Omnipresent physics in technologies and other scientific fields

from the physics knowledge in secondary/high schools

by

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Chapter 1: Classical mechanics laws and their technological applications

I.1. Introduction

Classical physics is based on Newtonian mechanics, thermodynamics and Maxwell's theory of electromagnetism. Most of its laws were discovered before the beginning of the twentieth century.

In this chapter, we are concerned with the presentation of the Newton's laws of motion and the universal gravitation law and their impacts on technology. Special attention is paid on some historical facts on these laws and on the scientists who discovered these laws.

I.2. Newton's laws of motion

I.2.1. Newton's biography

Newton was born on Christmas Day in 1642. He lived an amazing life. Here is a few interesting information about this important figure of the scientific revolution.

- **Newton's life started roughly**: His father died months before he was born. Newton's chances of survival seemed slim at the beginning. He was a premature and sickly infant and people thought he would not live long. When he was three years old, his mother, Hannah, remarried, and his new stepfather, Reverend Barnabas Smith, wanted nothing to do with Isaac. He was then sent to his maternal grandmother who raised him for many years. The loss of his mother put him in a lingering insecurity which affected the rest of his life.

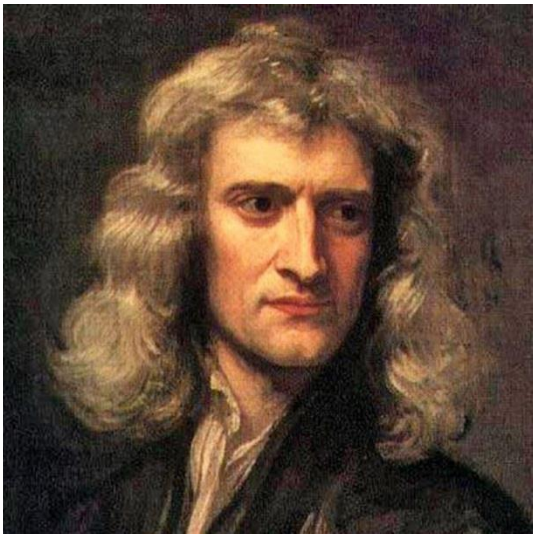

Figure I.1: Lord Isaac Newton, father of the classical mechanics

- **Newton was deeply religious :** Because of fear of God, he always wrote a list of his sins in one of his notebooks. At Trinity College at Cambridge University, he divided these sins into acts that happened before and after Whitsunday 1662, or the seventh Sunday after Easter. Newton took even small lapses quite seriously, such as having unclean thoughts or using the Lord's name. This list showed a darker side of Newton (as other humans). For instance, one of the sin he wrote was the threat to burn his mother and stepfather in their home.

- **A career boost from the Great Plague of 1665 :** Newton obtained his bachelor degree at Cambridge University Trinity College in 1665 and wanted to continue his studies. But because of an epidemic of the bubonic plague, the university closed its doors (during the first seven months of the outbreak, roughly 100,000 London residents died). Newton was thus compelled to return back home at Woolsthorpe Manor. Back there, Newton began working on some of his most important theories: explanation of planetary motion and understanding of light and colors. It is indicated that Newton made advances in his theory about gravity by observing an apple fall from a tree in his garden.

- **Newton was considered one of England's leading thinkers :** Long before the publication of his famous book on mechanics, Newton was already a famous scientist in England. He was named the Lucasian professor of mathematics at Cambridge in 1669, taking over the post from his mentor Isaac Barrow. Later geniuses to hold this position included Charles Babbage (also known as "the father of computing"), Paul Dirac and Stephen Hawking.

- **Newton's conflicts with other scientists and mathematicians :** With Robert Hooke, a scientist best known for his microscopic experiments, Newton had a long-lasting grudge match. Hooke thought Newton's theory of light was wrong and denounced the physicist's work. They later clashed over planetary motion with Hooke claiming that Newton had taken some of his work and included it in his great book "Philosophiae Naturalis Principia Mathematica". Newton also had dispute with the German mathematician Gottfried Leibniz the first discoverer of the infinitesimal calculus. Leibniz accused Newton of having stolen his ideas. Because of that, the Royal Society (known as the England Academy of Sciences) launched an investigation in 1712. The Royal Society came out with the conclusion that Leibnitz claim was not true. This conclusion was a little bit shadowed by the fact that Newton was the president of the Royal Society at that time. But, it was later determined that Newton and Leibnitz had probably made their discoveries independent of each other.

