatch(PBPhysErr);
    }
float mass = 0.1;
PBPhysParticleSetMass(particle, mass);
if (!ISEQUALF(particle->_mass, mass)) {
    PBPhysErr->_type = PBErrTypeUnitTestFailed;
    sprintf(PBPhysErr->_msg, "PBPhysParticleSetMass failed");
    PBErrCatch(PBPhysErr);
}
if (!ISEQUALF(PBPhysParticleGetMass(particle), mass)) {
    PBPhysErr->_type = PBErrTypeUnitTestFailed;
    sprintf(PBPhysErr->_msg, "PBPhysParticleGetMass failed");
    PBErrCatch(PBPhysErr);
}

```

```

    }
    float drag = 0.2;
    PBPhysParticleSetDrag(particle, drag);
    if (!ISEQUALF(particle->_drag, drag)) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysParticleSetDrag failed");
        PBErrCatch(PBPhysErr);
    }
    if (!ISEQUALF(PBPhysParticleGetDrag(particle), drag)) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysParticleGetDrag failed");
        PBErrCatch(PBPhysErr);
    }
    PBPhysParticleSetFixed(particle, true);
    if (PBPhysParticleIsFixed(particle) != true) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysParticleSetFixed failed");
        PBErrCatch(PBPhysErr);
    }
    char data[2];
    particle->_data = data;
    if (PBPhysParticleData(particle) != data) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysParticleData failed");
        PBErrCatch(PBPhysErr);
    }
    PBPhysParticleSetData(particle, data + 1);
    if (PBPhysParticleData(particle) != data + 1) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysParticleSetData failed");
        PBErrCatch(PBPhysErr);
    }
    PBPhysParticleFree(&particle);
    printf("UnitTestPBPhysParticleGetSet OK\n");
}

void UnitTestPBPhysParticleCloneIsSame() {
    PBPhysParticle* particle = PBPhysParticleCreate(2,
        ShapoidTypeSpheroid);
    VecFloat2D v = VecFloatCreateStatic2D();
    VecSet(&v, 0, 2.0); VecSet(&v, 1, 3.0);
    PBPhysParticleSetPos(particle, &v);
    VecFloat2D w = VecFloatCreateStatic2D();
    VecSet(&w, 0, 4.0); VecSet(&w, 1, 5.0);
    PBPhysParticleSetSpeed(particle, &w);
    VecSet(&w, 0, 6.0); VecSet(&w, 1, 7.0);
    PBPhysParticleSetAccel(particle, &w);
    PBPhysParticle* clone = PBPhysParticleClone(particle);
    if (PBPhysParticleIsSame(clone, particle) == false) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysParticleClone failed");
        PBErrCatch(PBPhysErr);
    }
    VecSet(&w, 0, 1.0); VecSet(&w, 1, 5.0);
    PBPhysParticleSetSpeed(particle, &w);
    if (PBPhysParticleIsSame(clone, particle) == true) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysParticleIsSame failed");
        PBErrCatch(PBPhysErr);
    }
    PBPhysParticleFree(&particle);
    PBPhysParticleFree(&clone);
}

```

```

    printf("UnitTestPBPhysParticleCloneIsSame OK\n");
}

void UnitTestPBPhysParticleLoadSave() {
    PBPhysParticle* particle = PBPhysParticleCreate(2,
        ShapoidTypeSpheroid);
    VecFloat2D v = VecFloatCreateStatic2D();
    VecSet(&v, 0, 2.0); VecSet(&v, 1, 3.0);
    PBPhysParticleSetPos(particle, &v);
    VecFloat2D w = VecFloatCreateStatic2D();
    VecSet(&w, 0, 4.0); VecSet(&w, 1, 5.0);
    PBPhysParticleSetSpeed(particle, &w);
    VecSet(&w, 0, 6.0); VecSet(&w, 1, 7.0);
    PBPhysParticleSetAccel(particle, &w);
    PBPhysParticleSetMass(particle, 8.0);
    FILE* fd = fopen("./particle.txt", "w");
    if (PBPhysParticleSave(particle, fd) == false) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysParticleSave failed");
        PBErrCatch(PBPhysErr);
    }
    fclose(fd);
    fd = fopen("./particle.txt", "r");
    PBPhysParticle* loaded = PBPhysParticleCreate(2,
        ShapoidTypeSpheroid);
    if (PBPhysParticleLoad(&loaded, fd) == false ||
        PBPhysParticleIsSame(loaded, particle) == false) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysParticleLoad failed");
        PBErrCatch(PBPhysErr);
    }
    fclose(fd);
    PBPhysParticleFree(&loaded);
    PBPhysParticleFree(&particle);
    printf("UnitTestPBPhysParticleLoadSave OK\n");
}

