



UP, UP, AND AWAY-

FORCES AND MOTION

JERRY SIEGEL AND JOSEPH SHUSTER'S

original conception of Superman was of a pulp action hero with a liberal dose of science fiction added to lend an air of plausibility for their hero's great strength. As described in *Superman # 1*, Jor-El, a scientist on the distant planet Krypton, discovers that his world is about to explode and kill its entire population. Possessing only a small prototype rocket ship, he and his wife elect to save their infant son Kal-El, sending him to Earth so that he will not share their fate.* After traveling great distances through the vastness of space, the rocket crash-lands on Earth with its sole passenger none the worse for wear. Discovered by the childless Kansas farmers the Kents, Kal-El is immediately given up to an orphanage. Later, driven by guilt, the Kents return to the orphanage (where the superbaby has been wreaking havoc) whereupon they adopt Kal-El/name him Clark, and raise him as their own human son. As Kal-Clark Kent grows into adulthood, he develops a series of extraordinary abilities with which he fights the never-ending battle for Truth, Justice, and the American Way.

The source of Superman's powers on Earth was originally credited to his Kryptonian heritage, specifically the fact that his home planet had a far stronger gravity than Earth's. For example, the

* As a father myself, I can certainly empathize with Jor-El. Many are the times I've been tempted to place my own kids in a rocket ship and send them off into deep space.

moon's much smaller size compared to Earth results in a weaker gravitational field, so objects on the moon weigh less than they do on Earth. Consequently, an Earthman whose muscles and bones are adapted to Earth's gravity is able to leap far greater distances and lift more massive objects on the lunar surface. Similarly Superman's great strength ("more powerful than a locomotive") and tougher skin ("nothing less than a bursting shell" could pierce it) resulted from his relocating to a planet with a far weaker gravity than Krypton's. Even though Superman was sent to Earth as an infant, presumably his Kryptonian DNA encoded for the development of muscles and bones suited to a stronger gravitational field.

By the late 1940s, Superman would gain the power of true flight, able to choose and alter his trajectory after leaving the ground. At this point Superman can be considered to have gained free will over the laws of physics. Over time he acquired a host of other abilities that could not be reasonably accounted for by the stronger gravity of his home planet. These powers included various visions (heat-, X-ray-, and others), super-hearing, super-breath, and even super-hypnotism.*

The origin of Superman's powers was subsequently revised in *Action Comics* # 262, to claim that Superman's fantastic abilities derived from the fact that the Earth orbited a yellow sun, as opposed to the red sun of Krypton. The color of a sun is a function of both its surface temperature and the atmosphere through which it is viewed. The blue portion of the solar spectrum is strongly scattered by the atmosphere, which is why the sky looks blue. Viewed straight on, our sun appears yellow because the atmosphere is also more absorbing toward the blue end of the spectrum, except at dawn or sunset when the position of the sun is low on the horizon and sunlight must travel a greater distance through the atmosphere. Nearly all wavelengths are then absorbed except for lower-energy red light, which gives sunsets their characteristic hues (the

* This last power was introduced to explain why only a simple pair of eyeglasses created such a perfect disguise that no one ever realized that mild-mannered reporter Clark Kent and the world-famous Superman were the same person. As described in *Superman* # 330, Superman apparently subconsciously hypnotizes everyone who sees him into believing that his face is markedly different from Clark Kent's.

greater number of particulates in the air at the end of the day compared with the beginning also contributes to the difference in shading between sunset and dawn). These spectral features are for the most part independent of the chemical composition of the gases making up the Earth's atmosphere. There is no physical mechanism by which a shift in the primary wavelength of sunlight from yellow (a wavelength of 570 nanometers, or 570 billionths of a meter) to red light (650 nanometers) would endow someone with the ability to bend steel in his bare hands. Consequently at this stage in his history, *Superman* ceased being a science-fiction strip, and became a comic book about a fantasy hero. Changing a superhero's origin in order to accommodate new powers or circumstances occurs so frequently in comic books that comic-book fans have coined a term, "retconning," to describe this retroactive continuity repair.