- **Political career:** Newton was elected Member of Parliament two times as a representative for Cambridge (first in 1689 and second in 1701). He actively contributed to the economic life of his country. Indeed, after being appointed Warden of the Royal

Mint in 1696, Newton became the master of the mint three years later and changed the English pound from a sterling to gold standard.

- **Newton honored by the king:** Newton was a famous and wealthy man at the time of his death in 1727. He was mourned by the nation and his body lay in state in Westminster Abbey. The Lord Chancellor was one of his pallbearers. Let us mention that the Westminster Abbey is a place where the remains of famous people are kept, such those of England monarchs and distinguished scientists (for instance Charles Darwin and recently Stephen Hawking remains are near those of Newton).

- **In 1687, Newton published one of the most important scientific books in history, the *Philosophiae Naturalis Principia Mathematica*, commonly known as the *Principa*** or **Mathematical Principles of the Natural Philosophy** in English It was in this work that he first laid out his three laws of motion which describe the motion of massive bodies and how they interact. They describe the relationship between a body mass and the forces acting upon it, and its motion in response to those forces. While Newton's laws may seem obvious to us today, they were considered revolutionary. They are given below. They form the foundation of what is now known as *classical mechanics*, which is the study of massive objects.

I.2.2- Formulation of the Newton's laws of motion and history

Newton's laws of motion describe the motion of massive bodies in an inertial reference frame, sometimes called a Newtonian reference frame. An inertial reference frame can be described as a three-dimensional coordinate system that is either stationary or in uniform linear motion (not accelerating or rotating). Newton found that the motion within such an inertial reference frame can be described by three simple laws.

I.2.2.1. First Newton's law and history

a- Formulation of the Newton's first law of motion

The First Law of Motion states, ***"A body at rest will remain at rest, and a body in motion will remain in motion unless it is acted upon by an external force."***

This simply means that bodies cannot start, stop, or change direction all by themselves. It takes some force acting on them from the outside to cause such a change.

This first law can be stated mathematically as

$$\sum \vec{F}_i = 0 \Leftrightarrow \frac{d\vec{v}}{dt} = 0 \qquad (1.1)$$

Meaning that if the resultant of forces $\vec{F}_i$ acting on a body is equal to zero, then its velocity v remains equal to zero or conserves a constant value.

Consequently,

- An object that is at rest will stay at rest unless a force acts upon it.
- An object that is in motion will not change its velocity unless a force acts upon it.

This law is used for uniform motion or for the problems of statics (static equilibrium in mechanics) for which one sometimes adds the equilibrium of torques.

b- Historical facts on the Newton's first law of motion

The Muslim scholar Abu ʻAlī ibn Sīnā (980–1037), known in the West as Avicenna, stated that "Nobody begins to move or comes to rest of itself.". This is probably the earliest precursor of the first law and that revelation would reemerge centuries later.

Galileo Galilei (1564–1642) wrote later "imagine any particle projected along a horizontal plane without friction; then we know that this particle will move along this same plane with a motion which is uniform and perpetual provided the plane has no limits."

Although Galileo was close to the law of inertia, he never fully articulated it. By contrast, the mathematician René Descartes (1596–1650) imagined that inertial motion was both uniform and rectilinear. Without experimentation, he reformulated Galileo's conception in the following manner: "It is one of the laws of Nature that all things will continue in the State they once are, unless any external cause interposes".

As early as 1613–1614, Beeckman maintained (as had Avicenna) that an object in motion stays in motion because it cannot, by itself, do otherwise. He knew that it takes an external force to change motion, but he wrongly thought inertia was both linear and circular. Intimidated by Descartes's denunciations, Beeckman never published his own brilliant conclusions, which he had freely shared with Descartes. Some of his journals did find their way into print (1644); but that was only years after his death.

While an undergraduate, Newton came to appreciate Galilean relativity. Galilei imagined a ship moving at constant velocity in a calm sea. He concluded (1632) that no observer could determine, from the behavior of any number of mechanical devices located in an isolated cabin, the speed of the vessel. He asserted that "Nor could you tell from any of them whether the ship was moving or standing still."

In 1684, prompted by Dr. Edmond Halley, Newton at 42 began the great work revolutionizing the dynamics of bodies. He produced a nine-page monograph titled De motu corporum in gyrum (i.e., On Motion of Bodies in Orbit). His efforts over the next two and half years culminated in the publication of Philosophiæ Naturalis Principia Mathematica (Mathematical Principles of the Natural Philosophy), a book that changed physics.

