Projectiles

By

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A *projectile* is any object that is cast, fired, flung, heaved, hurled, pitched, tossed, or thrown. (This is an informal definition.) The path of a projectile is called its *trajectory*. Some examples of projectiles include…

- a baseball that has been pitched, batted, or thrown
- a bullet the instant it exits the barrel of a gun or rifle
- a bus driven off an uncompleted bridge
- a moving airplane in the air with its engines and wings disabled
- a runner in mid stride (since they momentarily lose contact with the ground)
- the space shuttle or any other spacecraft after main engine cut off (MECO)

The force of primary importance acting on a projectile is gravity. This is not to say that other forces do not exist, just that their effect is minimal in comparison. A tossed helium-filled balloon is not normally considered a projectile as the drag and buoyant forces on it are as significant as the weight. Helium-filled balloons can't be thrown long distances and don't normally fall. In contrast, a crashing airplane would be considered a projectile. Even though the drag and buoyant forces acting on it are much greater in absolute terms than they are on the balloon, gravity is what really drives a crashing airplane. The normal amounts of drag and buoyancy just aren't large enough to save the passengers on a doomed flight from an unfortunate end. A *projectile* is any object with an initial non-zero, horizontal velocity whose acceleration is due to gravity alone.

An essential characteristic of a projectile is that its future has already been preordained. Batters may apply "body English" after hitting a long ball, but they do so strictly for psychological reasons. No amount of leaning to one side will make a foul ball turn fair. Of course, the pilot of a disabled airplane may regain control before crashing and avert disaster, but then the airplane wouldn't be a projectile anymore. An object ceases to be a projectile once any real effect is made to change its trajectory. The trajectory of a projectile is thus entirely determined the moment it satisfies the definition of a projectile.

The only relevant quantities that might vary from projectile to projectile then are initial velocity and initial position

This is where we run into some linguistic complications. Airplanes, guided missiles, and rocket-propelled spacecraft are sometimes also said to follow a trajectory. Since these devices are acted upon by the lift of wings and the thrust of engines in addition to the force of gravity, they are not really projectiles. To get around this dilemma, it is common to use the term *ballistic trajectory* when dealing with projectiles. The word ballistic has its origins in the Greek word βαλλω (*vallo*), to throw, and surfaces repeatedly in the technical jargon of weaponry from ancient to modern times. For example…

- The *ballista*, which looks something like a giant crossbow, was a siege engine used in medieval times to hurl large stones, flaming bundles, infected animal carcasses, and severed human heads into fortifications. Before the invention of gunpowder, ballistas (and catapults and trêbuchets) were the weapons of choice for conquerors.

- An *intercontinental ballistic missile* is a device for delivering nuclear warheads over long distances. At the start of its journey an ICBM is guided by a rocket engine and stabilizer fins, but soon thereafter it enters the phase of its journey where it is effectively in free fall, traveling fast enough to keep it above Earth's atmosphere for a while but not fast enough to enter orbit permanently. The adjective "intercontinental" refers to the long range capabilities, while the largely free fall journey it takes makes it "ballistic". ICBMs are the ultimate killing machines, but they have never been used in combat to date.