void UnitTestPBPhysParticleAccelMove() {
    PBPhysParticle* particle = PBPhysParticleCreate(2,
        ShapoidTypeSpheroid);
    VecFloat2D v = VecFloatCreateStatic2D();
    VecSet(&v, 0, 1.0); VecSet(&v, 1, -0.5);
    PBPhysParticleSetAccel(particle, &v);
    float dt = 0.1;
    float checkA[20] = {
        0.005000, -0.002500, 0.020000, -0.010000, 0.045000, -0.022500, 0.080000,
        -0.040000, 0.125000, -0.062500, 0.180000, -0.090000, 0.245000, -0.122500,
        0.320000, -0.160000, 0.405000, -0.202500, 0.500000, -0.250000};
    VecFloat* pos = ShapoidPos(PBPhysParticleShape(particle));
    for (int i = 0; i < 10; ++i) {
        PBPhysParticleMove(particle, dt);
        if (ISEQUALF(VecGet(PBPhysParticleSpeed(particle), 0),
            (float)(i + 1) * dt) == false ||
            ISEQUALF(VecGet(PBPhysParticleSpeed(particle), 1),
            (float)(i + 1) * dt * -0.5) == false) {
            PBPhysErr->_type = PBErrTypeUnitTestFailed;
            sprintf(PBPhysErr->_msg, "PBPhysParticleMove failed");
            PBErrCatch(PBPhysErr);
        }
        if (ISEQUALF(VecGet(pos, 0), checkA[2 * i]) == false ||
            ISEQUALF(VecGet(pos, 1), checkA[2 * i + 1]) == false) {
            PBPhysErr->_type = PBErrTypeUnitTestFailed;
        }
    }
}

```

```

        sprintf(PBPhysErr->_msg, "PBPhysParticleMove failed");
        PBErCatch(PBPhysErr);
    }
}
float drag = 0.1;
PBPhysParticleSetDrag(particle, drag);
VecSetNull(pos);
VecSetNull(PBPhysParticleSpeed(particle));
float checkC[20] = {
    0.100000,-0.050000,0.199000,-0.099500,0.297010,-0.148505,0.394040,
    -0.197020,0.490099,-0.245050,0.585199,-0.292599,0.679347,-0.339673,
    0.772553,-0.386277,0.864828,-0.432414,0.956179,-0.478090};
float checkD[20] = {
    0.005000,-0.002500,0.019950,-0.009975,0.044751,-0.022375,0.079303,
    -0.039651,0.123510,-0.061755,0.177275,-0.088637,0.240502,-0.120251,
    0.313097,-0.156549,0.394966,-0.197483,0.486017,-0.243008};
for (int i = 0; i < 10; ++i) {
    PBPhysParticleMove(particle, dt);
    if (ISEQUALF(VecGet(PBPhysParticleSpeed(particle), 0),
        checkC[2 * i]) == false ||
        ISEQUALF(VecGet(PBPhysParticleSpeed(particle), 1),
        checkC[2 * i + 1]) == false) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysParticleMove failed");
        PBErCatch(PBPhysErr);
    }
    if (ISEQUALF(VecGet(pos, 0), checkD[2 * i]) == false ||
        ISEQUALF(VecGet(pos, 1), checkD[2 * i + 1]) == false) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysParticleMove failed");
        PBErCatch(PBPhysErr);
    }
}
PBPhysParticleFree(&particle);
printf("UnitTestPBPhysParticleAccelMove OK\n");
}

void UnitTestPBPhysParticleTestTrajectory() {
    PBPhysParticle* am = PBPhysParticleCreate(2,
        ShapoidTypeSpheroid);
    PBPhysParticle* amd = PBPhysParticleCreate(2,
        ShapoidTypeSpheroid);
    VecFloat2D accel = VecFloatCreateStatic2D();
    VecSet(&accel, 0, 4.0); VecSet(&accel, 1, 4.0);
    PBPhysParticleSetSpeed(am, &accel);
    PBPhysParticleSetSpeed(amd, &accel);
    VecSet(&accel, 0, 0.0); VecSet(&accel, 1, -1.0 * PBPHYS_Gn);
    PBPhysParticleSetAccel(am, &accel);
    PBPhysParticleSetAccel(amd, &accel);
    float drag = 0.2;
    PBPhysParticleSetDrag(amd, drag);
    float dt = 0.01;
    float t = 0.0;
    FILE* fd = fopen("./traj.txt", "w");
    VecFloat* posam = ShapoidPos(PBPhysParticleShape(am));
    VecFloat* posamd = ShapoidPos(PBPhysParticleShape(amd));
    for (int i = 0; i < 100; ++i) {
        PBPhysParticleMove(am, dt);
        PBPhysParticleMove(amd, dt);
        t += dt;
        fprintf(fd, "%f %f %f %f %f\n", t,
            VecGet(posam, 0), VecGet(posam, 1),

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        VecGet(posamd, 0), VecGet(posamd, 1));
    }
    fclose(fd);
    PBPhysParticleFree(&am);
    PBPhysParticleFree(&amd);
    printf("UnitTestPBPhysParticleTestTrajectory OK\n");
}

void UnitTestPBPhysParticle() {
    UnitTestPBPhysParticleCreateFreePrint();
    UnitTestPBPhysParticleGetSet();
    UnitTestPBPhysParticleCloneIsSame();
    UnitTestPBPhysParticleLoadSave();
    UnitTestPBPhysParticleAccelMove();
    UnitTestPBPhysParticleTestTrajectory();
    printf("UnitTestPBPhysParticle OK\n");
}