I.2.2.2- Second Newton's law of motion and history

a- Formulation of the Newton's second law of motion

The Newton's second Law of Motion describes what happens to a body when it is acted upon by an external force. It states, ***"The force acting on an object is equal to the mass of that object times its acceleration."***

This is written in mathematical form as

$$\vec{F} = m\vec{a}, \tag{1.2}$$

where $\vec{F}$ is the force, m is the mass, and $\vec{a}$ is the acceleration. Force and acceleration are *vector* quantities, which means they have both magnitude and direction. The force can be a single force, or it can be the vector sum of more than one force, which is the net force after all the forces are combined.

In a more general perspective, the Newton's second law of motion indicates that the net force on a body is equal to the time rate of its momentum. Mathematically, it has the following form:

$$\vec{F} = \frac{d\vec{p}}{dt} \tag{1.3}$$

where $\vec{p}$ is the momentum. Substituting the definition of momentum into that expression, the quantitative expression of Newton's second law becomes:

$$\vec{F} = \frac{d\vec{p}}{dt} = m\frac{d\vec{v}}{dt} + \vec{v}\frac{dm}{dt} = m\vec{a} + \vec{v}\frac{dm}{dt} \tag{1.4}$$

When the mass is constant, equation (1.4) reduces to equation (1.2).

b- Historical facts on the Newton's second law of motion

The initial formulation of the Newton's second law of motion stated that there is a direct proportionality between the force acting on an object and something he called the "quantity of motion." In the Principia, the second law states that: A change in motion is proportional to the motive force impressed and takes place along the straight line in which that force is impressed.

I.2.2.3- Newton's third law of motion and history

a- Formulation of the Newton's second law of motion

The Third Law of Motion, or principle of action and reaction or principle of reciprocal actions, states, ***"For every action, there is an equal and opposite reaction."***

When you exert a force on the wall, you experience the wall exerting a force back on you. Forces act in pairs on different objects. The force exerted by the second object is **equal in strength** and **opposite in direction** to the first force. So when one body pushes against another, the second body pushes back just as hard. For example, when you push a cart, the cart pushes back against you. When you pull on a rope, the rope pulls back against you. When gravity pulls you down against the ground, the ground pushes up against your feet; and when a rocket ignites its fuel behind it, the expanding exhaust gas pushes on the rocket causing it to accelerate.

b- Historical facts on the Newton's third law of motion

In the English translation of the third edition of the Newton's book, Newton's own statement of the third of his three laws of motion reads "To every action there is always opposed and equal reaction; or the mutual actions of the two bodies upon each other are always equal, and directed to contrary parts" . Newton's examples, immediately following this statement, include the forces of a finger on a stone and the stone on the finger, the forces between a horse and a stone (both of which are connected by a rope), the forces between two colliding bodies, and 'attractions' between objects. That is, forces, such as gravity, which act at a distance rather than through direct contact.

I.2.3. Types of forces

We use forces every day of our lives. Our own body relies on forces. Our muscles pull on our bones to allow us to move. Our feet push on the ground when we walk. To open doors, to pick up our food. Everything we do involves some kind of force.

- Forces can change the shape of an object. This is called deformation.
- Forces can change the motion of an object. If an object is stationary, a force can cause the object to start moving. Or, if an object is already moving, a force can cause an object to speed up or slow down.
- Forces can change the direction in which an object is moving.

There are contact forces and non-contact forces.

a- Contact forces

Contact forces are those between objects which are touching each other. One can cite:

- friction forces caused by the contact (dry force and viscous force),
- normal forces created by a surface on which a body is seated,
- tension and compression forces,
- pressure forces,
- pulling and pushing forces.

b- Non-contact forces

Non-contact forces are due to fields (gravitational, magnetic and electric fields).

- The gravitational forces are attractive forces between massive bodies.

-Magnetic forces are those exerted between magnets, by magnets on magnetic materials (such as iron, nickel and cobalt), by magnets on electric wire in which an electric current is flowing, or by magnets on an electrically moving charged particle.

-Electric forces are forces exerted between electrically charged bodies or by an electric field on electrically charged bodies.

Let us note that both the magnetic and electric forces can act on an electrically charged body. In this case, one is in presence of the Lorentz force.

More details on some of these forces will be given in the document.

I.2.4. Technological applications of Newton’s laws of motion

The three Newton’s laws of motion have been verified by countless experiments. They are used in various technological applications which are familiar. Their familiarity is so that we do not even think that they have been conceived thanks to the Newton’s laws and their extension to rotating and elastic motions.

