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# Mechanical springs: from historical origins to modern applications

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*The history of springs is a fascinating narrative that spans from primitive uses to sophisticated applications in modern engineering, shaped by technological advancements, military necessities, and material innovations. Initially, proto-springs were crafted from bent wooden branches for hunting purposes by our ancestors during the Stone Age. Then, each historic milestone in material science and metallurgy enabled to enhance spring shapes and elastic properties. These progresses allowed springs to be integrated into siege engines in Antiquity, accurate clock mechanisms during Renaissance, valve in steam engines during the Industrial Revolution and vehicle suspensions in the last century. Today, springs play a vital role across a diverse range of applications, characterized by their various geometries, materials, and functions. From enhancing athletic performances to performing precise and delicate surgeries and deploying solar panels on satellites, springs are integral to modern daily life and technology. Their adaptability allows them to be designed in numerous forms and size, each tailored for specific tasks, from nano-cantilever springs for metrology to the several-meters-high helical springs for mining vehicles. The selection of materials, such as steel, plastic, ceramic and composites, further expands their applicability and durability in different environments. As innovation continues, the versatility of springs ensures their continued relevance and importance in both existing and emerging technologies.*

## 1 INTRODUCTION

Elastic components comprise the set of connections that absorb a specific amount of energy, received in the form of force or torque, during deformation, and subsequently release this energy by returning to their original shape at varying rates [1–3]. The restitution of energy can be either total or partial, with some degree of damping. This definition is quite broad, as it applies to any material entity exhibiting elastic behavior within a given range. Essentially, this includes solids, liquids, and gases such as a carbon/epoxy paddle shaft, a rubber golf ball, tree branches, air in a basketball, helicopter blades, or oil in a hydraulic cylinder. However, springs typically endure much larger elastic deformations than other materials [4]. It is generally accepted that mechanical springs, unlike elastomeric components, exhibit minimal damping and nearly fully return the energy stored during deformation. For this reason, the ISO standard [5] defines a spring as "mechanical devices designed to store energy when deformed and release the same amount of energy when relaxed." This paper will focus specifically on quasi-pure elastic components; elastomers, other polymers, and air springs that exhibit significant damping capacities are beyond the scope of this study.

Therefore, in this document, the term "spring" refers to the set of mechanical components specifically designed to absorb a certain amount of energy through deformation (received in the form of force or torque) and subsequently release it more or less quickly as they return to their initial

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shape, without significant damping. Elastic components can be employed to apply force, control motion, regulate vibration, or mitigate impacts, among other functions [6, 7]. This paper objectives are first to recount the historic evolution of mechanical springs and why these milestones have impacted the solids we know today, and in a second time to highlight the diversity of modern applications they are integrated in.

Historical periods are challenging to evaluate precisely because the pace of technological evolution varies significantly across different regions of the world. While some areas may undergo rapid advancements, others develop more slowly, influenced by unique cultural, environmental, and economic factors. As a result, a period defined by specific technological milestones in one region might not correspond to the same time-frame elsewhere [8]. Thus, the date ranges of the following section names are provided for informational purposes only, enabling the reader to more easily identify the sections where relevant data can be found.

## 2 HISTORIC REVIEW

### 2.1 Stone Age (~2.5 million years BCE - ~2,000 BCE)

It is often considered that the earliest elastic components appeared in the form of bows, which our ancestors used for hunting [2]. Bows function by storing elastic energy in the flexible wooden limbs when the string, made from fiber, leather, or gut, is drawn back [3, 9], then released to propel the arrow towards the target. The nocks, small depressions either at the ends of the bow or on the arrow, help secure the string or stabilize the arrow during release [10]. Stone arrowheads found in South Africa, dating back over 60,000 years [11], would suggest that the technology of elastic components is at least that old. However, projectile heads alone do not confirm the use of bows, as they could have been launched by other methods, such as spear-throwers [12] or like darts. Depictions of arrows appear in Franco-Cantabrian cave art, such as in Lascaux (~15,000 BCE) and Niaux (~13,000 BCE), where arrows are shown wounding animals like horses, reindeer, and bison [13–15]. Despite these representations, definitive proof of bow usage requires the discovery of actual bows or unmistakable depictions [12]. In Europe, painted bows first appear between 12,000 BCE and 10,000 BCE in the Mediterranean region, particularly in Spain's Levant (e.g., Morella la Vella's battle between archers [16, 17] and bow hunters in Remígia [18]). Additionally, well-preserved arrow shafts from ~8,800 BCE were found in the waterlogged sediments of Stellmoor

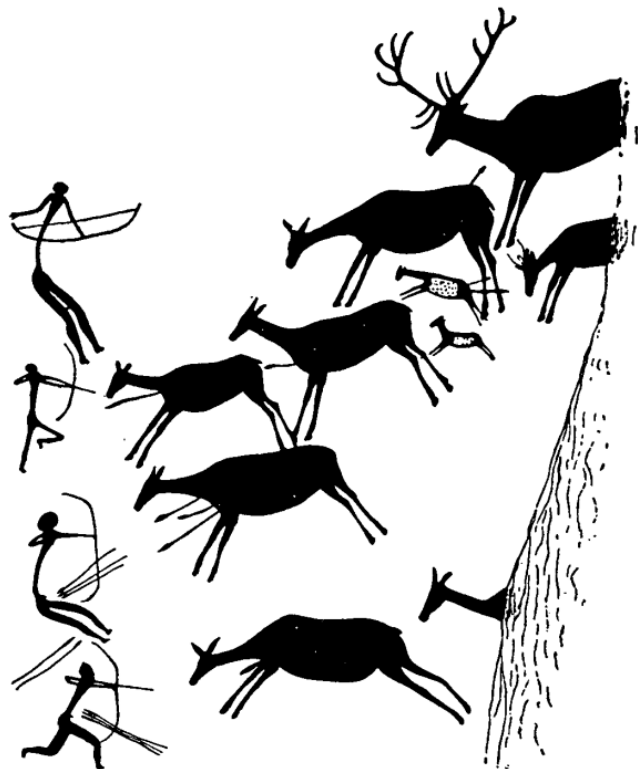


Fig. 1. Rock-painting from the Cueva de los Caballos, Castellón, east Spain, showing deer driven into a line of bowmen [12].

[12]. More recently, the discovery at Mandrin may push the origin of archery in Europe back by more than 40,000 years, as very light arrows, likely launched by bows, have been found [19].

Prehistoric people also employed spring snares to trap and hunt small animals. These snares used mechanical energy stored in a bent branch or bone, which was released when an animal triggered the mechanism. The noose would then catch the animal by the foot or neck. This method operated similarly to a bow, utilizing the potential energy stored in the bent branch, which would suddenly release when triggered, enabling a swift and efficient capture, either by lifting the animal off the ground or strangling it [20–23]. Snares were used worldwide [21–23]. Unfortunately, most prehistoric snares were crafted from perishable materials such as hair, plant fibers, or wood, which rarely survive due to exposure to non-dry environments. The oldest evidence of snare usage dates back to 7,000 BCE [24]. Some indigenous groups, such as the Eskimos, continued using snares well into recent times. For example, they crafted an S-shaped spit from whalebone tied with sinew and frozen in blubber. When swallowed by a polar bear or wolf, the warmth of the an-

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imal's stomach would cause the sinew to snap, releasing the spit, which would then spring open and fatally wound the animal [20, 21].

Stringed instruments likely originated around the same time as snares and bows, with the archer's bow and the musical bow being closely related in their development [25]. These one-string instruments, typically made from gut or sinew connected by a bent wooden stick, harness the elastic properties of the string. When tension is applied and released, the string not only returns to its original shape but also produces sound vibrations. The string's elasticity allows for repeated use of the instrument. Researchers have suggested [26] that early hunters may have also plucked these strings, altering the tension to vary the pitch by bending the stick or branch. Evidence supporting the use of these bows for musical purposes rather than hunting includes their small size, around 30 cm tall, which would not generate sufficient power for effective shooting [27].

A slingshot is a handheld projectile weapon that utilizes elastic materials to propel a projectile. The user pulls back on an elastic band attached to two prongs, with the projectile held in a pouch. Upon release, the stored elastic potential energy is converted into kinetic energy, launching the projectile with considerable force capable of puncturing skin or causing internal injuries [28]. While slingshots became widely popular in the 19th century, they have prehistoric analogs in various simple elastic weapons. Historical references to this ancient weapon appear in early writings, including the *Old Testament* [29], where David uses a slingshot against Goliath (approximately 650 BCE), as well as in Homer's *Odyssey* [30] (circa 750 BCE) and Sun Tzu's *The Art of War* [31] (approximately 500 BCE). However, studies indicate that slingshots likely first appeared during the Neolithic period, with archaeological evidence found in Iraq dating back to around 7,000 BCE [32].

## 2.2 Bronze Age (~3,300 BCE - ~1,200 BCE)

As a material for tools, metal offers two main kinds of advantages over wood, stone or bone: its mechanical and physical properties (hardness, yield, durability) and its chemical and forging characteristics (malleability, fusibility).

One of the oldest metallic elastic components is undoubtedly tweezers, along with their derived forms such as clamps, pliers, tongs, pincers, and forceps, with the terminology varying based on application and size. Tweezers typically consist of two opposing arms, often crafted



Fig. 2. Egyptian metal worker using tongs: tomb of Rekhmara [36].

from a single piece of metal (such as gold, silver, copper, or bronze), bent into a U-shape, allowing them to be pinched together to grasp objects. Historically, they were utilized for a variety of purposes, including the removal of hair, splinters, and thorns, handling small items for tool or jewelry creation, and managing hot pieces during forging or from the anvil. The term "forceps" is derived from the Latin words *ferrum* (meaning "iron") and *capere* (meaning "to hold"), reflecting their function in handling heated materials [33]. Evidence of tweezers' use has been found in various ancient civilizations. For instance, metalworkers' hieroglyphs depicting tweezers were discovered in the tomb of Rekhmara in Egypt, dating to approximately 1,400 BCE. Large forceps used for removing arrowheads have been traced back to around 3,300 BCE [34]. Further archaeological findings indicate that tweezers were also employed for epilation in Egypt around 3,100 BCE [35]. In addition to their use in Egypt, similar tools have been identified in the Middle East, Scandinavia, and the Alps of Europe, with records indicating their role in epilation and shaving as early as 3,000 BCE [34, 36–38]. Evidence from Mesopotamia also suggests their application in skin care around 2,500 BCE [34, 36, 39].