void UnitTestPBPhysCreateFreePrint() {
    int dim = 2;
    PBPhys* phys = PBPhysCreate(dim);
    if (phys == NULL ||
        phys->_dim != 2 ||
        !ISEQUALF(phys->_deltaT, PBPHYS_DELTAT) ||
        !ISEQUALF(phys->_downGravity, 0.0) ||
        !ISEQUALF(phys->_curTime, 0.0) ||
        phys->_gravity != 0 ||
        GSetNbElem(PBPhysParticles(phys)) != 0) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysCreate failed");
        PBErrCatch(PBPhysErr);
    }
    PBPhysAddParticles(phys, 2, ShapoidTypeSpheroid);
    PBPhysParticleSetMass(PBPhysPart(phys, 1), 1.0);
    PBPhysPrintln(phys, stdout);
    PBPhysFree(&phys);
    if (phys != NULL) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysFree failed");
        PBErrCatch(PBPhysErr);
    }
    printf("UnitTestPBPhysCreateFreePrint OK\n");
}

void UnitTestPBPhysGetSetAdd() {
    int dim = 2;
    PBPhys* phys = PBPhysCreate(dim);
    if (PBPhysGetDim(phys) != dim) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysGetDim failed");
        PBErrCatch(PBPhysErr);
    }
    phys->_curTime = 0.1;
    if (!ISEQUALF(PBPhysGetCurTime(phys), phys->_curTime)) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysGetCurTime failed");
        PBErrCatch(PBPhysErr);
    }
    if (!ISEQUALF(PBPhysGetDeltaT(phys), PBPHYS_DELTAT)) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysGetDeltaT failed");
        PBErrCatch(PBPhysErr);
    }
}

```

```

}
phys->_downGravity = 0.2;
if (!ISEQUALF(PBPhysGetDownGravity(phys), phys->_downGravity)) {
    PBPhysErr->_type = PBErrTypeUnitTestFailed;
    sprintf(PBPhysErr->_msg, "PBPhysGetDownGravity failed");
    PBErrCatch(PBPhysErr);
}
phys->_gravity = 0.3;
if (!ISEQUALF(PBPhysGetGravity(phys), phys->_gravity)) {
    PBPhysErr->_type = PBErrTypeUnitTestFailed;
    sprintf(PBPhysErr->_msg, "PBPhysGetGravity failed");
    PBErrCatch(PBPhysErr);
}
PBPhysSetCurTime(phys, 0.2);
if (!ISEQUALF(PBPhysGetCurTime(phys), phys->_curTime)) {
    PBPhysErr->_type = PBErrTypeUnitTestFailed;
    sprintf(PBPhysErr->_msg, "PBPhysSetCurTime failed");
    PBErrCatch(PBPhysErr);
}
PBPhysSetDeltaT(phys, 0.3);
if (!ISEQUALF(PBPhysGetDeltaT(phys), phys->_deltaT)) {
    PBPhysErr->_type = PBErrTypeUnitTestFailed;
    sprintf(PBPhysErr->_msg, "PBPhysSetDeltaT failed");
    PBErrCatch(PBPhysErr);
}
PBPhysSetDownGravity(phys, 0.4);
if (!ISEQUALF(PBPhysGetDownGravity(phys), phys->_downGravity)) {
    PBPhysErr->_type = PBErrTypeUnitTestFailed;
    sprintf(PBPhysErr->_msg, "PBPhysSetDownGravity failed");
    PBErrCatch(PBPhysErr);
}
PBPhysSetGravity(phys, 0.5);
if (!ISEQUALF(PBPhysGetGravity(phys), phys->_gravity)) {
    PBPhysErr->_type = PBErrTypeUnitTestFailed;
    sprintf(PBPhysErr->_msg, "PBPhysSetGravity failed");
    PBErrCatch(PBPhysErr);
}
if (PBPhysParticles(phys) != &(phys->_particles)) {
    PBPhysErr->_type = PBErrTypeUnitTestFailed;
    sprintf(PBPhysErr->_msg, "PBPhysParticles failed");
    PBErrCatch(PBPhysErr);
}
if (PBPhysGetNbParticle(phys) != 0) {
    PBPhysErr->_type = PBErrTypeUnitTestFailed;
    sprintf(PBPhysErr->_msg, "PBPhysGetNbParticle failed");
    PBErrCatch(PBPhysErr);
}
PBPhysAddParticles(phys, 2, ShapoidTypeSpheroid);
if (GSetNbElem(PBPhysParticles(phys)) != 2) {
    PBPhysErr->_type = PBErrTypeUnitTestFailed;
    sprintf(PBPhysErr->_msg, "PBPhysAddParticles failed");
    PBErrCatch(PBPhysErr);
}
if (PBPhysGetNbParticle(phys) != 2) {
    PBPhysErr->_type = PBErrTypeUnitTestFailed;
    sprintf(PBPhysErr->_msg, "PBPhysGetNbParticle failed");
    PBErrCatch(PBPhysErr);
}
if (GSetGet(PBPhysParticles(phys), 0) != PBPhysPart(phys, 0) ||
    GSetGet(PBPhysParticles(phys), 1) != PBPhysPart(phys, 1)) {
    PBPhysErr->_type = PBErrTypeUnitTestFailed;
    sprintf(PBPhysErr->_msg, "PBPhysPart failed");
}

```