Interestingly, Superman's foes went through a similar evolution around this same time. In the early years of *Action* and *Superman* comics, Siegel and Shuster gave voice to the revenge fantasies of their young and economically disadvantaged Depression-era readers. Superman first used his powers to fight corrupt slumlords, coal-mine owners, munitions manufacturers, and Washington lobbyists. In his very first story he psychologically tormented a lobbyist by holding him as they both fell from a tall building. At this early stage of his career, the story lines indicated that only a few people knew of Superman's existence, and the lobbyist believed that the fall would be fatal. He willingly divulged the information Superman was after rather than risk another such fall. By the 1950s, in addition to selling millions of comics per month, Superman had become a star of radio serials, movie shorts (both animated and live action), and a popular television program. Around this time his adversaries morphed into criminal masterminds with colorful personas and costumes, such as the Toyman, the Prankster, and Lex Luthor, whose schemes for grand larceny or world (or in the case of Brainiac, galactic) domination Superman was able to foil while keeping the corporate power structure safely undisturbed. As befits the escalating capabilities of the villains he faced, Superman entered a superpower arms race, eventually growing so powerful that it became difficult for writers to concoct credible threats to challenge his near godlike abilities. Radioactive fragments of his home planet, known as Kryptonite, became

a frequent device to extend any given story beyond the first page of the comic.*

It is the simpler, original Superman of the Golden Age, the last son of Krypton, that I wish to consider here.

THE PHYSICS OF JUMPING AND ALL OTHER MOTION

In the first years of his comic-book history, Superman was unable to fly but could simply "leap tall buildings in a single bound," thanks to Earth's weaker gravity.

Well, how high could he leap? According to his origin story in *Superman # 1*, Superman's range was about one eighth of a mile, or 660 feet. Assuming he could jump this high straight up, this is approximately equivalent to the height of a thirty- to forty-story building, which in 1938 would be considered quite tall. So our question can be rephrased as: What initial velocity would Superman need, lifting off from the sidewalk, so that he would vertically rise 660 feet?

Whether we describe the trajectory of a leaping man of steel or of the tossed ball from our earlier example, we must begin with the three laws of motion as first described by Isaac Newton in the mid-1600s. These laws are frequently expressed as: (1) an object at rest remains at rest, or if moving keeps moving in a straight line if no external forces act upon it; (2) if an external force is applied, the object's motion will change in either magnitude or direction, and the rate of change of the motion (its acceleration) when multiplied by the object's mass is equal to the applied force; and (3) for every force applied to an object there is an equal and opposite force

* How a radioactive element from his native planet would affect Superman so strongly, while he remained immune to radioactive isotopes found on Earth, is more an issue of literary necessity rather than physical plausibility. Kryptonite was first introduced in the radio serial *Adventures of Superman* in 1943, when the overworked radio actor portraying the Man of Steel wanted a vacation. The radio scriptwriters created Superman's mineral nemesis so that another actor could portray the stricken superhero by groaning into the microphone. Several years later the comic-book writers adopted and adapted this creative device, and a rainbow of Kryptonite (green, red, gold, silver, and others) with a broad range of effects on Superman was introduced into the comic-book universe.

exerted back by the object. The first two laws can be expressed succinctly through one simple mathematical equation:

$$\text{FORCE} = (\text{MASS}) \times (\text{ACCELERATION})$$

That is, the force F applied to an object is equal to the resulting rate of change in the object's velocity (its acceleration a) when multiplied by the object's mass m , or $F = ma$.

Acceleration is a measure of the rate of change of the velocity of an object. A car starting from rest (velocity = 0) and accelerating to 60 mph would have a change in velocity of $60 \text{ mph} - 0 \text{ mph} = 60 \text{ mph}$. The acceleration is then given by dividing this change in velocity by the time needed to make this change. The longer the time, the lower the acceleration needed for a given change in speed. An automobile speeding up from 0 to 60 mph in six seconds will have a much larger acceleration than if it does so in six hours or six days. The final speed will be the same for all three cases, namely 60 mph, but the accelerations will be radically different owing to the different times needed to affect this change in velocity. From Newton's $F = ma$, the force needed to create the former, faster acceleration is obviously much larger than for the latter, slower case.

When the acceleration is zero, there is no change in the motion. In that case a moving object keeps moving in a straight line, or if sitting still, remains so. From the expression $F = ma$, when $a = 0$, then the force $F = 0$, which is the whole point of Newton's first law of motion.