When Tutankhamun's tomb was opened in 1922, his personal chariots were unearthed, allowing archaeologists and historians to learn more about the technology used over 3,000 years ago (late Bronze Age). The chariots featured a complex suspension system made of wooden poles and leather, acting as leaf springs and shock absorbers, providing a more comfortable ride for the

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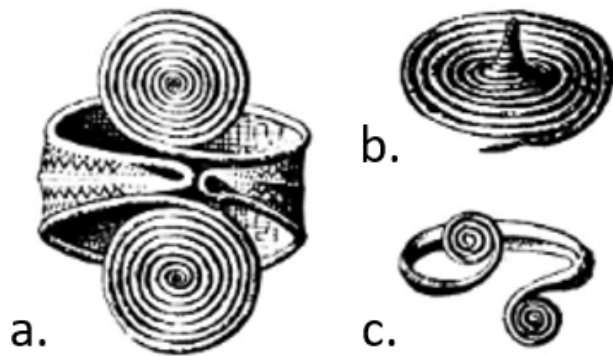


Fig. 3. Alsacian spiral-ended anklet (a), Hungarian armlet with spiral ends (b) Bavarian helical wire tutulus (c) [42].

pharaoh and also increasing the chariot's durability [40], while also providing more stability for chariot archers [41].

The Late Bronze Age also sees the emergence of the ancestors of modern helical springs, in the form of fibulae (brooches) and sophisticated jewelry. While jewelry was made of bronze or gold wire twisted into spirals for aesthetic purposes, fibulae served as small springs that fastened dresses or cloaks. This ancient safety pin was constructed from twisted wire, featuring a simple hooked end and a free end. A spring was incorporated to bring the free arm back into the hook catch. The number of coils in the spring part was dependent on the space required between the free and hooked arms to allow for the gripping of more fabric [42] (~1,350 BCE, Figure 3).

### 2.3 Iron Age (~1,200 BCE - ~600 BCE)

Throughout the Late Bronze Age, iron was present but remained relatively rare. It was primarily utilized for ornaments and for the repair of bronze items. The transition to the Iron Age was not characterized by the initial appearance of iron; rather, it began when the unique functional properties of iron were recognized, leading to its gradual replacement of bronze in the manufacture of tools and weapons.

The Iron Age saw significant improvements in older elastic tools, such as suspension systems in chariots for racing, introduced in 680 BCE during the Olympic Games [43], and for warfare, as evidenced by the Western Zhou Dynasty chariot excavated from the suburbs of Beijing, dating from 770 BCE [44]. Additionally, people from various regions, including Egyptians, Siberians, Mesopotamians, Europeans, Mongols, and Hittites, enhanced the power and range of wooden bows by creating



Fig. 4. Chinese three-spring lock [45].

composite bows made from wood, bronze, iron, and ivory [41]. By incorporating different materials along the bow, they modified its stiffness, allowing for a progressive evolution along the arm, which made the weapon more efficient [41].

Bronze leaf springs were utilized in China around 3,000 years ago as locks [45, 46] for the safety of doors, boxes, and chests (Figure 4). Barbed-spring locks are designed with a sliding peg and contain one to three flexible internal springs. These springs, akin to fish hooks, allow movement forward but resist backward movement. Upon entry into the lock, the barbed springs expand, preventing the removal of the lock peg until a key is used to compress the springs [47]. Leaf spring locks would not appear in Europe until centuries later [48].

### 2.4 Classical Antiquity (~800 BCE - ~600 CE)

In Classical Antiquity, elastic connections were extensively used in the creation of artillery and other siege engines, particularly by the Greeks and Romans [2], since at least 600 BCE [49]. Alexander of Macedon (356-323 BCE) was among those who encouraged their use; however, it was Archimedes, one of the greatest engineers of Antiquity, who created extraordinarily destructive engines during the siege of Syracuse by the Romans (214-212 BCE) [49]. Unlike trebuchets [50], which used a counterweight system, ancient catapults [49, 51-53] employed a torsion spring mechanism, with a bundle of fibers twisted to store energy (Figure 5). When triggered, the catapult's arm was propelled vertically by this stressed bundle, launching stones (or oil jars) into the air. The fiber bundle was typically made from horse or human hair. Ballistae [49, 51] operated similarly but resembled large crossbows. Instead of a bow, they utilized two bundles of twisted fibers on either side of the device to store torsion energy. The launched arrows could measure up to 3.5 meters in length and travel up to 300 meters. Catapults and ballistae employed complex winding mechanisms to draw the system. Onagers [51, 53] were lightweight cat-

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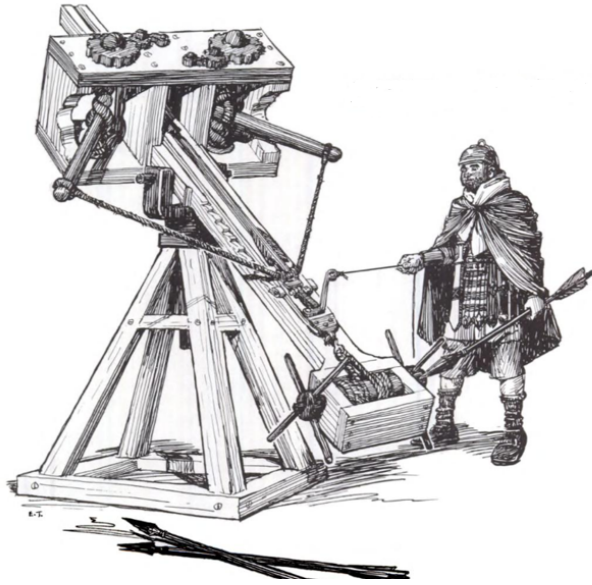


Fig. 5. Ancient catapult for javelins [49].

apult derivatives, equipped with a sling at the end of their throwing arms, enabling them to increase the distance a stone could be thrown by a third. Stronger or lighter variants of ballistae and catapults were developed during the same period, including Roman scorpions, *palintonon*, *oxybeles*, *euthytonon*, *cheiromballista*, and *polybolos* [53, 54]. The projectile energy evaluation of some of these siege engines, still visible on ancient wall damages, was recently assessed using modern spring calculations [54].

As for the crossbow, it was created in China during the Han dynasty (300 BCE) and only gained prominence in Europe in the 11th century [55, 56]. The crossbow operates by storing mechanical energy in a drawn string and flexed prod, which is released to propel a bolt when the trigger is pulled. A crossbow's locking mechanism maintains the draw, thereby reducing the shooter's effort to simply pulling the string into the lock and releasing it with a trigger. This design allows for greater draw weight and reduces physical strain, leading to improved precision and usability by less-skilled personnel. In Europe, a derivative of the crossbow, the *gastrophete* [49, 53], is described by the Greco-Roman scientist Heron of Alexandria in 100 BCE [52, 57].

## 2.5 Middle Ages (~500 CE - ~1,500 CE)

During the Middle Ages, an industrial revolution occurred in the 13th and 14th centuries, characterized by the use of windmills and watermills as wire drawing mecha-



Fig. 6. Medieval wire drawing process [59].

nisms, which had previously relied on hand-pulling [9] (as shown in Figure 6). By situating watermills under the arches of bridges on major rivers, the induced forces were significantly greater, enabling the working of metals and the production of brass and iron wires, as well as gold and silver [26]. These wires and cables enhanced musical instruments and ancient siege engines. The torsion bundles of organic fibers in these engines were replaced with bundles of metal wires, increasing their power and range. The *gastrophete* and crossbow evolved into the *arbalet*, while catapults and ballistae transformed into *mangonels* and *springalds* [58].

One of the greatest engineers of the Middle Ages, Villard de Honnecourt (~1200-1250), designed an automated vertical saw in the 13th century. This saw was powered by a watermill to cut into the wood log positioned below it. The backward movement of the saw was generated by a bent massive branch acting as a spring, which recoiled when the saw reached its lowest position under excessive stress [50, 60]. Similar sapling springs were used to reverse the motion of a lathe, which included a refinement in the form of a foot treadle. The pedal was usu-

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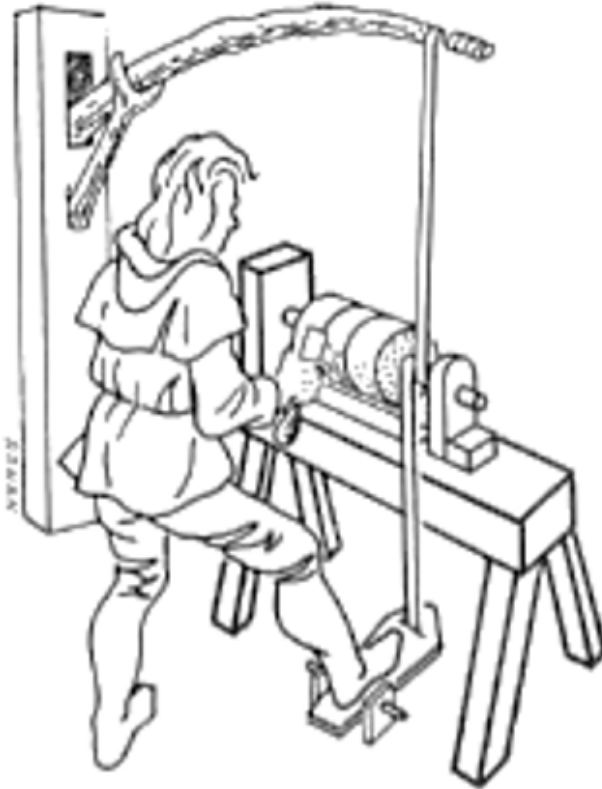


Fig. 7. Medieval spring-powered lathe [61].

ally connected by a cord to a pole, pulled in tension downward, so that after pushing the pedal, it would spring back due to the deflection of the pole [61] (Figure 7). Proofs of this spring-pole lathe mechanism are visible in a stylized stained glass window of Chartres Cathedral (1240) in France [62] and in an illustration from the *Bible of St. Louis* (1226-1234) [63].

In order to prevent locks from being picked, leaf springs were incorporated into European locks. Four types of springs were developed: the *ressort de renvois en paillette* (8th century [64]), the *ressort à gorge* (Carolingian dynasty, 9th century [64]), the *ressort de gâchette* (15th century [64]), and latch springs (15th century [65]). The first three types enable the latch and other lock components to be secured and held in position, rather than being locked solely by gravity [64]. The last type, a M-shaped leaf spring, facilitates the locking of two shutters from the inside [65]. The development of padlocks also led locksmiths to employ leaf springs [65, 66].