```

        PBErrCatch(PBPhysErr);
    }
    PBPhysFree(&phys);
    printf("UnitTestPBPhysGetSetAdd OK\n");
}

void UnitTestPBPhysCloneIsSame() {
    int dim = 2;
    PBPhys* phys = PBPhysCreate(dim);
    PBPhysAddParticles(phys, 2, ShapoidTypeSpheroid);
    PBPhysParticleSetMass(PBPhysPart(phys, 1), 1.0);
    PBPhys* clone = PBPhysClone(phys);
    if (!PBPhysIsSame(clone, phys)) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysClone failed");
        PBErrCatch(PBPhysErr);
    }
    PBPhysParticleSetMass(PBPhysPart(clone, 1), 2.0);
    if (PBPhysIsSame(clone, phys)) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysIsSame failed");
        PBErrCatch(PBPhysErr);
    }
    PBPhysFree(&phys);
    PBPhysFree(&clone);
    printf("UnitTestPBPhysCloneIsSame OK\n");
}

void UnitTestPBPhysLoadSave() {
    int dim = 2;
    PBPhys* phys = PBPhysCreate(dim);
    PBPhysAddParticles(phys, 2, ShapoidTypeSpheroid);
    PBPhysParticleSetMass(PBPhysPart(phys, 1), 1.0);
    FILE* fd = fopen("./phys.txt", "w");
    if (!PBPhysSave(phys, fd)) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysSave failed");
        PBErrCatch(PBPhysErr);
    }
    fclose(fd);
    PBPhys* loaded = PBPhysCreate(dim);
    fd = fopen("./phys.txt", "r");
    if (!PBPhysLoad(&loaded, fd) ||
        !PBPhysIsSame(phys, loaded)) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysLoad failed");
        PBErrCatch(PBPhysErr);
    }
    fclose(fd);
    PBPhysFree(&phys);
    PBPhysFree(&loaded);
    printf("UnitTestPBPhysLoadSave OK\n");
}

void UnitTestPBPhysStepFree() {
    int dim = 2;
    PBPhys* phys = PBPhysCreate(dim);
    PBPhysAddParticles(phys, 1, ShapoidTypeSpheroid);
    VecFloat2D v = VecFloatCreateStatic2D();
    VecSet(&v, 0, 1.0); VecSet(&v, 1, 0.5);
    PBPhysParticleSetSpeed(PBPhysPart(phys, 0), &v);
    float check[20] = {

```

```

    0.010000,0.005000,0.020000,0.010000,0.030000,0.015000,0.040000,
    0.020000,0.050000,0.025000,0.060000,0.030000,0.070000,0.035000,
    0.080000,0.040000,0.090000,0.045000,.100000,0.050000};
for (int i = 0; i < 10; ++i) {
    PBPhysNext(phys);
    VecSet(&v, 0, check[2 * i]); VecSet(&v, 1, check[2 * i + 1]);
    if (!VecIsEqual(
        ShapoidPos(PBPhysParticleShape(PBPhysPart(phys, 0))),
        &v)) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysStep failed");
        PBErrCatch(PBPhysErr);
    }
}
PBPhysFree(&phys);
printf("UnitTestPBPhysStepFree OK\n");
}

void UnitTestPBPhysStepDownGravity() {
    int dim = 2;
    PBPhys* phys = PBPhysCreate(dim);
    PBPhysSetDownGravity(phys, PBPHYS_Gn);
    PBPhysAddParticles(phys, 1, ShapoidTypeSpheroid);
    VecFloat2D v = VecFloatCreateStatic2D();
    VecSet(&v, 0, 1.0); VecSet(&v, 1, 0.5);
    PBPhysParticleSetSpeed(PBPhysPart(phys, 0), &v);
    float check[20] = {
        0.010000,0.004510,0.020000,0.008039,0.030000,0.010587,0.040000,
        0.012155,0.050000,0.012742,0.060000,0.012348,0.070000,0.010974,
        0.080000,0.008619,0.090000,0.005283,0.100000,0.000967};
    for (int i = 0; i < 10; ++i) {
        PBPhysNext(phys);
        VecSet(&v, 0, check[2 * i]); VecSet(&v, 1, check[2 * i + 1]);
        if (!VecIsEqual(
            ShapoidPos(PBPhysParticleShape(PBPhysPart(phys, 0))),
            &v)) {
            PBPhysErr->_type = PBErrTypeUnitTestFailed;
            sprintf(PBPhysErr->_msg, "PBPhysStep failed");
            PBErrCatch(PBPhysErr);
        }
    }
    PBPhysFree(&phys);
    printf("UnitTestPBPhysStepDownGravity OK\n");
}

void UnitTestPBPhysStepGravity() {
    int dim = 2;
    PBPhys* phys = PBPhysCreate(dim);
    PBPhysSetGravity(phys, 1.0);
    PBPhysAddParticles(phys, 2, ShapoidTypeSpheroid);
    VecFloat2D v = VecFloatCreateStatic2D();
    VecSet(&v, 0, 1.0); VecSet(&v, 1, 0.5);
    PBPhysParticleSetSpeed(PBPhysPart(phys, 0), &v);
    PBPhysParticleSetMass(PBPhysPart(phys, 0), 1.0);
    VecSet(&v, 0, 1.0); VecSet(&v, 1, 1.0);
    PBPhysParticleSetPos(PBPhysPart(phys, 1), &v);
    PBPhysParticleSetMass(PBPhysPart(phys, 1), 1.0);
    PBPhysParticleSetFixed(PBPhysPart(phys, 1), true);
    float check[20] = {
        0.010018,0.005018,0.020071,0.010071,0.030160,0.015161,0.040286,
        0.020287,0.050449,0.025452,0.060649,0.030654,0.070887,0.035896,
        0.081164,0.041177,0.091479,0.046499,.101834,0.051862};

```