Indeed,

- Any technological and natural object in static equilibrium obeys the first and third Newton’s laws.
- Any technological and natural object which moves obeys the first and second Newton’s laws.

A house, a skyscraper, a bridge stands still because of the applications of the Newton’s laws which help to prepare the ground on which the huge mass will stand and applying a reaction equal to the weight without deformation. A ship can stand over the sea because of the principle of action and reaction (the Newton’s third law). An airplane flies at a given fixed altitude without going down to the ground because engineers have worked so that the lifting force due to the air is equal to the airplane weight including passengers and goods. A tree stands still in a given position because of the equivalence between the pressure (or tree weight) of its roots on the soil and the reaction created by the soil (in this case, the nature has found out how to distribute the weight through the roots which also help the tree to rest in its vertical position by imposing a reaction to wind pressures).

We can seat still on chairs or a benches in class because they are made of materials which are capable of creating reaction opposed to our weight; if not the bench or chair will collapse.

A car can stay fixed on inclined plane thanks to the brakes which are managed so as to compensate the difference between the component of the car weight along the plane line and the dry friction on the wheels.

At the other side, a bird flying applies the Newton’s second law of motion to monitor its velocity. Same for a human who can walk or run at constant velocity (first law) or at varying velocity (second law). If we want to change our velocity, we naturally increase our efforts so as to attain what we want. Similarly, a bicycle push, a motor for motorbikes, cars, ship and airplane is constituted so that we have means to create motion forces which will lead to an appropriate constant or variable velocity. These means to manage motors are based on Newton’s first and second laws which guide how to obtain the good internal structure and functioning of the motors (either thermal or electric).

Having a satellite moving from the ground to the space requires a good use of the Newton’s laws.

Figure I.2: Bamiléké wooden house and a cement house

Figure I.2 presents two types of houses which stand still because of the Newton’s first law is satisfied inside their parts and in their contact with the ground. The first one is a Bamiléké house in Cameroon, made of wood (bamboo) and covered with special grass. The second one is what is termed modern house, made of concrete.

Figure I.3: Wooden skyscraper in Norway

Figure I.3 is skyscraper constructed in Norway. It is surprisingly made of wood contrary to most skyscrapers which are made of concrete and metal. This is an interesting application of the Newton's first law both for the solid structure and for the flexible structure. Several high skyscrapers exist in the World and one of the highest is the Kingdom or Jeddah Tower in Saudi Arabia whose height will reach 1000 m.

Figure I.4: An airplane

Figure I.5: A ship in the sea

Figures I.4 and I.5 are another demonstrations of human skills in applying physics laws. These are the plane and ship which are constructed under a high respect of the Newton's first law for rigid and flexible mechanical structures. At the same time, they move in the air and in the sea thanks to appropriate shapes and motors which function to make respect of the Newton's second law for different types of motion and under different types of constraints.

I.3. Universal gravitation law

I.3.1. Historical facts

Newton's earliest studies on the laws of motions occurred during the Winter of 1664. As in the case of mathematics, his starting point was Descartes. He commented upon Book 2 of Descartes's Principia philosophiae (1644) with particular penetration. It is believed that the title of Newton's book was conceived of as a criticism to the French philosopher, whose work would have lacked adequate mathematical principles. From Descartes, Newton learned about the law of inertia: what was to become the first law of motion of the Principia.

By the early 1660s, natural philosophers had concerned themselves with two cases of accelerated motion: rectilinear uniformly accelerated and uniform circular motion. The first case occurred in the fall of bodies and gave rise (as Galileo had taught) to parabolic trajectories by composition of inertial and uniformly accelerated motions. From the very beginning of his studies, Newton was trying to subject the motions of bodies to mathematical laws. His first mathematical law in this field is nowadays attributed to Christiaan Huygens (1629–1695) since it was first published in 1673 in the Horologium oscillatorium. In modern terms, the laws say that the centripetal acceleration of a body which moves in a circular trajectory with constant speed is proportional to the square of the speed and inversely proportional to the radius. In 1665, Newton tried to generalize his mathematical results on uniform circular motion to more general cases. Newton understood that the instantaneous normal acceleration a_N in a non-circular orbit can be calculated by applying locally Huygens laws for circular uniform motion. In modern terms, this normal acceleration is given by formula (1.5):

$$a_N = \frac{v^2}{r} \tag{1.5}$$

(v is the instantaneous speed, r is the radius of curvature).

Prehistoric man realized a long time ago that when objects are released near the surface of the Earth, they always fall down to the ground. In other words, the Earth attracts objects near its surface to itself.