While this may be straightforward from a mathematical point of view, from a common-sense perspective it is nothing short of revolutionary. Newton is saying (correctly) that if an object is moving, and there is no outside force acting on it, then the object will simply continue moving in a straight line. However, you and I, and Isaac Newton for that matter, have *never* seen this occur! Our everyday experiences tell us that to keep something moving, we must always keep pulling it or pushing it with an external force. A car in motion does *not* remain in motion, unless we keep pressing the accelerator pedal, which ultimately provides a force. Of course, the reason that moving objects slow down and come to rest when we stop pushing or pulling them is that there are forces of friction and air resistance that oppose the object's motion. Just because we stop pulling or pushing does not mean, in the real

world, that there are no forces acting on the object. There's nothing wrong with Newton's laws—we just have to make sure we account for friction and air resistance when applying them. It is these unseen "drag forces" that we must overcome in order to maintain uniform motion. Once our pulling or pushing exactly balances the friction or air drag, then the *net* force on the object is zero, and the object will then continue in straight-line motion. Increasing the push or pull further will yield a net nonzero force in the direction of our push or pull. In this case, there will be an acceleration proportional to the net force. The constant of proportionality connecting the force to the acceleration is the mass, m , reflecting how much the object resists changing its motion.

It is worth pointing out here that mass is not the same as weight. "Weight" is another term for "force on an object due to gravity." Mass, on the other hand, is a measure of how much stuff ("atoms" for you specialists) an object contains. The mass of the atoms in an object is what gives it its "inertia," a fancy term to describe its resistance to change when a force is applied. Even in outer space, an object's mass is the same as on the Earth's surface, because the number and type of atoms it contains does not change. An object in outer space may be "weightless," in that it is subject to a negligible attractive force from nearby planets, but it still resists changes in motion, due to its mass. A space-walking astronaut in deep space cannot just pick up and toss a space station around (assuming she had a platform on which to stand), even though the station and everyone on it is "weightless." The mass of the space station is so large that the force the astronaut's muscles can apply produces only a negligible acceleration.

For objects on the Earth's surface (or that of any other planet, for that matter), the acceleration due to gravity is represented by the letter g (we'll discuss this more in a moment). The force that gravity exerts on the object of mass m is then referred to as its Weight. That is, $\text{Weight} = (\text{mass}) \times (\text{acceleration due to gravity})$ or $W = mg$, which is just a restatement of $F = ma$ when $a = g$. Mass is an intrinsic property of any object, and is measured in kilograms in the metric system, while Weight represents the force exerted on the object due to gravity, and is measured in pounds in the United States. In Europe, Weight is commonly expressed in units of kilograms, which is not strictly correct, but easier to say than "kilogram-meter/sec," the unit of force in the metric system (also known as a "Newton").

When something weighing one Newton in the metric system is compared to an object weighing one pound in the United States, the conversion ratio is *1 kilogram is equivalent to 2.2 pounds*. I say "equivalent" and not "equal" because a pound is a unit of force, while kilograms measure mass. An object will weigh less than 2.2 pounds on the moon and more than 2.2 pounds on Jupiter, but its mass will always be 1 kilogram. When calculating forces in the metric system, we'll stick with kg-meter/sec² rather than "Newtons," in order to remind ourselves that *any* force can always be described by $F = ma$.

To recap, Superman's mass at any given moment is a constant, because it reflects how many atoms are in his body. His weight, however, is a function of the gravitational attraction between him and whatever large mass he is standing on. Superman has a larger weight on the surface of Jupiter, or a lesser weight on the Moon, compared to his weight on Earth, but his mass remains unchanged. The gravitational attraction of a planet or moon decreases the farther away one moves from the planet, though technically it is never exactly zero unless one were infinitely far from the planet. It is tempting to equate mass with weight, and easy to do so when dealing only with objects on Earth for which the acceleration due to gravity is always the same. As we will soon be comparing Superman's weight on Krypton to that on Earth, we will resist this temptation.

Finally, the third law of motion simply makes explicit the commonsense notion that when you press on something, that thing presses back on you. This is sometimes expressed as "For every action, there is an equal and opposite reaction." You can only support yourself by leaning on the wall if the wall resists you—that is, pushes back with an equal and opposite force. If the force were not exactly equal and in the opposite direction, then there would be a *net* nonzero force, which would lead to an acceleration and you crashing into the wall. When the astronaut mentioned above pushes on the space station, the force her muscles exert provides a very small acceleration to the station, but the station pushes back on her, and her acceleration is much larger (since her mass is much smaller).

Imagine Superman and the Hulk holding bathroom scales against each other (which are simply devices to measure a force, namely your weight due to gravity). When they press against each other's

scale, no matter how hard Superman pushes on the left, if they remain stationary, then the Hulk's scale on the right will read exactly the same force. Moreover, no matter how hard Superman is pushing, his scale will read zero pounds of force if the Hulk offers no resistance and just moves his scale out of the way and steps aside.* *Forces always come in pairs*, and you cannot push or pull on something unless it pushes or pulls back. When you stand on the sidewalk, your feet exert a force on the ground due to gravity pulling you toward the center of the Earth. People on the opposite side of the planet do not fall off, because gravity pulls everyone in toward the center of the planet, regardless of where they are located. You do not accelerate while standing; the ground provides an equal and opposite force exactly equal to your weight. During the brief moment when Superman jumps, his legs exert a force greater than just his normal standing weight. Because forces come in pairs, his pushing down on the pavement causes the pavement to push back on him. Thus he experiences an upward force lifting him up and away.