```

for (int i = 0; i < 10; ++i) {
    PBPhysNext(phys);
    VecSet(&v, 0, check[2 * i]); VecSet(&v, 1, check[2 * i + 1]);
    if (!VecIsEqual(
        ShapoidPos(PBPhysParticleShape(PBPhysPart(phys, 0))),
        &v)) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysStep failed");
        PBErrCatch(PBPhysErr);
    }
}
//VecFloatPrint(ShapoidPos(PBPhysParticleShape(PBPhysPart(phys, 0))), stdout, 6);printf("\n");
}
PBPhysFree(&phys);
printf("UnitTestPBPhysStepDownGravity OK\n");
printf("UnitTestPBPhysStepGravity OK\n");
}

void UnitTestPBPhysStepToCollisionApplyElasticCollision() {
    int dim = 2;
    PBPhys* phys = PBPhysCreate(dim);
    PBPhysAddParticles(phys, 3, ShapoidTypeSpheroid);
    VecFloat2D v = VecFloatCreateStatic2D();
    VecSet(&v, 0, 1.0); VecSet(&v, 1, 1.0);
    PBPhysParticleSetSpeed(PBPhysPart(phys, 0), &v);
    PBPhysParticleSetMass(PBPhysPart(phys, 0), 1.0);
    VecSet(&v, 0, 0.0); VecSet(&v, 1, 2.0);
    PBPhysParticleSetPos(PBPhysPart(phys, 1), &v);
    VecSet(&v, 0, 0.5); VecSet(&v, 1, -0.5);
    PBPhysParticleSetSpeed(PBPhysPart(phys, 1), &v);
    PBPhysParticleSetMass(PBPhysPart(phys, 1), 1.0);
    VecSet(&v, 0, 2.0); VecSet(&v, 1, 2.0);
    PBPhysParticleSetPos(PBPhysPart(phys, 2), &v);
    VecSet(&v, 0, -1.0); VecSet(&v, 1, -1.0);
    PBPhysParticleSetSpeed(PBPhysPart(phys, 2), &v);
    PBPhysParticleSetMass(PBPhysPart(phys, 2), 2.0);
    PBPhysSetDeltaT(phys, 2.0);
    GSetPBPhysParticle* set = PBPhysStepToCollision(phys);
    if (!ISEQUALF(PBPhysGetCurTime(phys), 0.646447) ||
        !ISEQUALF(PBPhysPart(phys,0)->_shape->_pos->_val[0], 0.646447) ||
        !ISEQUALF(PBPhysPart(phys,0)->_shape->_pos->_val[1], 0.646447) ||
        !ISEQUALF(PBPhysPart(phys,1)->_shape->_pos->_val[0], 0.323223) ||
        !ISEQUALF(PBPhysPart(phys,1)->_shape->_pos->_val[1], 1.676777) ||
        !ISEQUALF(PBPhysPart(phys,2)->_shape->_pos->_val[0], 1.353553) ||
        !ISEQUALF(PBPhysPart(phys,2)->_shape->_pos->_val[1], 1.353553) ||
        GSetNbElem(set) != 2 ||
        GSetGet(set, 0) != PBPhysPart(phys,0) ||
        GSetGet(set, 1) != PBPhysPart(phys,2)) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg, "PBPhysStepToCollision failed");
        PBErrCatch(PBPhysErr);
    }
    PBPhysParticleApplyElasticCollision(GSetGet(set, 0), GSetGet(set, 1));
    if (!ISEQUALF(PBPhysPart(phys,0)->_speed->_val[0], -1.666667) ||
        !ISEQUALF(PBPhysPart(phys,0)->_speed->_val[1], -1.666667) ||
        !ISEQUALF(PBPhysPart(phys,2)->_speed->_val[0], 0.333334) ||
        !ISEQUALF(PBPhysPart(phys,2)->_speed->_val[1], 0.333334)) {
        PBPhysErr->_type = PBErrTypeUnitTestFailed;
        sprintf(PBPhysErr->_msg,
            "PBPhysParticleApplyElasticCollision failed");
        PBErrCatch(PBPhysErr);
    }
}
GSetFree(&set);

```

