Collision Physics

There are some cases when you can compute the collision in closed-form

We need to answer the question:

What will cause the ball to stop flying freely through the air?

The answer is – it will hit a wall or the floor.

From our rules of physics, the next bounce will happen at one of the solutions to these equations:

\[ X_{RIGHT} - RADIUS = x + v_x t \]
\[ X_{LEFT} + RADIUS = x + v_x t \]
\[ Y_{BOTTOM} + RADIUS = y + v_y t + \frac{1}{2} g t^2 \]

Note: \( g < 0 \).

How do you know which of the 4 \( t \) values is the one that you should use?

Use the time that is the smallest positive number.

We want positive, because negative time values happened ago.

We want smallest because we are interested in the collision that happens first.

There are some cases when you can compute the collision in closed-form

The next bounce will happen at one of the solutions to these equations:

\[ t_1 = \frac{X_{RIGHT} - RADIUS - x}{v_x} \]
\[ t_2 = \frac{X_{LEFT} + RADIUS - x}{v_x} \]
\[ t_3, t_4 = \pm \sqrt{\frac{2(y - Y_{BOTTOM} - RADIUS)}{g}} \]

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The Physics of Collisions – Definitions

Line of Impact

- If the objects’ velocities are parallel to the Line of Impact, this is a Direct Impact.
- If the objects’ velocities are perpendicular to the Line of Impact, this is a Tangential Impact.
- A combination of the two is called an Oblique Impact.

Direct Impact
Tangential Impact
Oblique Impact (both direct and tangential)

The Physics of Collisions – Fundamental Quantities

The momentum of an object is defined as its mass multiplied by its velocity:

\[ \text{Momentum} = mv \]

The energy of an object is defined as one half of its mass multiplied by its velocity squared:

\[ \text{Energy} = \frac{1}{2}mv^2 \]

The Physics of Collisions – Conservation of Momentum

In a collision, the total momentum after the impact is equal to the total momentum before the impact. Always.

\[ m_a v_a + m_b v_b = m_a v'_a + m_b v'_b \]

where the primes ' refer to velocities after the impact.

This is referred to as the Conservation of Momentum Law.

Momentum is always conserved through any collision.

Conservation of Momentum as Explained by Newton’s Cradle

And, of course, where would any topic be without kittens? 😼
In a collision, energy is conserved in the entire system, but not necessarily in the form of velocities. (It can become permanent deformation, heat, light, etc.) This loss of velocity is expressed as the **Coefficient of Restitution** (COR). The COR, $e$, is how much less the relative velocities of the objects are after impact than they were before impact:

$$v'_b - v'_a = -e(v_b - v_a)$$

(the negative sign is there to indicate the "bounce")

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Starting with these two equations:

$$m_a v_a + m_b v_b = m_a v'_a + m_b v'_b$$

$$v'_b - v'_a = -e(v_b - v_a)$$

Treat the two initial velocities as inputs and solve for the two resulting velocities. This gives:

$$v'_a = \frac{m_a v_a + m_b v_b + e m_b (v_b - v_a)}{m_a + m_b}$$

$$v'_b = \frac{m_a v_a + m_b v_b - e m_b (v_b - v_a)}{m_a + m_b}$$

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Since mass $b$ is immoveable, its velocity is zero, so that $a$’s post-collision velocity is:

$$v'_a = -e v_a$$

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Velocities are hard to measure live, but distances are not. So, drop the object from a height $h$, and measure its bounce to a height $h'$:

Before the bounce: $v_2^2 = 0^2 + 2gh$

After the bounce: $0^2 = v'^2 - 2gh'$

$$\frac{v'}{v} = \sqrt{\frac{2gh'}{2gh}} = \sqrt{\frac{h'}{h}}$$

$$e = \frac{v'}{v}$$
Collisions – Some Coefficients of Restitution of Balls Bounced on a Concrete Surface

<table>
<thead>
<tr>
<th>Ball Material</th>
<th>CoR</th>
</tr>
</thead>
<tbody>
<tr>
<td>range golf ball</td>
<td>0.858</td>
</tr>
<tr>
<td>tennis ball</td>
<td>0.712</td>
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<tr>
<td>billiard ball</td>
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<tr>
<td>hand ball</td>
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<tr>
<td>wooden ball</td>
<td>0.603</td>
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<tr>
<td>steel ball bearing</td>
<td>0.587</td>
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<tr>
<td>glass marble</td>
<td>0.658</td>
</tr>
<tr>
<td>ball of rubber bands</td>
<td>0.828</td>
</tr>
<tr>
<td>NikeRx, hard plastic ball</td>
<td>0.668</td>
</tr>
</tbody>
</table>


The Physics of Collisions – Totally Plastic Collisions

If \( e = 0 \), then the objects stick together and end up with the same resulting velocity:

\[
\begin{align*}
\mathbf{v}'_a &= \frac{m_a \mathbf{v}_a + m_b \mathbf{v}_b}{m_a + m_b} \\
\mathbf{v}'_b &= \frac{m_a \mathbf{v}_a + m_b \mathbf{v}_b}{m_a + m_b}
\end{align*}
\]

The Physics of Collisions – Totally Elastic Collisions

What happens when \( e = 1 \)? The two fundamental equations are:

\[
\begin{align*}
m_a \mathbf{v}'_a + m_b \mathbf{v}'_b &= m_b \mathbf{v}_b + m_a \mathbf{v}_a \\
\mathbf{v}'_b - \mathbf{v}'_a &= -e(\mathbf{v}_b - \mathbf{v}_a) = (\mathbf{v}_a - \mathbf{v}_b)
\end{align*}
\]

Rearranging:

\[
\begin{align*}
m_a (\mathbf{v}'_a - \mathbf{v}_a) &= m_b (\mathbf{v}_b - \mathbf{v}'_b) \\
\mathbf{v}'_a + \mathbf{v}_a &= \mathbf{v}_b + \mathbf{v}'_b
\end{align*}
\]
The Physics of Collisions – Elastic Collisions

\[ m_a (v_a' - v_a) = m_b (v_b' - v_b) \]
\[ v_a' + v_a = v_b' + v_b \]

This shows that energy is conserved when the Coefficient of Restitution is 1.0.

Then, multiplying the two together gives:

\[ m_a v_a'^2 - m_a v_a^2 = m_b v_b^2 - m_b v_b'^2 \]

Or:

\[ \frac{1}{2} m_b v_b'^2 + \frac{1}{2} m_a v_a'^2 = \frac{1}{2} m_b v_b^2 + \frac{1}{2} m_a v_a^2 \]

The Physics of Collisions – Oblique Impacts

Oblique Impacts are then handled by using vector math to determine the direct and tangential velocity components with respect to the Line of Impact.

The direct components are changed using the equations we just derived.

The tangential components are left unchanged. (This assumes no friction.)

The new components are then combined to produce the resulting velocity vectors.