And that's it—all of Newton's laws of motion can be summarized in two simple ideas: that any change in motion can only result from a external force ($F = ma$), and that forces always come in pairs. This will be all we need to describe all motions, from the simple to the complex, from a tossed ball to the orbits of the planets. In fact, we already have enough physics in hand to figure out the initial velocity Superman needs to leap a tall building.

IN A SINGLE BOUND

Superman starts off with some large initial velocity (fig. 4). At the top of his leap, a height $h = 660$ feet above the ground, his final velocity must be zero, or else this wouldn't be the highest point of his jump, and he would in fact keep rising. The reason Superman slows down is that an external force, namely gravity, acts on him. This force acts downward, toward the surface of the Earth, and opposes his rise. Hence the acceleration is actually a deceleration,

* The Hulk is brighter than everyone gives him credit for (his alter ego is a physicist, after all).



Fig. 4. Panel from Superman # 1 (June 1939) showing Superman in the process of leaping a . . . well, you know.

slowing him down, until at 660 feet, he comes to rest. Imagine ice-skating into a strong, stiff wind. Initially you push off from the ice and start moving quickly into the wind. But the wind provides a steady force opposing your motion. If you do not push off again, then this steady wind slows you down until you are no longer moving and you come to rest. But the wind is still pushing you, so you still have an acceleration and now start sliding backward the way you came, with the wind. By the time you reach your initial starting position, you are moving as fast as when you began, only now in the opposite direction. This constant wind in the horizontal direction affects you as an ice-skater the same way gravity acts on Superman as he jumps. The force of gravity is the same at the start, middle, and highest point of his leap. Since $F = ma$, his acceleration is the same at all times as well. In order to determine what starting speed Superman needs to jump 660 feet, we have to figure out how his velocity changes in the presence of a uniform, constant acceleration g in the downward direction.

As common sense would indicate, the higher one wishes to leap, the faster the liftoff velocity must be. How, exactly, are the starting speed and final height connected? Well, when you take a trip, the distance you travel is just the product of your average speed and the length of time of the trip. After driving for an hour at an average speed of 60 mph, you are 60 miles from your starting

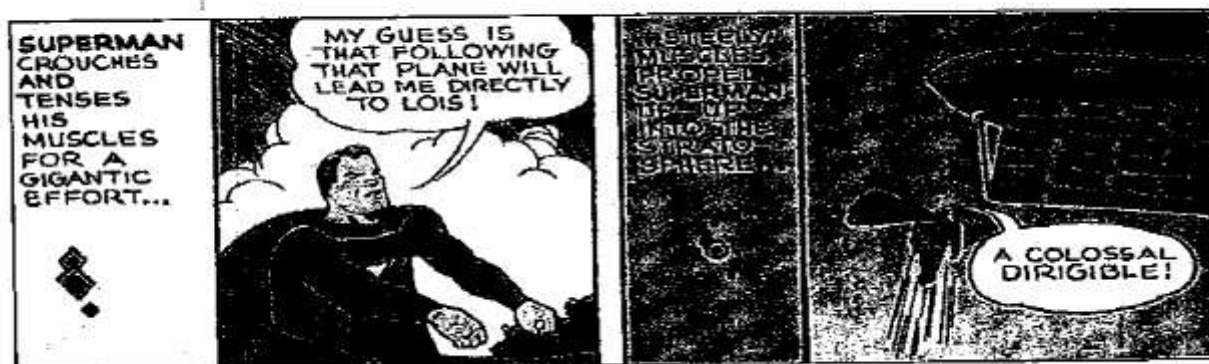
point. Because we don't know how long Superman's leap lasts, but only his final height of $h = 660$ feet, we perform some algebraic manipulation of definition that acceleration is the change in speed over time and that velocity is the change in distance over time. When the dust settles we find that the relationship between Superman's initial velocity v and the final height h of his leap is $v \times v = v^2 = 2gh$. That is, the height Superman is able to jump depends on the *square* of his liftoff velocity, so if his starting speed is doubled, he rises a distance four times higher.