```

set = PBPhysStepToCollision(phys);
if (!ISEQUALF(PBPhysGetCurTime(phys), 0.878937) ||
    !ISEQUALF(PBPhysPart(phys,0)->_shape->_pos->_val[0], 0.258963) ||
    !ISEQUALF(PBPhysPart(phys,0)->_shape->_pos->_val[1], 0.258963) ||
    !ISEQUALF(PBPhysPart(phys,1)->_shape->_pos->_val[0], 0.439468) ||
    !ISEQUALF(PBPhysPart(phys,1)->_shape->_pos->_val[1], 1.560532) ||
    !ISEQUALF(PBPhysPart(phys,2)->_shape->_pos->_val[0], 1.431050) ||
    !ISEQUALF(PBPhysPart(phys,2)->_shape->_pos->_val[1], 1.431050) ||
    GSetNbElem(set) != 2 ||
    GSetGet(set, 0) != PBPhysPart(phys,1) ||
    GSetGet(set, 1) != PBPhysPart(phys,2)) {
    PBPhysErr->_type = PBErrTypeUnitTestFailed;
    sprintf(PBPhysErr->_msg, "PBPhysStepToCollision failed");
    PBErrCatch(PBPhysErr);
}
PBPhysParticleApplyElasticCollision(GSetGet(set, 0), GSetGet(set, 1));
if (!ISEQUALF(PBPhysPart(phys,1)->_speed->_val[0], 0.138846) ||
    !ISEQUALF(PBPhysPart(phys,1)->_speed->_val[1], -0.452840) ||
    !ISEQUALF(PBPhysPart(phys,2)->_speed->_val[0], 0.513910) ||
    !ISEQUALF(PBPhysPart(phys,2)->_speed->_val[1], 0.309754)) {
    PBPhysErr->_type = PBErrTypeUnitTestFailed;
    sprintf(PBPhysErr->_msg,
        "PBPhysParticleApplyElasticCollision failed");
    PBErrCatch(PBPhysErr);
}
GSetFree(&set);
VecSet(&v, 0, 0.0); VecSet(&v, 1, 0.0);
PBPhysParticleSetPos(PBPhysPart(phys, 0), &v);
VecSet(&v, 0, 1.0); VecSet(&v, 1, 1.0);
PBPhysParticleSetSpeed(PBPhysPart(phys, 0), &v);
VecSet(&v, 0, 0.0); VecSet(&v, 1, 2.0);
PBPhysParticleSetPos(PBPhysPart(phys, 1), &v);
VecSet(&v, 0, 0.5); VecSet(&v, 1, -0.5);
PBPhysParticleSetSpeed(PBPhysPart(phys, 1), &v);
VecSet(&v, 0, 2.0); VecSet(&v, 1, 2.0);
PBPhysParticleSetPos(PBPhysPart(phys, 2), &v);
VecSet(&v, 0, -1.0); VecSet(&v, 1, -1.0);
PBPhysParticleSetSpeed(PBPhysPart(phys, 2), &v);
ShapoidScale(PBPhysParticleShape(PBPhysPart(phys, 2)), (float)2.0);
PBPhysSetDeltaT(phys, 0.05);
PBPhysSetCurTime(phys, 0.0);
FILE* fd = fopen("./collision.txt", "w");
for (int i = 0; i < 20; ++i) {
    PBPhysStep(phys);
    fprintf(fd, "%f %f %f %f %f %f %f\n", PBPhysGetCurTime(phys),
        PBPhysPart(phys,0)->_shape->_pos->_val[0],
        PBPhysPart(phys,0)->_shape->_pos->_val[1],
        PBPhysPart(phys,1)->_shape->_pos->_val[0],
        PBPhysPart(phys,1)->_shape->_pos->_val[1],
        PBPhysPart(phys,2)->_shape->_pos->_val[0],
        PBPhysPart(phys,2)->_shape->_pos->_val[1]);
}
fclose(fd);
PBPhysFree(&phys);
printf("UnitTestPBPhysStepToCollisionApplyElasticCollision OK\n");
}

void UnitTestPBPhysNext() {
    UnitTestPBPhysStepFree();
    UnitTestPBPhysStepDownGravity();
    UnitTestPBPhysStepGravity();
    UnitTestPBPhysStepToCollisionApplyElasticCollision();
}

```

```

    printf("UnitTestPBPhysStep OK\n");
}

void UnitTestPBPhys() {
    UnitTestPBPhysCreateFreePrint();
    UnitTestPBPhysGetSetAdd();
    UnitTestPBPhysCloneIsSame();
    UnitTestPBPhysLoadSave();
    UnitTestPBPhysNext();

    printf("UnitTestPBPhys OK\n");
}

void UnitTestAll() {
    UnitTestPBPhysParticle();
    UnitTestPBPhys();
    printf("UnitTestAll OK\n");
}

int main() {
    UnitTestAll();
    // Return success code
    return 0;
}

```

## 6 Unit tests output

```

Type: Spheroid
Dim: 2
Pos: <0.000,0.000>
Axis(0): <1.000,0.000>
Axis(1): <0.000,1.000>
speed: <0.000,0.000>
accel: <0.000,0.000>
mass: 0.000
drag: 0.000
unfixed
UnitTestPBPhysParticleCreateFreePrint OK
UnitTestPBPhysParticleGetSet OK
UnitTestPBPhysParticleCloneIsSame OK
UnitTestPBPhysParticleLoadSave OK
UnitTestPBPhysParticleAccelMove OK
UnitTestPBPhysParticleTestTrajectory OK
UnitTestPBPhysParticle OK
dimension: 2
t: 0.000000
dt: 0.010000
down gravity: 0.000000
gravity: 0.000000
nb particles: 2
particle #0:
Type: Spheroid
Dim: 2
Pos: <0.000,0.000>
Axis(0): <1.000,0.000>
Axis(1): <0.000,1.000>
speed: <0.000,0.000>
accel: <0.000,0.000>

```