The medieval period is also known for its wide range of torture devices, reaching its peak around the 12th century. One such device, the Pear of Anguish, featured a

pear-shaped spring mechanism designed to be inserted into rectal, oral, or vaginal orifices [67]. The remaining examples of these ‘pears’ consist of three or four metal lobes connected at one end by a hinge. A coiled, spring-loaded internal mechanism forces the lobes apart, spreading them inside the victim, while retraction of the lobes is only possible through the manipulation of a secondary pin [68]. However, historians are skeptical about the use and dating of this object. Evidence for such anachronism includes a 19th-century boom in the production of counterfeit items related to medieval torture equipment [68], with some museum pieces revealing recent manufacture, the lack of written mention of the device before the 17th century [69] (despite it being considered an antiquity by that time), the high level of decoration on the surface of the lobes [68] (which is superfluous for torture devices), and the presence of the coiled spring [68] (as European metallurgy was unable to produce coiled springs until the 15th century). Therefore, the pear should be considered a surgical instrument, shoe extender, sock stretcher, or glove widener [68].

## 2.6 Renaissance (~1,400 CE - ~1,600 CE)

Indeed, the 15th century saw one of the major revolutions in metallurgy and spring making. Almost all previously mentioned spring devices are derivatives of modern leaf/flat springs. These consist of a thin piece of wood, bronze, or iron, designed to be bent to store propelling energy or ensure contact with other components. With the development of heat treatment [70], finery [70], uniform drawing [70], and foundry techniques [71, 72], as well as the mining and trading of resources from Africa and the Americas [73–75], the new manufacturing processes enabled the production of spiral springs [68, 76].

After sundials, water clocks, and hourglasses, mechanical clocks became omnipresent with weight- and pendulum-driven clocks from the 12th century onwards [77]. In both cases, a complex verge escapement mechanism controls the release of energy from the clock’s power source (either a weight or a pendulum), ensuring that the gears advance in precise and regular increments. Unfortunately, weight and pendulum clocks are significantly heavy and bulky. At the beginning of the Renaissance, the desire among the wealthy for cheaper, lighter, smaller, more accurate, and independent clocks grew stronger, driven by status, prestige, and practicality. Recent advances in spring manufacturing enabled blacksmiths in France, Italy, Germany, and Switzerland to develop the first clocks powered by spiral springs. Compared to weight-and-rope drives, a wound-up steel spring

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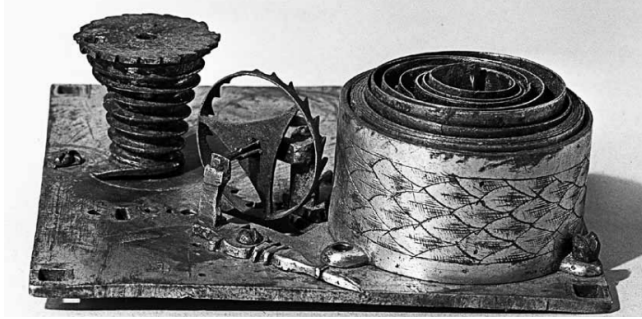


Fig. 8. Clock movement fragment with fusee and spiral mainspring dated 1509. Munich, *Bayerisches Nationalmuseum* [80].

(called the mainspring) has the advantage of releasing energy in any position and even while in motion, and it is significantly more compact. The disadvantages include uneven force release due to the progressive unwinding of the spring and the necessity for regular rewinding (daily, weekly, or yearly) [78]. To mitigate this problem, blacksmiths connected the spring to a conical drum (the fusee, first created in 1424 [61]) via a rope. As the spring uncoiled, the diameter of the cone increased, enhancing leverage and compensating for the weakening of the spring's pull force [57, 61, 78, 79] (Figure 8). There is no consensus regarding the dating of the first spring-driven clock; sources either mention the first example of a spring-driven chronometer (a chamber clock made in 1430 for Philippe the Good, Duke of Burgundy [76, 80]), the first spring-driven clock house (The Clock of Wisdom built in 1450 in Sapience [61]), or the first written mention of spring as a clockwork component from an Italian architect's biography at the beginning of the 15th century [78].

Leonardo da Vinci (1452-1519) is undoubtedly the greatest engineer of the Renaissance, renowned for his intricate machine drawings. Many of these designs feature one or several springs, including springs used as contact keepers in various motion conversion mechanisms [57, 81] (for instance, rotation to translation and alternative to continuous motion). Notable examples include the two large spiral springs beneath his self-propelled cart [81–84], which functioned similarly to modern toy cars by storing energy in the springs and then, by releasing the brakes, propel the wheels. He also designed an arrangement of springs to prevent the shuttle rebound in his loom [57], and the spring mechanism for the flapping wings of his ornithopter [82], allowing the wings to return to the upper position. Additionally, he incorporated two spring tines to hold the crowns of his two-speed

hoist [85, 86], a double leaf spring in his spring catapult [81], spiral springs to control his knight and lion 'robots' [87], and a spring pressing a pawl against the teeth of one of his ratchet wheel designs [85]. His giant and mobile crossbow measured 20m wide and 30m long, featuring elastic arms. Unfortunately, it is highly probable that these designs never progressed beyond the drawing board into functioning devices. Leonardo also experimented with mechanical clock devices, attempting to mitigate mainspring irregularities by using two independent mainsprings [59, 86] instead of a fusee. Furthermore, he worked on spring-making mechanisms, documenting them in multiple codices [9, 59], which represent the only detailed descriptions of 15th-century spring-making processes (see Figure 9). Da Vinci may have acquired this knowledge from clockmakers. His drawings feature spring-drawing devices, including a screw for pulling sheet metal and a conical feeder for reducing the thickness of sheet metal. He also designed a spring-drawing device capable of producing mainsprings of varying thickness. The accompanying texts in his plans are quite detailed, specifically addressing the manufacture of mainsprings for clocks and the heat treatment between drawing passes. Additionally, Leonardo studied basic elements, such as gears, wheels, and springs [81, 83]. He analyzed the forces and mechanical properties of springs but strongly refuted what would later be known as Hooke's law, further illustrating the experimental approach to springs that was still in its infancy during his time [83]. Finally, he extensively explored helical structures inspired by nature but did not utilize them as spring geometries [88].

At the beginning of the 15th century, gunpowder, discovered in China six centuries earlier, arrived in Europe [61]. Shortly thereafter, firearms were developed, initially using a matchlock mechanism [76, 89, 90] (approximately 1410), which employed a slowly burning cord to ignite a pan of gunpowder. This technology was characterized by its dangers: it was smelly, visible, slow to fire, slow to reload, and cumbersome. Consequently, engineers across the European continent, including da Vinci [61], sought to improve the triggering mechanisms. During this period, three mechanisms employing a flat spring [90–92] were used, enabling the weapon to be ready to fire at any moment. The wheel-lock [61, 89, 90, 93] (~1450) operated by releasing a spring that drove a serrated wheel against a piece of pyrite, creating sparks that ignited the powder. The snap-lock [94] (~1510) ignited the weapon's propellant by generating sparks when a spring-powered cock struck flint against a hardened steel piece. The flint-lock [61, 89, 93] (~1600), when triggered by a latch, engaged with the sear to release a spring

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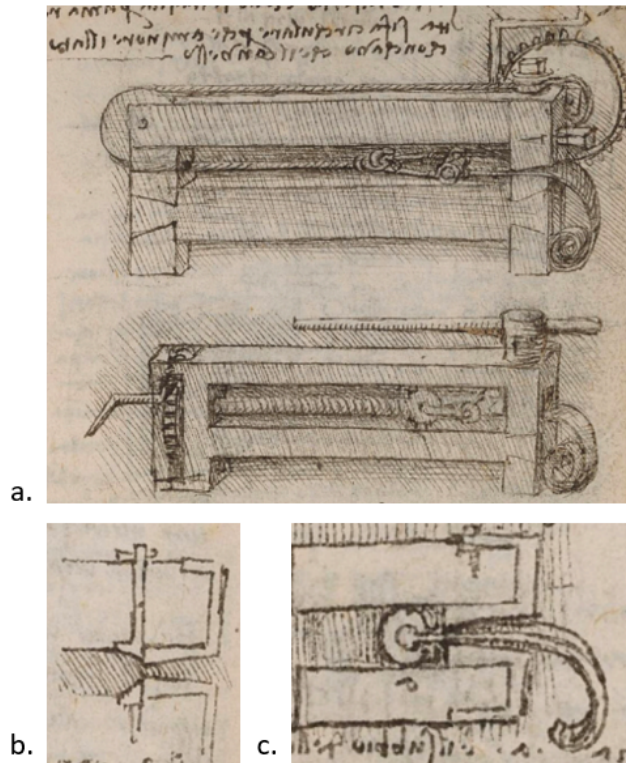


Fig. 9. Leonardo da Vinci's spring-drawing devices, on a bench, with a screw for pulling the sheet metal (a), a conical feeder for the reduction of sheet metal thickness (b) and details of the conical intake and winding process (c) [59].

linked to a hammer, striking the frizzen to fire the gun. By the end of the 16th century, spiral springs were also utilized in air guns [76], assisting in compressing air to propel bullets upon release.

In the 16th century, portable horology was enhanced by the creation of the stackfreed (first drawn by da Vinci in 1493 [80, 83]), a spring-loaded mechanism that evened out the force of the mainspring and was smaller than the fusee. The stackfreed mechanism operates as follows: a spring arm presses against an eccentric, snail-shaped cam. The force of the spring arm against the cam induces a retarding force on the mainspring, reducing its torque and thus compensating for the uneven loading of the mainspring [57]. This improvement, along with other technological discoveries, allowed blacksmiths to create the first pocket watches, including Pomander watches (Peter Henlein, 1520 [80, 95–97]), the first stackfreed neck-watches (1548 [80, 97]), ornamental ladies' watches (mid-16th century [95, 98]), and Nuremberg Eggs (1540 [95, 98–100]). However, accounts of Peter Henlein indicate that by 1521, miniature clocks were no longer valued at a 'pre-

mium' [80], suggesting they were produced at least several years earlier (around 1511 [99]).

## 2.7 Enlightenment (~1,600 CE - ~1,800 CE)

The Enlightenment period was marked by profound advancements in science and technology, characterized by significant innovations and the systematic application of scientific principles to engineering and manufacturing processes. During this time, the development of precise instruments and machinery laid the groundwork for the Industrial Revolution. Metallurgy advanced with new smelting techniques and the production of stronger, more resilient metals. This era also saw the dissemination of knowledge through publications and societies, fostering a culture of experimentation and innovation that revolutionized mechanical design and metallurgical processes [101–104].