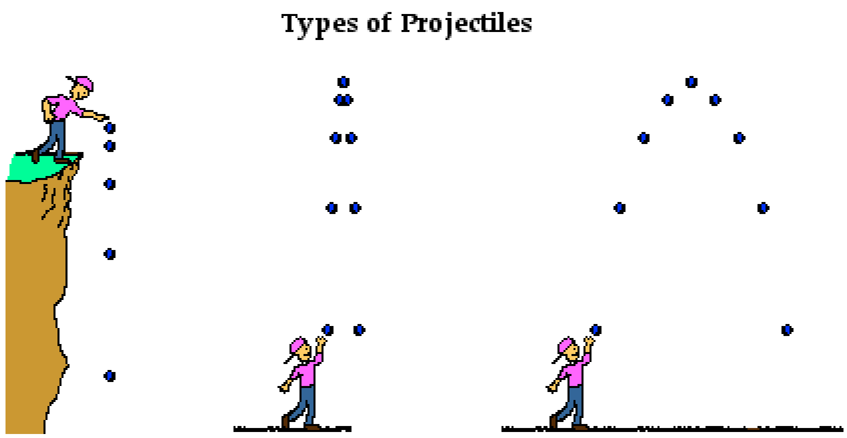
The wide geographic range as well as the wide historic range of these things we call projectiles raises some problems for the typical student of physics. When a projectile is sent on a very long journey, as is the case with ICBMs, the magnitude and direction of the acceleration due to gravity changes. Gravity isn't constant to begin with, but the variation is not noticeable over everyday ranges in altitude. From the deepest mines in South Africa to the highest altitudes traversed by commercial airplanes, the *magnitude* of the acceleration due to gravity is always effectively 9.8 m/s^2 ± 0.05 m/s^2. Similarly, unless you routinely travel medium to long distances, you aren't likely to experience much of a change in the *direction* of gravity either. To experience a 1° shift in "down" would require traveling $^1{}_{360}$ of the circumference of the Earth — roughly 110 km (70 mi) or the length of a typical morning commute to work in Southern California. Thus for projectiles that won't rise higher than an airplane nor travel farther than the diameter of L.A., gravity is effectively constant. This covers the first five of the examples described at the beginning of this section (baseballs, bullets, buses in action-adventure movies, distressed airplanes, and joggers) but not the sixth (the space shuttle after MECO).

To distinguish such simple projectiles from those where variations in gravity and the curvature of the Earth are significant, I propose using the term *simple projectile*. For the remaining problems, the term *general projectile* seems appropriate since a general solution in mathematics is one that also includes the special cases, but I'm less adamant about this term.

Consider an effectively spherical earth with a single tall mountain sticking out of it like a giant tumor. Now imagine using this location as a place to launch projectiles horizontally with varying initial velocities. What effect would velocity have on range? Well obviously fast projectiles will travel farther than slow ones. A basic concept associated with speed is that "faster means farther", but the relationship is only approximately linear on a spherical earth. For a while, doubling speed would mean doubling distance, but eventually the curvature of the Earth would start to mess things up. At some speed our hypothetical projectile would make it a quarter of the way around the Earth and then half way around and then eventually all the way around. At this point our general projectile ceases to be an object with a launch point and a landing point and it starts being a *satellite*, permanently circling the Earth, perpetually changing direction and thus accelerating under the influence of gravity, but never landing anywhere. Technically, such an object would still be a general projectile, since gravity is the primary source of its acceleration, but somehow this doesn't seem right. Objects traveling through what we call "outer space" hardly seem like projectiles any more. They seem like they reside more in the realm of *celestial mechanics* than *terrestrial mechanics*. Such distinctions are arbitrary, however, as there is only one mechanics. The laws of physics are assumed universal until it can be demonstrated otherwise. The unification of physical law is a theme that surfaces from time to time in physics.

A projectile and a satellite are both governed by the same physical principles even though they have different names. A simple projectile is made mathematically simple by an idealization (basically a lie of convenience). By assuming a constant value for the acceleration due to gravity, we make the problem easier to solve and (in many cases) do not really lose all that much in the way of accuracy.

A projectile is an object upon which the only force acting is gravity. There are a variety of examples of projectiles. An object dropped from rest is a projectile (provided that the influence of air resistance is negligible). An object that is thrown vertically upward is also a projectile (provided that the influence of air resistance is negligible). And an object which is thrown upward at an angle to the horizontal is also a projectile (provided that the influence of air resistance is negligible). A projectile is any object that once *projected* or dropped continues in motion by its own inertia and is influenced only by the downward force of gravity.

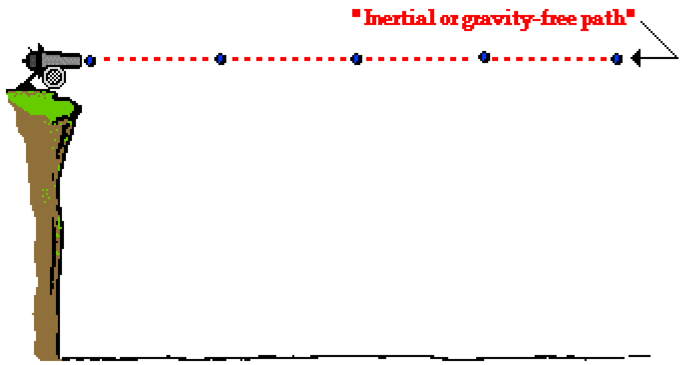


By definition, a projectile has a single force that acts upon it - the force of gravity. If there were any other force acting upon an object, then that object would not be a projectile. Thus, the free-body diagram of a projectile would show a single force acting downwards and labeled force of gravity (or simply F_{grav}). Regardless of whether a projectile is moving downwards, upwards, upwards and rightwards, or downwards and leftwards, the free-body diagram of the projectile is still as depicted in the diagram at the right. By definition, a projectile is any object upon which the only force is gravity.