```

mass: 0.000
drag: 0.000
unfixed
particle #1:
Type: Spheroid
Dim: 2
Pos: <0.000,0.000>
Axis(0): <1.000,0.000>
Axis(1): <0.000,1.000>
speed: <0.000,0.000>
accel: <0.000,0.000>
mass: 1.000
drag: 0.000
unfixed
UnitTestPBPhysCreateFreePrint OK
UnitTestPBPhysGetSetAdd OK
UnitTestPBPhysCloneIsSame OK
UnitTestPBPhysLoadSave OK
UnitTestPBPhysStepFree OK
UnitTestPBPhysStepDownGravity OK
UnitTestPBPhysStepDownGravity OK
UnitTestPBPhysStepGravity OK
UnitTestPBPhysStepToCollisionApplyElasticCollision OK
UnitTestPBPhysStep OK
UnitTestPBPhys OK
UnitTestAll OK

```

traj.txt:

```

0.010000 0.040000 0.039510 0.039960 0.039470
0.020000 0.080000 0.078039 0.079840 0.077880
0.030000 0.120000 0.115587 0.119640 0.115232
0.040000 0.160000 0.152155 0.159361 0.151530
0.050000 0.200000 0.187742 0.199002 0.186773
0.060000 0.240000 0.222348 0.238564 0.220966
0.070000 0.280000 0.255974 0.278047 0.254110
0.080000 0.320000 0.288619 0.317451 0.286207
0.090000 0.360000 0.320283 0.356776 0.317259
0.100000 0.400000 0.350967 0.396023 0.347268
0.110000 0.440000 0.380670 0.435191 0.376236
0.120000 0.480000 0.409392 0.474280 0.404166
0.130000 0.520000 0.437134 0.513292 0.431060
0.140000 0.560000 0.463895 0.552225 0.456918
0.150000 0.600000 0.489675 0.591081 0.481745
0.160000 0.640000 0.514475 0.629858 0.505541
0.170000 0.680000 0.538294 0.668559 0.528309
0.180000 0.720000 0.561132 0.707182 0.550051
0.190000 0.760000 0.582990 0.745727 0.570768
0.200000 0.800000 0.603867 0.784196 0.590464
0.210000 0.840000 0.623763 0.822587 0.609139
0.220000 0.880000 0.642679 0.860902 0.626797
0.230000 0.920000 0.660614 0.899140 0.643438
0.240000 0.960000 0.677568 0.937302 0.659066
0.250000 1.000000 0.693542 0.975388 0.673681
0.260000 1.040000 0.708535 1.013397 0.687287
0.270000 1.080000 0.722547 1.051330 0.699885
0.280000 1.120000 0.735579 1.089187 0.711477
0.290000 1.160000 0.747630 1.126969 0.722065
0.300000 1.200000 0.758701 1.164675 0.731651
0.310000 1.240000 0.768790 1.202306 0.740237
0.320000 1.280000 0.777899 1.239861 0.747826

```

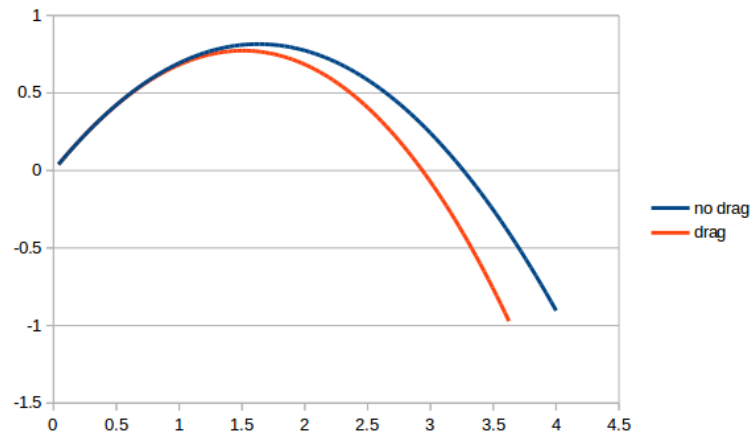


0.330000	1.320000	0.786028	1.277341	0.754419
0.340000	1.360000	0.793175	1.314746	0.760018
0.350000	1.400000	0.799342	1.352077	0.764625
0.360000	1.440000	0.804529	1.389333	0.768242
0.370000	1.480000	0.808735	1.426514	0.770871
0.380000	1.520000	0.811960	1.463621	0.772514
0.390000	1.560000	0.814204	1.500654	0.773174
0.400000	1.600000	0.815468	1.537613	0.772851
0.410000	1.640000	0.815751	1.574497	0.771548
0.420000	1.679999	0.815053	1.611308	0.769268
0.430000	1.719999	0.813375	1.648046	0.766011
0.440000	1.759999	0.810716	1.684710	0.761780
0.450000	1.799999	0.807076	1.721300	0.756577
0.460000	1.839999	0.802456	1.757818	0.750403
0.470000	1.879999	0.796855	1.794262	0.743262
0.480000	1.919999	0.790274	1.830634	0.735153
0.490000	1.959999	0.782711	1.866932	0.726081
0.500000	1.999999	0.774168	1.903159	0.716046
0.510000	2.039999	0.764645	1.939312	0.705050
0.520000	2.079999	0.754140	1.975394	0.693096
0.530000	2.119999	0.742656	2.011403	0.680185
0.540000	2.159999	0.730190	2.047340	0.666319
0.550000	2.199999	0.716744	2.083205	0.651500
0.560000	2.239999	0.702317	2.118999	0.635730
0.570000	2.279999	0.686909	2.154721	0.619011
0.580000	2.319999	0.670521	2.190372	0.601345
0.590000	2.359999	0.653152	2.225951	0.582733
0.600000	2.399999	0.634803	2.261459	0.563178
0.610000	2.439999	0.615472	2.296896	0.542681
0.620000	2.479999	0.595161	2.332262	0.521245
0.630000	2.519999	0.573870	2.367558	0.498871
0.640000	2.559999	0.551598	2.402783	0.475561
0.650000	2.599999	0.528345	2.437937	0.451317
0.660000	2.639999	0.504111	2.473021	0.426141
0.670000	2.679999	0.478897	2.508035	0.400034
0.680000	2.719999	0.452702	2.542979	0.372999
0.690000	2.759999	0.425526	2.577853	0.345038
0.700000	2.799999	0.397370	2.612658	0.316152
0.710000	2.839998	0.368233	2.647392	0.286342
0.720000	2.879998	0.338116	2.682057	0.255612
0.730000	2.919998	0.307018	2.716653	0.223963
0.740000	2.959998	0.274939	2.751180	0.191396
0.750000	2.999998	0.241879	2.785638	0.157914
0.760000	3.039998	0.207839	2.820027	0.123517
0.770000	3.079998	0.172818	2.854347	0.088210
0.780000	3.119998	0.136816	2.888598	0.051992
0.790000	3.159998	0.099834	2.922781	0.014865
0.800000	3.199998	0.061871	2.956895	-0.023167
0.810000	3.239998	0.022928	2.990941	-0.062104
0.820000	3.279998	-0.016996	3.024919	-0.101944
0.830000	3.319998	-0.057901	3.058830	-0.142685
0.839999	3.359998	-0.099787	3.092672	-0.184326
0.849999	3.399998	-0.142653	3.126446	-0.226863
0.859999	3.439998	-0.186500	3.160154	-0.270296
0.869999	3.479998	-0.231327	3.193793	-0.314623
0.879999	3.519998	-0.277136	3.227366	-0.359842
0.889999	3.559998	-0.323925	3.260871	-0.405951
0.899999	3.599998	-0.371694	3.294309	-0.452949
0.909999	3.639998	-0.420444	3.327681	-0.500833
0.919999	3.679998	-0.470175	3.360985	-0.549602
0.929999	3.719998	-0.520887	3.394223	-0.599255
0.939999	3.759998	-0.572579	3.427395	-0.649788