Why does the height that Superman can leap depend on the square of his starting speed? Because the height of his jump is given by his speed multiplied by his time rising in the air, and the time he spends rising *also* depends on his initial velocity. When you slam on your auto's brakes, the faster you were driving, the longer it takes to come to a full stop. Similarly, the faster Superman is going at the beginning of his jump, the longer it takes gravity to slow him down to a speed of zero (which corresponds to the top of his jump). Using the fact that the (experimentally measured) acceleration due to gravity g is 32 feet per second per second (that is, an object dropped with zero initial velocity has a speed of 32 feet/sec after the first second, 64 feet/sec after the next second, and so on) the expression $v^2 = 2gh$ tells us that Superman's initial velocity must be 205 feet/sec in order to leap a height of 660 feet. That's equivalent to 140 miles per hour! Right away, we can see why we puny Earthlings are unable to jump over skyscrapers, and why I'm lucky to be able to leap a trash can in a single bound.

In the above argument we have used Superman's average speed, which is simply the sum of his starting speed (v) and his final speed (zero) divided by two. In this case his average speed is $v/2$, which is where the factor of two in front of the gh in $v^2 = 2gh$ came from. In reality, both Superman's velocity and position are constantly decreasing and increasing, respectively, as he rises. To deal with continuously changing quantities, one should employ calculus (don't worry, we won't) while so far we have only made use of algebra. In order to apply the laws of motion that he described, Isaac Newton had to first *invent* calculus before he could carry out his calculations, which certainly puts our difficulties with mathematics into some perspective. Fortunately for us, in this situation, the rigorous, formally correct expression found using

calculus turns out to be exactly the same as the one obtained using relatively simpler arguments, that is $v^2 = 2gh$.

How does Superman achieve this initial velocity of more than 200 feet/sec? As illustrated in fig. 5, he does it through a mechanical process that physicists term "jumping." Superman crouches down and applies a large force to the ground, causing the ground to push back (since forces come in pairs, according to Newton's third law). As one would expect, it takes a large force in order to jump up with a starting speed of 140 mph. To find exactly how large a force is needed, we make use of Newton's second law of motion, $F = ma$ —that is, Force is equal to mass multiplied by acceleration. If Superman weighs 220 pounds on Earth, he would have a mass of 100 kilograms. So to find the force, we have to figure out his acceleration when he goes from standing still to jumping with a speed of 140 mph. Recall that the acceleration describes the change in velocity divided by the time during which the speed changes. If the time Superman spends pushing on the ground using his leg muscles is $1/4$ second, then his acceleration will be the change in speed of 200 feet/sec divided by the time of $1/4$ second, or 800 feet/sec^2 (approximately 250 meters/sec^2 in the metric system, because a meter is roughly 39 inches). This acceleration would correspond to an automobile going from 0 to 60 mph in a tenth of a second. Superman's acceleration results from the force applied by his leg muscles to get him airborne. The point of $F = ma$ is that for any change in motion, there must be an applied force



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Fig. 5. Panels from Action comics # 23, describing in some detail the process by which Superman is able to achieve the high initial velocities necessary for his mighty leaps.

and the bigger the change, the bigger the force. If Superman has a mass of 100 kilograms, then the force needed to enable him to vertically leap 660 feet is $F = ma = (100 \text{ kilograms}) \times (250 \text{ meters/sec}^2) = 25,000 \text{ kilograms meters/sec}^2$, or about 5,600 pounds.

Is it reasonable that Superman's leg muscles could provide a force of 5,600 pounds? Why not, if Krypton's gravity is stronger than Earth's, and his leg muscles are able to support his weight on Krypton? We calculated that when making his greatest leap, Superman's legs must provide a force of 5,600 pounds. Suppose that this is 70 percent larger than the force his legs supply while simply standing still, supporting his weight on Krypton. (This is being generous, as when most people jump they can only apply a force approximately equal to their standing weight.) In this case, Superman on his home planet would weigh 3,300 pounds. His weight on Krypton is determined by his mass and the acceleration due to gravity on Krypton. We assumed that Superman's mass is 100 kilograms, and this is his mass regardless of which planet he happens to stand on. If Superman weighs 220 pounds on Earth and nearly 3,300 pounds on Krypton, then the acceleration due to gravity on Krypton must have been 15 times larger than that on Earth.

So, just by knowing that $F = ma$, making use of the definitions "distance = speed \times time" and "acceleration is the change in speed over time," and the experimental observation that Superman can "leap a tall building in a single bound," we have figured out that **the gravity on Krypton must have been 15 times greater than on Earth.**

Congratulations. You've just done a physics calculation!