In 1660, Sir Robert Hooke [105–107] (1635-1703) published a law (first as a Latin anagram and then in 1678) applicable to any body (gas, liquid, or solid) stressed in extension, compression, and bending, stating "*ut tensio, sic vis*", which translates to "the extension is proportional to the force." This premise explains the elastic properties of solid bodies. Based on his experiments with springs (Figure 10), stretching wires, and coils, Hooke stated that the deflection of a spring  $x$  and the associated applied load  $F$  are directly proportional, leading to the conclusion that the elastic stiffness  $k$  of a spring is a constant:  $F = kx$ . Here, the stiffness  $k$  depends on the material and geometry of the studied spring. In this book, he also described spiral springs and how to create what we now call a tension spring [105, 107]:

Coil a wire on an even cylinder into a helix of whatever length or number of turns you please, then turn the ends of the wire into loops, by one of which suspend this coil upon a nail and by the other sustain the weight that you would have to extend it.

Thus, it indicates that tension springs were created at least several years before. He also addressed the vibrational properties of springs. Hooke, in his detailed work on springs, would have developed the isochronous balance spring or hairspring in 1660, a new escapement mechanism enabling watches and clocks to be fully independent [57]. To this day, this system utilizes a pre-stressed spiral spring in torsion, which, when released, moves toward its initial shape; however, due to the momentum of this motion, it overshoots, compressing the spring and causing the balance to oscillate back and forth across the free

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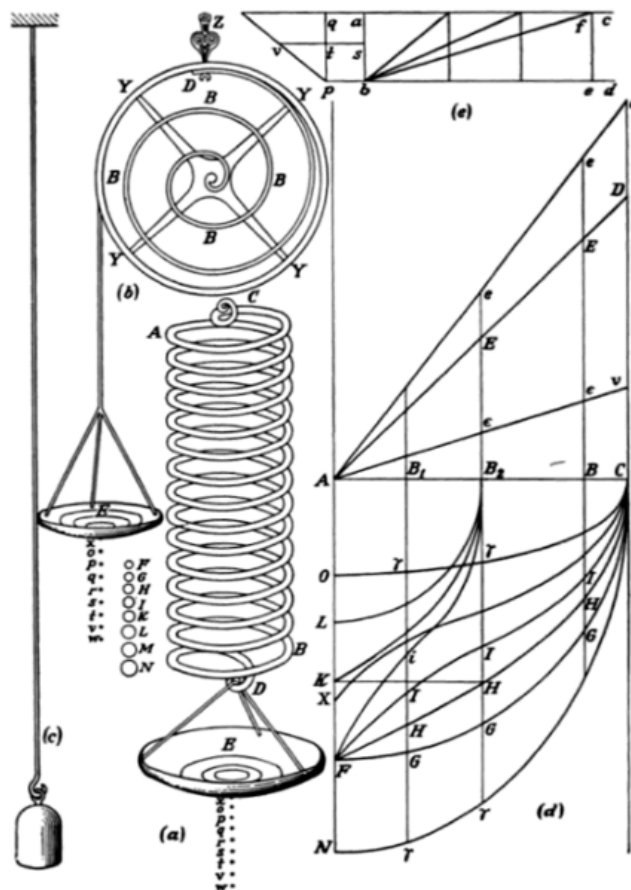


Fig. 10. Devices used in Hooke's experiments [107].

shape of the spring (Figure 11). Unfortunately, the paternity of the balance spring is contested by C. Huygens and J. de Hautefeuille [57, 98, 108], making it difficult to determine the true origin of this mechanism. A century later, P. Le Roy [57] enhanced the balance spring by adding a temperature-sensitive mechanism that compensates for variations in the modulus of elasticity of the material, thus enabling the spring to tick at a regular speed under any environmental temperature.

At the beginning of the 18th century, other scientists worked on mechanical engineering, including the understanding of spring behavior. V. Mandey [109] (1702) focused on screws and mechanisms and also mentioned a spring made of a "thin piece of metal in the manner of a helix," which was likely a helical tension spring. Notably, he mentioned and illustrated in this book [109] what is believed to be the first historical reference to a "pressing hælix" (i.e., a helical compression spring) that pushes a pulley along its axis when explaining a raising mechanism (Figure 12). Helical conical springs were also il-

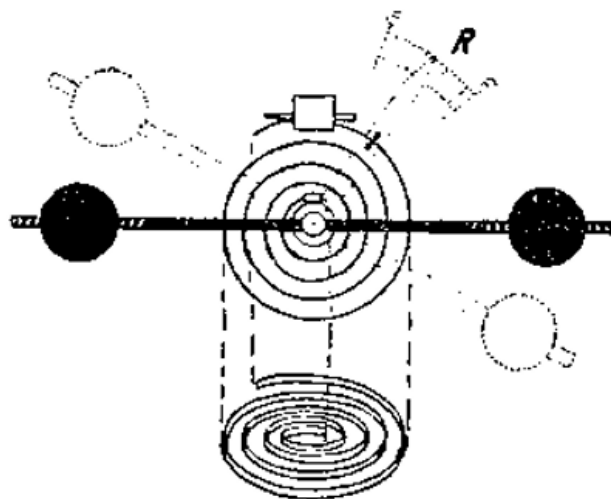


Fig. 11. Early form of the balance spring [57].

lustrated by G. Thrupp, used in a carriage presented in 1703 to the French Academy of Sciences [110], as shown in Figure 13. J.T. Desaguliers [111] (1719) stated that when compressing an elastic body between a weight and a support, the body produces an upward load equal to the downward load on the support, even when deformed. He referred to helical compression and tension springs as "worm-springs." This theory is derived from Newton's third law [112] (1687). In a broader context, other scholars contributed to the mechanical understanding of elasticity in materials. Leonhard Euler [113] (1750) worked on beam theory and material resistance, creating a calculation method linking deflection, load, and stress (internal pressure) applied to a body in torsion, bending, shear, tension, and compression. He first introduced the notion of the modulus of elasticity. Thomas Young [107, 114] (1807) developed a method to express the elasticity modulus  $E$  of a material, defined as the ratio of the stress  $\sigma$  applied to a body and the associated strain  $\varepsilon$ , yielding  $\sigma = E\varepsilon$ . Unlike Hooke's stiffness  $k$ , Young's modulus  $E$  depends solely on the material and not the geometry of the studied body, allowing for the preservation of experimental data between different springs made from the same material. He also examined the lateral buckling of compressed columns and noted the exponential cumulative stiffening of bending leaf springs.

During this century, the global industrialization of vehicles led spring makers to patent their inventions, marking significant advancements in spring technology [115, 116]. Thomas Rogers patented a "steel worm or rolling spring" (1724, British patent 470) as a suspen-

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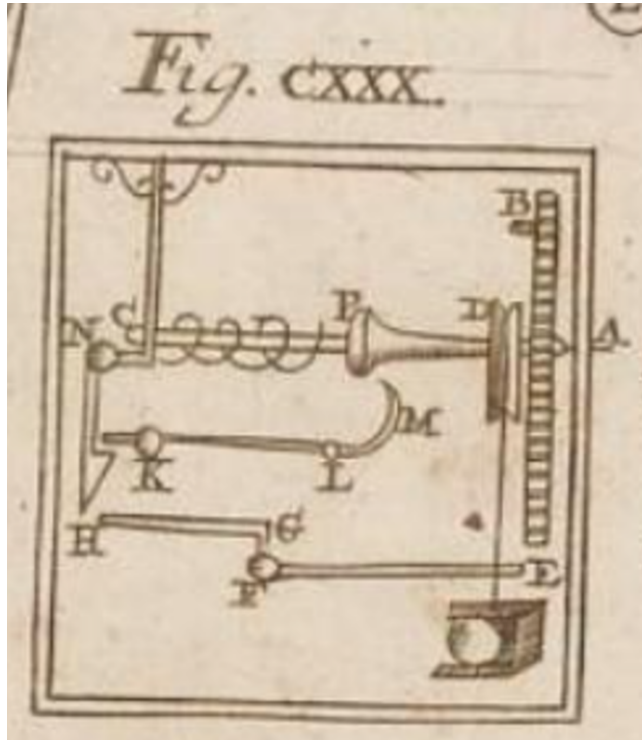


Fig. 12. Raising mechanism including a pressing hælix, the oldest found illustration of a helical compression spring, 1702 [109].

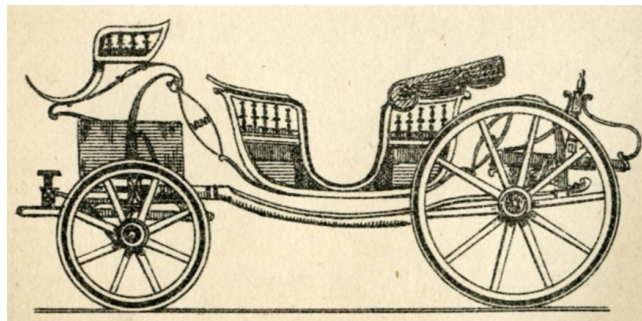


Fig. 13. Suspended carriage, presented in 1703 to the French Academy of Sciences, featuring helical conical springs between leaf springs [110].

sion tension spring for carriages. Following this, Richard Tredwell patented a "ribbed spring" (1759, British patent 738), a lighter leaf spring; an "iron machine for molding and setting all kinds of springs" (1762, British patent 768); a "spring for hanging coaches" (1762, British patent 769); and finally, a "new invented method of making springs" (1763, British patent 792), which marks the official creation of the helical compression spring as we know it today. This new patent represented a significant ad-

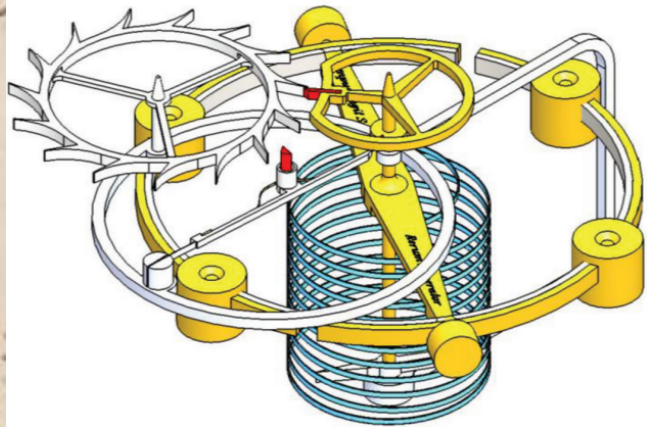


Fig. 14. Thomas Earnshaw's chronometer detent escapement mechanism, featuring a helical torsion spring with rectangular section and pitch [117].

vancement over the leaf spring, which required frequent separation and lubrication. John Arnold patented a "helical spring as escapement for watch" (1782, British patent 1328), which introduced the specific helical characteristics of these springs (previously referred to as "coiled springs," making it difficult to distinguish them from spiral springs without figure). This particular patent for a torsion spring was later modified by Thomas Earnshaw [117]. The torsion helical spring features coils of smaller radius at each end [99, 118], allowing attachment close to its winding axis (Figure 14). This design continues to be utilized in most precision mechanical watches and marine chronometers [118]. Notably, this helical torsion spring has a rectangular cross-section (deriving from both spiral and leaf springs) and includes a pitch to eliminate the need for lubrication [117].