```

0.949999 3.799998 -0.625252 3.460500 -0.701201
0.959999 3.839998 -0.678905 3.493539 -0.753493
0.969999 3.879997 -0.733539 3.526512 -0.806660
0.979999 3.919997 -0.789154 3.559419 -0.860701
0.989999 3.959997 -0.845750 3.592260 -0.915615
0.999999 3.999997 -0.903326 3.625036 -0.971400

```



collision.txt:

```

0.050000 0.050000 0.050000 0.025000 1.975000 1.950000 1.950000
0.100000 0.100000 0.100000 0.050000 1.950000 1.900000 1.900000
0.150000 0.150000 0.150000 0.075000 1.925000 1.850000 1.850000
0.200000 0.200000 0.200000 0.100000 1.900000 1.800000 1.800000
0.250000 0.250000 0.250000 0.125000 1.875000 1.750000 1.750000
0.300000 0.300000 0.300000 0.150000 1.850000 1.700000 1.700000
0.350000 0.350000 0.350000 0.155565 1.827215 1.659718 1.648893
0.400000 0.400000 0.400000 0.085599 1.813041 1.657201 1.593480
0.450000 0.450000 0.450000 0.015633 1.798866 1.654684 1.538068
0.500000 0.500000 0.500000 -0.054334 1.784691 1.652167 1.482655
0.550000 0.454424 0.469154 -0.124300 1.770516 1.697439 1.467666
0.600000 0.394305 0.426006 -0.194267 1.756341 1.749981 1.458827
0.650000 0.334186 0.382858 -0.264233 1.742166 1.802524 1.449989
0.700000 0.274067 0.339710 -0.334199 1.727992 1.855067 1.441150
0.750000 0.213948 0.296562 -0.404166 1.713817 1.907610 1.432312
0.800000 0.153829 0.253414 -0.474132 1.699642 1.960153 1.423473
0.850000 0.093709 0.210266 -0.544099 1.685467 2.012695 1.414634
0.900000 0.033590 0.167118 -0.614065 1.671292 2.065238 1.405796
0.950000 -0.026529 0.123970 -0.684032 1.657117 2.117781 1.396957
1.000000 -0.086648 0.080822 -0.753998 1.642943 2.170323 1.388119

```