Galileo (1564-1642) pointed out that heavy and light objects fall toward the earth at the same rate (so long as air resistance is the same for each). But it took Sir Isaac Newton (in 1666) to realize that this force of attraction between masses is universal. Newton proved that the force that causes, for example, an apple to fall toward the ground is the same force that causes the moon to fall around, or orbit, the Earth. This universal force also acts between the Earth and the Sun, or any other star and its satellites. Each attracts the other.

According to early accounts, Newton was inspired to make the connection between falling bodies and astronomical motions when he saw an apple fall from a tree and realized that if the gravitational force could extend above the ground to a tree, it might also reach the Sun. The inspiration of Newton's apple is a part of worldwide folklore and may even be based in fact. Great importance is attached to it because Newton's universal law of gravitation and his laws of motion answered very old questions about nature and gave tremendous support to the notion of underlying simplicity and unity in nature.

I.3.2. Formulation of the universal gravitational law

Gravitational attraction is along a line joining the centers of mass of these two bodies (see Figure I.6). The magnitude of the force is the same on each, consistent with Newton's third law.

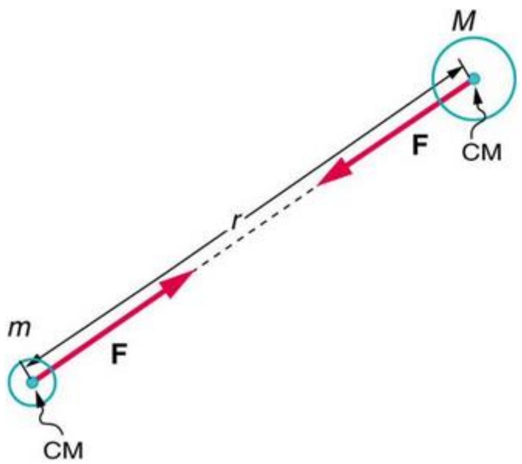

Figure I. 6: Two bodies interacting through the gravitational force

The Law of Universal Gravitation states that every mass attracts every other mass in the universe by a force pointing in a straight line between the centers-of-mass of both masses, and this force is proportional to the masses of the objects and inversely proportional to their separation. This attractive force always points inward, from one point to the other. The law applies to all objects with masses, big or small. Two big objects can be considered as point-like masses, if the distance between them is very large compared to their sizes or if they are spherically symmetric. For these cases, the mass of each object can be represented as a point mass located at its center-of-mass. While Newton was able to articulate his Law of Universal Gravitation and to verify it experimentally, he could only calculate the relative gravitational force in comparison to another force. Since a body of mass *M* experiencing a force *F* accelerates at a rate *F*/*M*, a force of gravity proportional to *M* would be consistent with Galileo's observation that all bodies accelerate under gravity toward Earth at the same rate). In 1798, Henry Cavendish's determined the gravitational constant and the Law of Universal Gravitation received its final algebraic form (Newton's equation):

$$F = \frac{GmM}{r^2} \tag{1.6}$$

where F represents the force in Newton, M and m represent the two masses in kilograms, and r represents the separation in meters. G represents the gravitational constant, which has a value of $6.674\times10^{-11}\ N(m/kg)^2$. Because of the magnitude of G, gravitational forces are very small unless large masses are involved.

Isaac Newton put forward the law in 1687 and used it to explain the observed motions of the planets and their moons, which had been reduced to mathematical form by Johannes Kepler early in the 17th century. Kepler published the first two laws for orbital motion in 1609 in Astronomia nova then the third in 1619 in Harmonices Mundi.

I.3.3. Impact of the universal gravitational law on technology

a- **Planets orbiting around the Sun**.

We can now use Newton's Law to derive some results concerning planets in circular orbits. Although we know from Kepler's Laws that the orbits are not circular, in most cases approximating the orbit by a circle gives satisfactory results. All the planets in our solar system are held in orbit around the Sun by the gravitational force of attraction between the Sun and planets (Figure I. 7).