## 2.8 Industrial Revolution (1,760 CE - 1,900 CE)

The Industrial Revolution fundamentally transformed metallurgy by enhancing the efficiency of iron and steel production, promoting the development of alloys, and introducing mass production techniques for wires and other metal components [119, 120]. This period saw the rise of machinery that enabled large-scale production of metal goods, with factories replacing smaller workshops. The widespread adoption of steam engines [120] necessitated substantial amounts of metal for their components, thereby increasing the demand for iron and steel and driving advancements in metallurgical processes [121]. Prior to the Industrial Revolution, wire production was a labor-intensive process, involving hand-pulling through dies or using powered mills. However, the introduction of steam-

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powered wire-drawing machines allowed for the manufacture of wire in greater quantities and with higher precision [9]. As mass production techniques evolved, wire emerged as a vital component across various industries, finding extensive use in telegraphy, railways, fencing, telephony, and electricity transmission as the century progressed [9, 121].

During the Industrial Revolution, scientific research on materials, solids, and structures expanded significantly. Jean-Victor Poncelet (1788-1867) made important contributions to the dynamics and strength of materials as applied to industry and machinery [107]. His notable works include "Lessons on Applied Mechanics on Machines" (1826) [122] and "Introduction to Industrial Mechanics" (1829) [123]. In these texts, he introduced tensile-test diagrams and concepts such as the safety factor, resonance effects, and fatigue. Poncelet emphasized that "under the action of alternating tension and compression, the most perfect spring may fail in fatigue" [123], underscoring the necessity of sizing springs for both static and fatigue conditions. He also conceptualized springs as "work tanks," capable of storing and restoring energy with minimal loss. Furthermore, Poncelet highlighted the use of springs as devices for material characterization and various measuring instruments [122], including the spring scale, which consists of a tension spring housed within a graduated scale to measure weight.

Carlo Ignazio Giulio (1803-1859) [124, 125] was the first to analyze helical springs in detail, developing equations to evaluate their stiffness, although his aim was primarily to utilize springs as material characterization devices. By neglecting curvature effects, the impact of end coils, and the helix angle of helical springs, he derived significant results in 1841 [124]:

$$\delta = \frac{PD^3\omega}{16GI} \quad (1)$$

With  $\delta$  the spring's deflection,  $P$  the applied load,  $D$  the helix winding diameter,  $\omega$  the wire angular length of the spring,  $G$  the shear modulus of the material and  $I$  the moment of inertia of the wire section. By substituting  $\omega = 2\pi n_a$  with  $n_a$  the number of active coils and  $I = \pi d^4/64$  with  $d$  the diameter of the wire, we find the stiffness  $K$ :

$$K = \frac{P}{\delta} = \frac{Gd^4}{8n_a D^3} \quad (2)$$

Adhémar Barré de Saint-Venant (1797-1886) [107, 125], three years later, working on beam theory applied

on curved beams and large deflection, described how fibers work in an elastic circular wire of double curvature. He derived a stress equation for the extension of a helical spring when the forces applied at the ends act along the axis of the helix. He introduced the evolution of the number of active coils during the compression and considered the influence of the inclination of the section in the helical wire. By taking into account the helix angle  $\alpha$ , he took Giulio's deflection equation over [125]:

$$\delta = \frac{PD^3\omega}{8\cos(\alpha)} \left( \frac{\cos^2(\alpha)}{2GI} + \frac{\sin^2(\alpha)}{EI} \right) \quad (3)$$

Thus, if the helix angle is important, the wire is stressed in bending, and if it is small, the wire is stressed in torsion. Édouard Phillips (1821-1889) investigated railroad springs, based on bending straight beams theory. He derived formulas for the change of curvature of the laminas of the leaf spring, integrated the deflection formulas of these springs and differentiated the expression of pressure between laminas [107].

With the development of electrical components, wire coiling and winding technology advanced significantly. By the mid-19th century, steam-powered mandrels emerged, which could be smooth, grooved, or screw-shaped, allowing for the production of springs with the appropriate diameter and pitch [126, 127]. However, these mandrels were limited to manufacturing only one specific spring geometry [128]. In 1878, P. Cucherat patented the first fully automatic spring-coiling machine (US206300A) [129]. This innovative machine fed wire between rollers and employed cams and tools to bend the wire as needed, effectively forming the pitch and outer diameter of the spring. Additionally, a cam-driven cutting tool enabled continuous production of springs. The only components that required adjustment to achieve different spring geometries were the cams.

Poncelet described efficient machinery as a self-controlled automaton that minimizes the need for continuous and arduous human oversight [122]. This concept of independence is central to the Industrial Revolution and the development of mass production. Starting in 1829, steam engines were improved by integrating spring-retracted non-gravitational governors [122], which enabled automatic adjustments to the volume of motor fluid allowed into the machine. Springs also played a crucial role in transforming motion, facilitating conversions from continuous to alternating movement, as exemplified by spring-loaded lathes [123] and helical springs in the safety valve mechanisms of steam locomotives dating

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Fig. 15. Negative X-ray of a collapsible spring-loaded top hat (1901-1904) [134].

back to 1798 [130, 131]. Additionally, springs were essential for movement control and return, utilized in steam carriage control pedals, the free wheels of locomotive engines, and various spring pawls and camming devices [130].

In the wardrobes of the English and French bourgeoisie during the 19th century, helical springs were ubiquitous, appearing in girdles, stockings, suspenders, and belts [132]. However, in the 1840s, hygienists criticized the use of suspenders and belts equipped with metal springs, asserting that they “deformed bodies and impeded bone and muscle growth” [132], deeming them excessively rigid. At the end of the 18th century, a new type of hat, the top hat, began to replace the popular tricorne. This new design posed challenges regarding storage and handling, as these hats could no longer be easily tucked under the arm. In 1812, Dollman [133] patented the first collapsible top hat, featuring an inner elastic steel spring that allowed it to be neatly tied for travel. However, this solution proved inefficient for everyday use. In 1834, Antoine Gibus patented a foldable top hat that used hinges [134]. The foldable top hat gained popularity in 1837 with Gabriel Gibus’s invention of the *chapeau mécanique*, which incorporated springs along with the hinges, allowing the hat to snap open when unfolding and earning it the nickname *chapeau-claque* [134]. These hats are also referred to as Gibus hats or opera hats due to the common practice of storing them in a flattened state under seats at the opera (Figure 15). By 1870, the Gibus family had patented around twenty collapsible top hats that incorporated spring mechanisms [134].

In the 1840s [135], springs began to be integrated into upholstery, such as seats and mattresses, providing greater comfort, durability, and breathability compared to the previously used hay-filled versions. In 1846, F. Frost

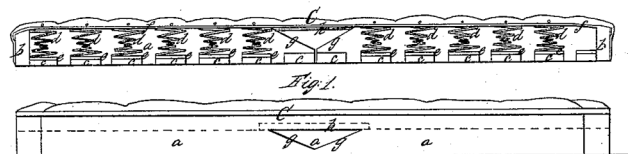


Fig. 16. Patent US4578A featuring hourglass-shaped helical springs in mattress dated 1846 [136].

patented a foldable spring mattress, representing an improvement over traditional spring mattresses [136]. This innovation implied the use of helical hourglass-shaped springs in mattresses, seats, and upholstery, indicating that such designs existed prior to this date. These mattresses comprised an arrangement of helical springs, either attached to a wooden support [136] or linked to a steel wire frame [137] (Figure 16). The choice of hourglass-shaped springs over cylindrical ones stemmed from their ability to stack their coils within themselves, allowing for a greater possible deflection.

The growing knowledge and technology surrounding springs at the end of the 19th century led to the development of various new spring forms. These included multi-wired and stranded helical springs, conical, hourglass (concave), and barrel-shaped (convex) springs, as well as canted coil and arc springs, volute springs, and springs with non-circular exterior geometries, such as oblong (magazine springs) and rounded triangle-shaped springs. Additional innovations included undulating flat springs, complex laminated assemblies in leaf springs, double-helical torsion springs (which allowed both arms to be at the same end), and springs with evolving wire diameters [138–144]. As these advancements unfolded, the applications of springs evolved significantly, leading to a transition from leaf springs to helical springs, which were more compact and did not require assembly or lubrication.

Carriages, coaches, and wagons incorporated leaf springs as suspension systems [142]. However, neither the world’s first self-propelled automobile in 1769 nor the first motorcycle in 1885 included a suspension system [145]. It was for bicycle comfort that springs were first considered, with these early bicycles referred to as “boneshakers” due to the lack of vibration absorbers. Various designs featured springs under the saddle, including a flat spring in Michaux’s velocipede (1863), a curved flat spring in Lawson’s chain-driven ‘bicyclette’ (1879), helical torsion springs in early Rover safety bikes (1885), and helical compression springs in later Rover safety bikes (1889) [146]. In 1869, the first leaf spring compensating fork for velocipedes was patented [147]. By 1887, Amer-

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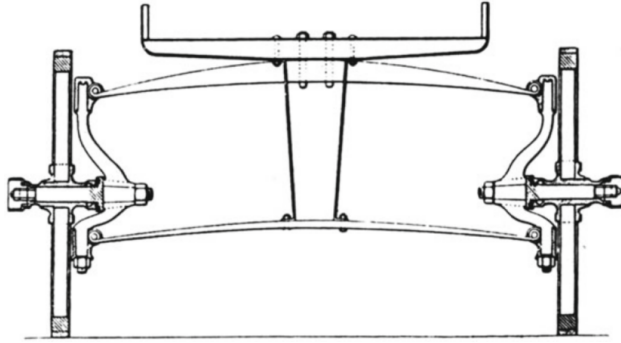


Fig. 17. Drawing of the front steering axle of the Mancelle in 1878 featuring double leaf springs [148].

ican Victoria bicycles showcased a helical spring fork [147]. Additionally, Bordino's steam coach (1854) and the Mancelle (1878) both integrated metal leaf springs, the latter featuring a more complex arrangement [148], as shown in Figure 17. The 1886 Peugeot Type 1 steamer utilized elliptical leaf springs on the rear axle and front wheels [145]. Passengers seeking comfort would have to wait until the early 20th century for the development of more sophisticated automotive suspension systems.