Projectile Motion and Inertia

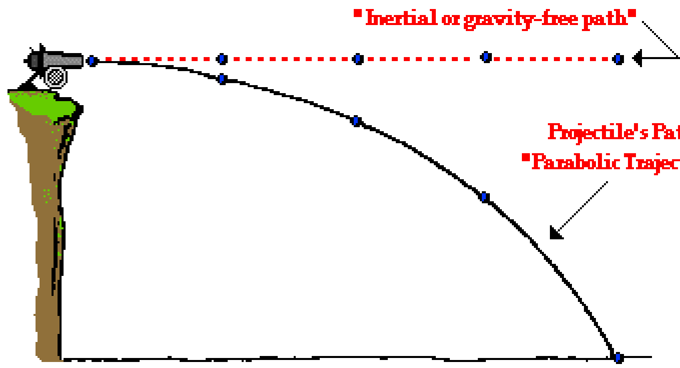
Many students have difficulty with the concept that the only force acting upon an upward moving projectile is gravity. Their conception of motion prompts them to think that if an object is moving upward, then there *must* be an upward force. And if an object is moving upward and rightward, there *must* be both an upward and rightward force. Their belief is that forces cause motion; and if there is an upward motion then there must be an upward force. They reason, "How in the world can an object be moving upward if the only force acting upon it is gravity?" Such students do not *believe* in Newtonian physics (or at least do not believe strongly in Newtonian physics). Newton's laws suggest that forces are only required to cause an acceleration (not a motion). Recall from the Unit 2 that Newton's laws stood in direct opposition to the common misconception that a force is required to keep an object in motion. This idea is simply <u>not</u> true! A force is <u>not</u> required to keep an object in motion. A force is only required to maintain an acceleration. And in the case of a projectile that is moving upward, there is a downward force and a downward acceleration. That is, the object is moving upward and slowing down.

To further ponder this concept of the downward force and a downward acceleration for a projectile, consider a cannonball shot horizontally from a very high cliff at a high speed. And suppose for a moment that the *gravity switch* could be *turned off* such that the cannonball would travel in the absence of gravity? What would the motion of such a cannonball be like? How could its motion be described? According to Newton's first law of motion, such a cannonball would continue in motion in a straight line at constant speed. If not acted upon by an unbalanced force, "an object in motion will ...". This is Newton's law of inertia.



In the absence of gravity, an object in motion will continue in motion with the same speed and in the same direction.

Now suppose that the *gravity switch* is turned on and that the cannonball is projected horizontally from the top of the same cliff. What effect will gravity have upon the motion of the cannonball? Will gravity affect the cannonball's horizontal motion? Will the cannonball travel a greater (or shorter) horizontal distance due to the influence of gravity? The answer to both of these questions is "No!" Gravity will act downwards upon the cannonball to affect its vertical motion. Gravity causes a vertical acceleration. The ball will drop vertically below its otherwise straight-line, inertial path. Gravity is the downward force upon a projectile that influences its vertical motion and causes the parabolic trajectory that is characteristic of projectiles.



With gravity, a "projectile" will fall below its inertial path. Gravity acts downward to cause a downward acceleration. There are no horizontal forces needed to maintain the horizontal motion - consistent with the concept of inertia.

Animation

A projectile is an object upon which the only force is gravity. Gravity acts to influence the vertical motion of the projectile, thus causing a vertical acceleration. The horizontal motion of the projectile is the result of the tendency of any object in motion to remain in motion at constant velocity. Due to the absence of horizontal forces, a projectile remains in motion with a constant horizontal velocity. Horizontal forces are <u>not</u> required to keep a projectile moving horizontally. The only force acting upon a projectile is gravity!