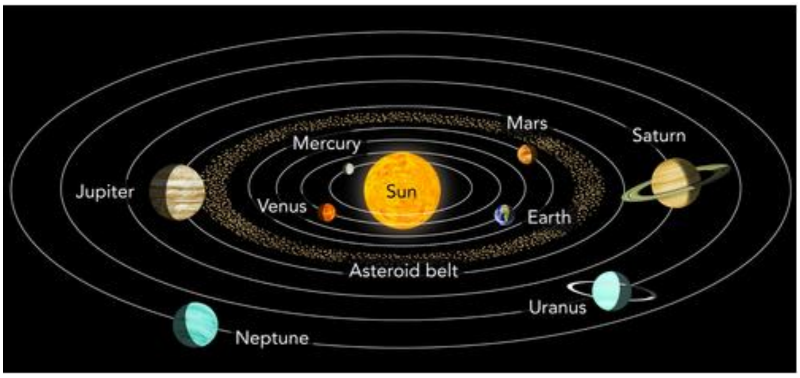

Figure I.7: The planetary system

b- Placing satellites in orbits and applications

To put satellites in orbits, the Newton laws and gravitational law are used as the mechanical part is concerned. To launch the satellites from the ground to the air, one needs to create a force able to compensate the huge mass of the satellite and the fuel, but also to provide the appropriate acceleration necessary to put the satellite at the required orbit.

For the first stage of the satellite propulsion, the main mechanical law used (assuming that all other requirements are met, for instance resistance of materials to heat and pressure), is the Newton's second law applied on the whole satellite system, but also on individual parts in the system including humans. This law is applied while taking into account the fact that the total mass is variable because of the exhaust of gas coming from the consumption of fuel. This application of the Newton's second law for satellites propulsion is explained in physics textbooks either in the course or in an exercise.

Now when the satellite moves upwards, it finally reaches an altitude where there is a compensation between the centrifugal force and the satellite weight which is the centripetal force (the application of the gravitational law). One thus uses the equilibrium condition between the two forces to obtain the linear and rotational velocity of the satellite in its orbit. This is also well described in physics text books in secondary/high schools.

A satellite is placed in orbit for technological applications which can be divided as follows:

- weather forecast: analysis of the current state of the atmosphere for safety prevision.

- broadcasting services: television and radio stations are nowadays based on satellites which contain the electronic and computing devices to receive, treat and transmit messages.

- mobile telecommunication broadcasting services: same as for radio and television.

- earth observation: In this case, the satellite has observation systems which help to see many features that are difficult to see from the earth surface or at the altitudes at which aircrafts fly.

- the Global Positioning System (GPS): GPS is used to determine accurately the geographical locations or exact positions of any object or being on the Earth using radio waves propagating at the speed of light. It is based on an ensemble of more than 24 satellites evolving around the Earth at the altitude of about 20 000 km (Figure I.8). It is thus used for several tracking purposes. One of its current applications is the navigation system in cars, ships and airplanes.

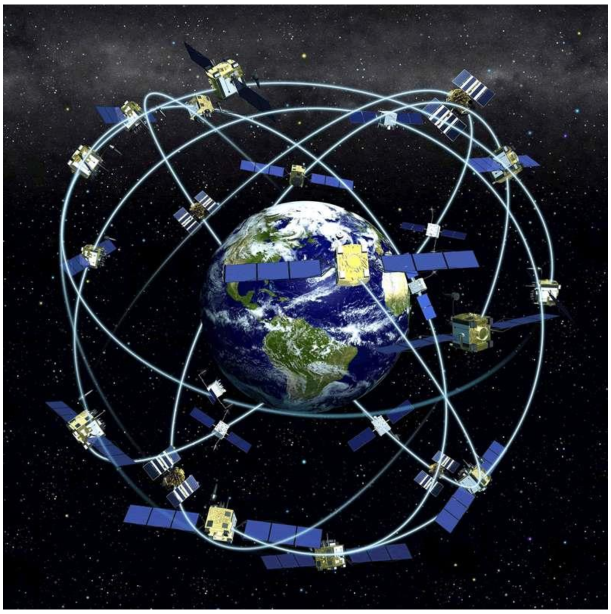

Figure I.8: The GPS satellites system around the Earth

I.4. Conclusion

This chapter has been concerned with the Newton's laws of motion and the universal gravitation law. Historical facts behind the formulation of these laws have been presented. Some technical and technological applications have been indicated. Other applications of these laws exist. But they cannot be part of this book because of the target of the book. For instance, Newton's laws have been extended to the mechanics of deformable bodies such as elastic materials and fluids. Understanding this extension during the university studies will open ways to discover the huge list of the classical mechanics applications in technology. This is also the case for the gravitational law which is important for the understanding of the mechanics of the whole universe.

In the following chapter, we are interested by other laws of classical physics and their applications. Specifically, the next chapter presents historical facts and applications of laws derived by Ohm, Faraday, Lenz and Snell plus Descartes.