## 2.9 20th century (1,900 CE - 2,000 CE)

Advancements in material science, industrial processes, and manufacturing have transformed industries significantly over the last century. The development of new alloys has enhanced strength, durability, and corrosion resistance, with stainless steel becoming widely adopted due to its anti-corrosive properties established in 1908 [149]. Advanced steel-making techniques have allowed for better control over composition and properties, contributing to the overall performance of materials. The automation of wire drawing processes, coupled with improvements in lubrication and die technologies, has significantly increased the speed and precision of wire production since 1923 [9]. Additionally, coiling technology has advanced through the implementation of automated machines, facilitating the mass production of consistent, high-quality springs. This innovation was crucial for various industries throughout the century, particularly in the automotive sector, which saw growth in the first half of the century, alongside military applications, and later in aerospace developments during the second half.

At the beginning of this century, steam engines were gradually replaced by diesel engines (1898 [150, 151]), gasoline engines (late 1880s [152]), and electrical motors (late 1880s [153]), which were more efficient and powerful. Oil engines incorporated several mechanical springs

to operate, as opposed to the earlier steam and piston engines, generally incorporating camshafts and desmodromic mechanisms (air sprung poppet valves). First, some starters were springs, compressed by a crank motion and then quickly released to ignite the engine (as in modern lighters mechanisms) [154]. Then, reciprocating engines included a cylinder head to manage combustion, with intake and exhaust valves, each of them controlled by helical springs. The integration of return helical springs enabled an "automatic" fluid movement control, driven by pressure variation in the combustion chamber, simpler and safer than camshafts mechanisms and more efficient at high speed than poppet valves [155, 156]. These engines spread in all motorized vehicle since the late 19th century.

This rise in power enabled faster production processes and the ability to work with heavier and larger rods and bars. However, the production of helical springs could no longer rely on the same cold coiling methods as before. To deform larger diameter rods, it was necessary to heat the material first. Hot coiling requires that the spring be wound from stock at or above the recrystallization temperature [157]. Hot coiling machines, using a mandrel (and optional external rollers), not only allowed for the production of heavier springs but also enabled the manufacturing of quadrilateral section rods (1907 [158]) or any irregular cross-sectional contour (1908 [159]). Coiling techniques continued to evolve with the establishment of helical spring recyclability processes (1906, by uncoiling railway springs to reuse the wire for an other geometry [160]), the introduction of the first machined springs (1907 [161]), and the development of an eight-rotating arms spring forming machine in 1941 [162], which displaced the spring with jaws from one forming step to another. Nevertheless, some complex geometries, such as torsion springs, remained handmade as of 1916 [163]. Spring manufacturers also introduced improved heat treatment techniques, including in-line annealing or tempering, to reduce internal stress immediately after coil forming, as the inner fibers are compressed while the outer fibers are stretched [9, 164–166].

At the beginning of the 20th century, vehicle suspension technology in automobiles, trains, bicycles, and airplanes entered a transitional era between the previously used leaf spring suspensions and modern helical spring suspensions. This transition was driven by four main issues. First, leaf spring suspension systems were often avoided due to their noisiness, difficulty in replacement, lubrication requirements, and dependence on left-right deflection. Secondly, pneumatic rubber tires, popularized by the Michelin L'Éclair [167] in 1895, were not partic-

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ularly reliable: a rubber shortage occurred in the early 1900s, the tires lacked the strength to support heavy vehicles like trucks, and they were fragile and prone to punctures. Additionally, tire changes were complicated as they were frequently nailed to the rim [168]. The First World War also led to the use of heavy military vehicles and bicycles in rough, obstacle-laden terrains [169]. Finally, the hot coiling process was not sufficiently developed in the automotive industry, which was primarily focused on railroad vehicles, making it easier to manufacture only small wire diameters. The objectives during this time were to propose lightweight, cost-effective, independent left-right suspensions with easy-to-replace mechanisms, utilizing the available coiling technology. Therefore, between 1900 and 1925, innovations such as spring-wheels (also referred to as soft wheels or elastic wheels), spring tires, spring spokes, and spring rims flourished. By integrating the suspension directly within the wheel, the required springs were necessarily small, allowing individual failures without compromising the integrity of the entire vehicle. This design facilitated easier access and replacement, enabling a smoother ride over lateral obstacles, and was compatible with puncture-proof materials such as steel, rope, wood, or leather tires. Although the first known elastic wheel technology dates back to 1823 [130], the advancements in spring technology by the end of the 19th century allowed for a significant diversity of solutions (see Figure 18), underscoring the growing interest in springs within the fields of science and engineering [130, 138, 170–191].

Along with the expansions in the rubber market and pneumatic tire technology, vehicle speed and weight increased, particularly during both World Wars. Consequently, mechanical engineers began to favor suspension systems between the wheel and the car chassis over spring-wheels [145]. Helical springs have been integrated since the production of Ford's Model T in 1908 [169], but they did not serve as the primary elastic link in suspension systems, with elliptical springs fulfilling that role. It was not until 1922 that the helical coil spring, along with a hydraulic shock absorber, was included for the first time as an independent wheel suspension mechanism in the Lancia Lambda [148]. In 1935, Fiat integrated the helical spring into the same oil as the shock absorber [148], and in 1947, E.S. McPherson developed the eponymous front strut suspension (Figure 19) with a double wishbone for the Ford Vedette [148]. Further modifications and improvements were made by Volkswagen in 1969, Alfa Romeo in the 1970s, and Mercedes in 1982 [148]. In these designs, helical coil springs with variable coil diameters were advantageous for reducing pack-

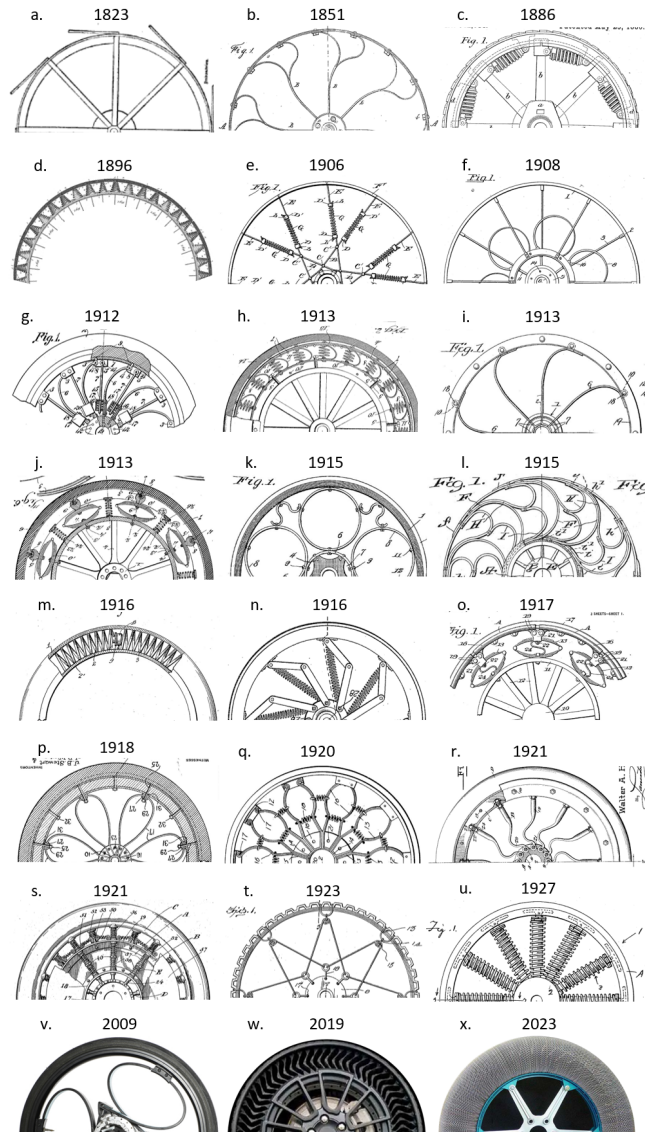


Fig. 18. Spring-wheels, -spokes, -tires and -rims. Neville's first elastic wheel [130] (a), patents [170] (b), [171] (c), [138] (d), [172] (e), [173] (f), [174] (g), [175] (h), [176] (i), [177] (j), [178] (k), [179] (l), [180] (m), [181] (n), [182] (o), [183] (p), [184] (q), [185] (r), [186] (s), [187] (t), [188] (u), Pearce's Loopwheel [189] (v), Michelin's UPTIS wheel [190] (w) and NASA's SMA spring tire [191] (x). Adapted figures.

aging requirements when solid. Variable pitch springs were particularly beneficial for smaller vehicles like motorbikes. Both of these geometries resulted in two different stiffness levels: a lower stiffness to absorb vibrations from road roughness and a higher stiffness to absorb shocks and large deflections caused, for example, by speed bumps or potholes [192].

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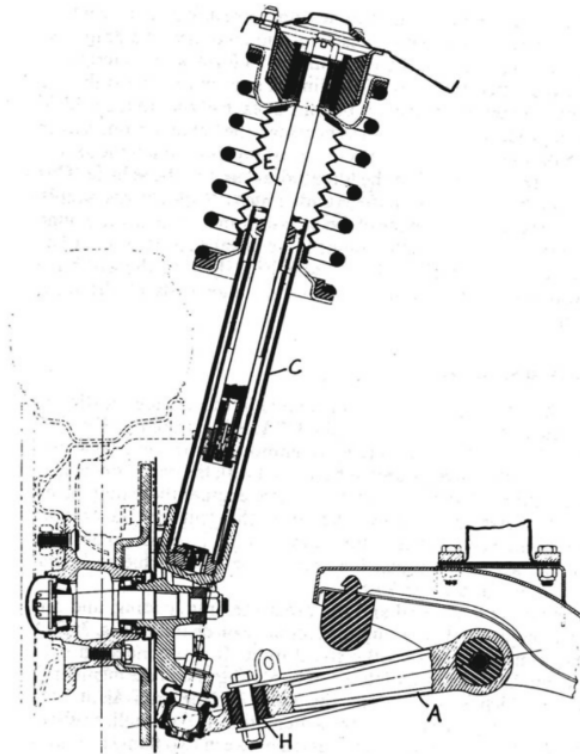


Fig. 19. McPherson strut suspension system developed in 1947 for Ford [148].

In 1903, lightbulbs integrated small coiled filaments for the first time [193]. Later, between 1914 and 1921, these filaments were upgraded to double-coiled tungsten filaments, where a thin wire (approximately  $20\mu\text{m}$  thick) was itself wrapped into a coil using a mandrel, as shown in Figure 20. Machinery for the mass production of coiled-coil filaments was developed in 1936 [194, 195]. However, the coiling techniques for fine ( $\leq 0.1\text{mm}$ ) and ultra-fine wires ( $\leq 0.01\text{mm}$ ) had already been adopted in spring manufacturing [196–198], enabling the creation of the first precision helical springs for small applications. These included early aviation measuring instruments, such as accelerometers, photo-multi-manometers, engine revolution indicators, altimeters, compasses, gyroscopic turn indicators, and airspeed indicators, developed between 1909 and 1915 [199]. Additionally, the first portable lighters emerged in 1911 [200, 201], as the action of the thumb alone could not release sufficient energy quickly enough to create a spark. The same year, the first reduced-size pin tumbler locks were introduced [202, 203], followed by modern pens in the 1910s [204–206], where the spring either pressurized the ink reservoir for consistent delivery or attached the safety clip to the

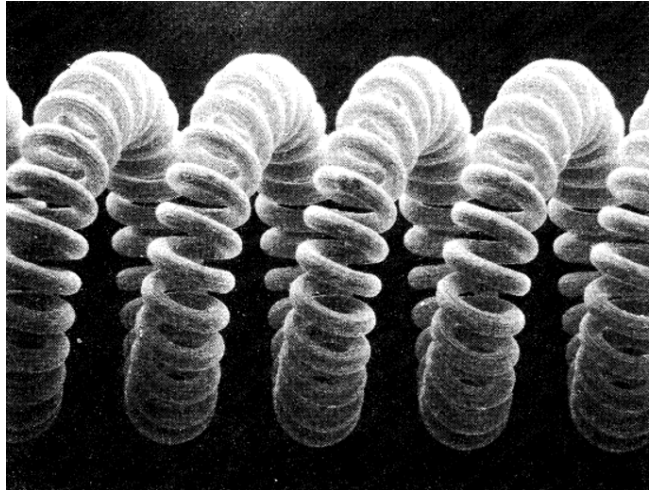


Fig. 20. Double-coiled tungsten filament for light-bulb as seen on scanning electron microscope [195]. The overall diameter is about  $0.75\text{mm}$ .

pen's end. Finally, the mass production of wristwatches began to rise between 1914 and 1918 [207, 208], facilitating battle coordination during the First World War.

Indeed, the mechanical advances of the 20th century were significantly influenced by geopolitical conflicts and the associated investments in research and industrial mass production. During World War I (1914–1918), springs became ubiquitous in artillery and infantry weapons, serving vital roles in recoil, return, and triggering mechanisms. Infantry utilized spring-loaded revolvers, pistols, and rifles that had been designed in the previous century, along with new spring-triggered grenades [209, 210]. Meanwhile, the first tank, known as the Mark I, appeared at the Battle of the Somme in 1916, featuring valve springs in its engine [211] and a specialized suspension system adapted for the rough terrain characteristic of trench warfare. The suspension systems of the first tank models employed various solutions, as spring wheels did, including volute springs, leaf springs, coiled springs, torsion bars, rubber torsion springs, and hydro-pneumatic spring systems [212, 213] (Figure 21). However, unlike spring wheels, the suspension systems for heavy fighting vehicles converged towards a unique solution: torsion bars. Their primary advantage is their relatively high energy storage capacity per unit weight. Furthermore, as torsion bars are housed inside the vehicle, they are better protected from ballistic attacks, and when made from suitable materials, they exhibit a reasonably long lifespan [212]. Before 1914, airplanes were primarily experimental crafts, attracting sports enthusiasts and wealthy amateurs. It was during World War I that aviation was first

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effectively utilized, generating military interest among all nations involved. This shift presented new challenges for mechanical engineers. Instruments previously designed with gravity-controlled mechanisms for ground use were largely converted to spring-controlled mechanisms in aviation for three primary reasons: first, to prevent instrument collapse due to engine and flight vibrations; second, because spring solutions were smaller and lighter than their pendulum counterparts; and third, gravity-controlled instruments demonstrated poor performance during aircraft rolling or pitching [199]. Aviation also introduced challenges in suspension systems, as World War I fighters needed to land at high descent speeds while tilted in any direction and required quick braking after landing. Consequently, a variety of solutions emerged, paralleling the diversity of aircraft models [214, 215]. The first bi-planes (1914) already featured spring-controlled rudders, ailerons, and elevators to enhance maneuverability and stability [216–219].

World War II (1939-1945) was marked by rapid advancements in aviation, artillery, and nuclear research. Jet engines revolutionized aviation by enabling aircraft to achieve much higher speeds and altitudes than piston-engine planes. Springs were integrated into various components of jet engines, including the fuel nozzle control unit [220], the speed governor bypass valve [220, 221], and the nozzle throat area control system [222], as well as in storage and shipment safety mechanisms [222]. The increased flying altitudes necessitated the incorporation of pressurized cabins in warplanes, powered by the action of several springs [223]. Additionally, airplanes, along with tanks and bunkers, began to feature radial and turret gun systems that allowed for faster and more accurate targeting. These heavy mechanisms were controlled in motion by helical springs [211, 224].

Unfortunately, both World Wars underscored reliability issues regarding mechanical components in machinery, vehicles, and weapons, including springs [212, 225]. Until World War II, there were few standards related to vocabulary, materials, processes, quality, and design in mechanics. It is in this context that the Spring Manufacturer Institute (SMI) was founded in 1933, serving as an American research center that brought together spring manufacturers, wire suppliers, and spring machinery developers from across North America [2]. To disseminate scientific knowledge, the SMI published its first international technical paper titled “Spring” in 1962. In 1942, the Coil Spring Federation (CSF) was established, its British counterpart, now known as the Institute of Spring Technology (IST) [2]. In 1948, the Japan Spring Manufacturers Association (JSMA) was created,

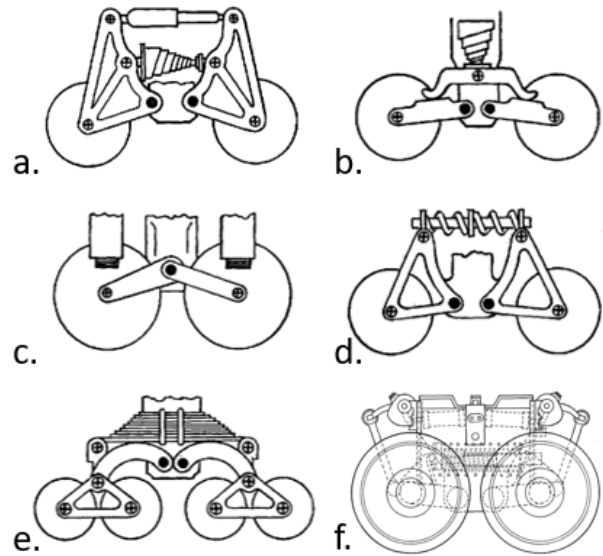


Fig. 21. Tank bogies including horizontal volute spring (a), vertical volute spring (b), torsion bar (c), helical spring (d), leaf springs (e) and helical springs (f) [212].

followed by the establishment of the European Spring Federation (ESF) in 1989.

In parallel with these specialized institutes, the American Standards Association (ASA), the French Association of Standardization (AFNOR), the British Standards Institution (BSI), and 22 other standardization organizations founded the International Organization for Standardization (ISO) in 1947 [226]. However, the ISO did not publish many standards related to spring technology (leaving it to national standard organizations) until 2004, when a specialized Technical Committee (TC272) was established, focusing exclusively on product specifications, calculations, and terminology (ISO 2162, ISO 26909, ISO 16249, ISO 18137, ISO 19690), test methods (ISO 22705), and process technology for springs (ISO 11891 and ISO 26910) [5, 227–233]. Additionally, springs are also subject to standards concerning unique manufacturing processes (ISO 10243), specific applications (ISO 17254), and wire materials (ISO 6931 and ISO 8458) [234–237].

During both World Wars, slide rules were extensively used to design springs included in defense equipment, prior to the advent of modern computers [238]. Although the fundamental equations related to spring design are not overly complex, they involve a variety of numbers raised to different powers and multiplied or divided together, complicating quick calculations. The earliest recorded mention of these instruments dates back to 1901, enabling

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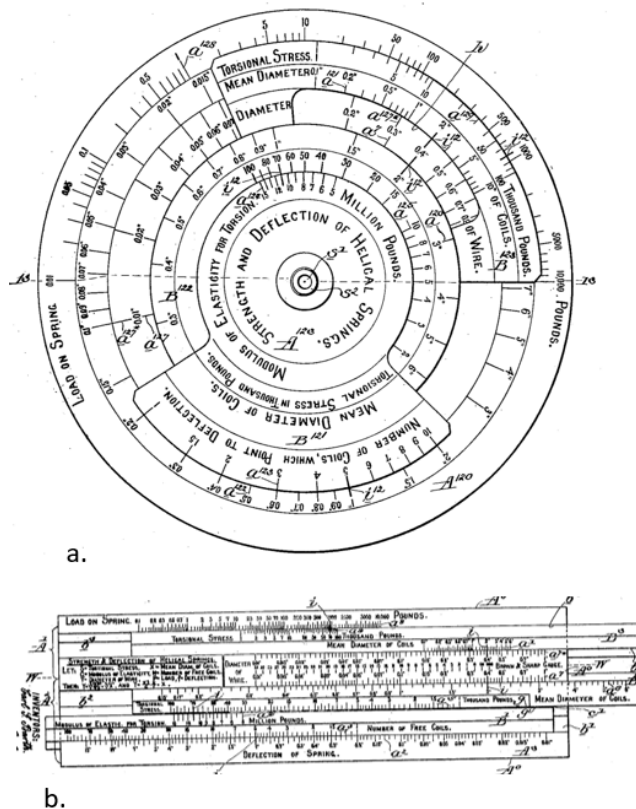


Fig. 22. Slide-rules for spring calculation, 1901 [239].

users to quickly calculate the stiffness and torsional stress of a helical spring (given the material) or determine the modulus of elasticity of the material (given the load for a specific deflection) by adjusting sets of sliding rules or disks marked with logarithmic scales [239] (Figure 22). Other examples of spring-rate calculating devices emerged in 1907, including a slide-disc rule for calculating the number of laminas and the geometry required for locomotive leaf springs to function correctly [240], and in 1914 for helical springs with round and square sections, evaluating the "safe load" [241]. Additionally, tables and charts were commonly utilized for these calculations [7].

Thanks to advancements in reliability, the establishment of standards, and the creation of research institutes, mechanical springs during the second half of the century found applications in scenarios requiring accuracy, speed, and extreme environmental resistance, all within geopolitical contexts. The Vietnam War (1955-1975) saw the development of automatic firearms (such as the AK-47 and M16), necessitating the ability to fire ammunition continuously while the trigger is pressed. To meet this requirement, every spring in the weapon was enhanced,

either to accommodate larger deflections (for example, a higher number of bullets for the magazine spring) or to increase reliability for sustained high-speed firing. The recoil spring absorbs and returns the bolt or slide to the forward position after firing, the magazine spring feeds rounds into the chamber from the magazine, the hammer or striker spring drives the hammer or striker forward to fire a round, the disconnect spring resets the firing mechanism after each shot, and the ejector spring assists in ejecting spent cartridges from the chamber [242]. The Cold War (1947-1991) ushered in a technological race that included the development of intercontinental ballistic missiles (ICBMs), spacecraft, and submarines. Mechanical springs were particularly attractive in space and submarine applications for two reasons: they do not require an external power source, making them ideal for energy-limited environments, and they perform consistently across a wide range of temperatures, humidity, and pressure—conditions under which electronic or chemical components might degrade or behave unpredictably. To prevent missiles from being intercepted, decoy deployment mechanisms were developed: upon reaching space, the missile would separate into ten warheads presenting the same radar signature (one true and nine decoys). This deployment was ensured by pre-loaded conical springs [243]. Missiles and rockets launched from either ground or submarines incorporated helical springs to absorb launch vibrations [244]. The engines of submarines were also suspended to mitigate vibrations from the hull and depth charges [245]. Submarine mines were triggered by sets of springs [246]. The Apollo 9 spacecraft, in 1968, failed certification during thermal-vacuum tests due to an undersized helical spring in the landing gear deployment mechanism [247]. This was subsequently replaced with a 10-leaf spring system, underscoring the critical role of these components. Apollo 11 (1969) also employed numerous spring solutions for suspension, control, and deployment mechanisms [248, 249].

During this century, spring researchers established a variety of laws, theories, and principles that remain relevant in 2024 standards. In 1913, A. Röver [250] first recognized that the stress distribution in a spring, due to pure torsion, did not exhibit a linear relationship with the distance from the coil axis to the wire fiber. This so-called "Röver effect" indicated that additional stresses arise in the inner fibers of the spring due to its curvature. To address this, he proposed a correction factor based on the curvature of the wire (spring's index and helix angle). Over the century, several versions of this stress correction factor were developed, including by Latshaw (1930), Honegger (1930), Göhner (1932), Bergsträsser (1933),

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Wahl (1939), Berry (1953), Henrici (1955), and Ancker (1958) [251]. E.W. Stewart in 1925 [238] noted the pre-load effect in tension spring coils and emphasized that the classical equations for tension and compression springs were only valid if the number of active coils exceeded two. He mentioned that these equations enable to characterize the material if, and only if, there is a sufficient amount of coils (i.e. errors arose with springs with few coils due to the "inactive coils effect"). Furthermore, Stewart emphasized that load tolerances should be at least  $\pm 10\%$  for proper spring production, with  $\pm 3\%$  only achievable under unusually high funding, as seen during WWI. Between 1935 and 1940, J.W. Rockefeller Jr., serving as the editor of the spring section of the *Wire and Wire Products* journal, published numerous advanced research papers on spring design. His contributions included material analysis, spring instrumentation, hysteresis in helical springs, end coil rotation during loading, fatigue life, presetting, stress distribution within the wire, non-linear stiffness behaviors, and manufacturing processes [252–255]. In 1944, Arthur Munzenmaier Wahl published a reference book titled *Mechanical Springs*, which was republished in 1963 with complementary theories and formulas on various spring types, including helical, spiral, leaf, torsion-bar, volute, ring, flat, and Belleville springs. This book consolidated much of the global research on springs, covering materials for specific applications (corrosion resistance, electrical conductivity, temperature endurance) [253, 256], surface and heat treatments, fatigue testing and estimation [254, 257], material property variations due to temperature, the impact of presetting [252], and the buckling and instability of compression springs [258, 259]. It also discussed spring design [260], lateral loading, diametral expansion during loading, natural frequency, shock resistance, standard tolerances [7], and spring defect analysis [260]. Modern standards still incorporate much of Wahl's work, though he acknowledged the simplifying assumptions and limitations of the presented equations [251, 261]. Research on end coils (1934-1940) also revealed their impact on load-length curves, which softened the spring by acting as an equivalent supplementary half-active coil [262–264].

## 2.10 Present days (1,980 CE - present)

Over the past 40 years, the design, materials, and manufacturing processes of springs have evolved significantly. Advances in research, technology, computer modeling, optimization, and material science have enhanced spring performance, durability, and efficiency across various applications.

In the 1980s, the rapid increase in computer processing power revolutionized engineering analysis, particularly with the rise of the Finite Element Method (FEM). This computational technique allowed engineers to model complex structures, including springs, under various load conditions with unprecedented accuracy. FEM enabled the simulation of spring behaviors, such as stress distribution and deformation, leading to more optimized and reliable spring designs across industries like automotive and aerospace. Springs were first modeled as 1D trusses with equivalent stiffness [4], though this was limited by the simplifying assumptions. Discretization helped engineers to better approximate the complex helical spring geometry by dividing the helical mean-line of the wire into a finite number of straight elements. Using FEM, researchers improved spring calculations by reducing the number of simplifying assumptions in classical models. These results were compared with experimental data or later with numerical data [265–268]. These numerical data were extracted from dedicated simulation software, enabling greater modeling freedom for geometry, loading (static, dynamic, thermal, magnetic), and boundary conditions. The model could then be constructed with either 1D-beams (to evaluate frequencies or stiffness) or 3D-cells (to evaluate contact or stress) [4, 269]. In 2003, M. Shimoseki et al. [4] developed a convergence analysis to obtain an optimal solution for achieving both fast and accurate results in FE analysis simulation software using 1D-elements (solution: 50 nodes per coil). In 2024, a review conducted by G. Cadet et al. [269] identified the analogous result for 3D-models (solution: 16 nodes along the section circumference, O-grid section structure, quadratic elements, and high aspect ratio).

The introduction of computer numerical control (CNC) machining has revolutionized spring production. CNC allows for more precise and automated manufacturing of springs, improving consistency and reducing waste. CNC machines were developed for spring manufacturing primarily in Germany and Japan during the late 1980s and early 1990s. These machines efficiently handled more complex spring geometries, especially the end coils and arms of tension and torsion springs [270–272], as well as the evolving pitches and diameters of helical compression springs [273, 274], polygonal cross-section springs [275], and pre-tensioned spiral springs [276]. For helical springs, two typologies were developed in CNC machining. In the first, the tools are aligned on the same plane as the feeding axis. The wire is fed in a straight line between rollers to the winding station, which includes two pin-shaped winding tools (to permanently bend the wire into the desired diameter), a pitch tool, and a cutting tool.

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All these tools are adjustable, replaceable, and movable. However, this type of CNC machine cannot form tension or torsion springs. The second, more complex typology, enables the production of all helical spring geometries. In this configuration, the tools are positioned orthogonally to the feeding axis. The wire is fed inside the machine and exits at its front center, where numerous CNC-driven tools are circularly arranged around the wire exit. Each tool can move radially toward the center of the working plane (toward the wire exit) and rotate about a pivot perpendicular to the working plane. This combination of movements, along with the variety of forming tools on these arms, allows for the creation of almost any helical spring geometry, regardless of end coil or arm design. In both typologies, the movement of each tool was initially controlled by cams, and only later by various servomotors.

One main axis of research in mechanical engineering over the past few decades has been problem optimization. This evolving domain has naturally extended to spring design, spring sizing, and spring manufacturing processes. The shape of the wire's cross-section is often modified to minimize maximum stress while preserving the cross-sectional area [277, 278], a process known as shape optimization. However, spring optimization generally focuses on either mass minimization or stiffness and buckling optimizations. These are achieved by varying the values of the primary spring parameters. In 1984, G.A. Hassan et al. [279] conducted one of the first mass minimization studies, taking operational constraints into account and modifying the wire diameter, mean coil diameter, and number of coils. These three variables remain central to many spring sizing optimization problems [280], including the Tension/Compression Spring Design (TCSD) problem [281], a mechanical engineering solver problem introduced in 2012 by J.S. Arora. M. Paredes [2] focused on more constrained industrial environments, considering six variables. Some research addresses the complexity of wire selection, resulting in a discrete problem [282, 283], while others develop robust procedures aimed at finding solutions far from any constraint or bound [284–286], or tackle multi-objective problems [280, 287–289]. In 2024, G. Cadet et al. [280] proposed a robust and reliable sizing optimization algorithm for helical compression springs, accounting for manufacturing uncertainties and material variabilities, with five variables, 15 parameters, and up to 58 constraints. These are referred to as sizing or parametric optimizations. Finally, some spring optimizations focus on altering the manufacturing process and, consequently, the spring typology, such as using hollow composite materials [290].

Since 1841 [124], the stiffness formula for helical compression and tension springs has been repeatedly questioned and modified due to its numerous simplifying assumptions. It has been observed that the actual load-length curve of springs does not strictly follow the predicted linear path, exhibiting a stiffening effect near the solid length and a softening effect at the beginning of the deflection [261]. While these deviations have been either neglected, noted, or commented on by researchers, standards tend to recommend avoiding these regions when sizing the spring and determining its operating range [227]. Instead of overlooking the errors in the classical formula, some studies have aimed to improve it by incorporating beam theory and FEM [124, 125, 261, 268, 291–301]. The evolution of these model hypotheses is summarized in Table 1. This evolution in stiffness calculation methods for helical cylindrical compression springs also applies to stress [251, 297] and natural frequency calculations [302, 303], as well as to other spring types like conical springs [3, 304, 305], variable pitch springs [192, 304], and tension springs [306, 307]. Researchers continue to refine these formulations by reducing the number of simplifying assumptions, each time pointing out the commonly accepted errors in the classical formula. Notable contributions have been made by M. Paredes and G. Cadet in the field of helical spring geometries, particularly through the integration of end coils into the equations [192, 251, 261, 301, 305, 307], allowing for more accurate stiffness and stress estimations (Figure 23). General knowledge about springs continues to expand through the work of V. Kobelev [157], who developed models addressing stress, fatigue, creep, relaxation, and failure probability, as well as Y. Yamada [308], who focused on non-metallic springs (e.g., polymeric and inorganic materials). Additionally, M. Shimoseki et al. [4] advanced the field by applying FEM techniques to spring analysis.

As previously mentioned, dedicated national and international associations and institutes, such as the SMI, IST, and JSMA, were established to help spring manufacturers gather and share scientific and technical knowledge. These organizations have developed technical journals and design software to assist engineers in sizing springs according to standards [280]. They also organize conferences, such as the International Congress of Spring Industry by the ESF [309] and the SpringWorld Expo by the SMI. Some of these associations, along with significant spring manufacturers, operate their own research laboratories to enhance spring manufacturing and design processes. Unfortunately, due to industrial competition, much of this research is not published, whether

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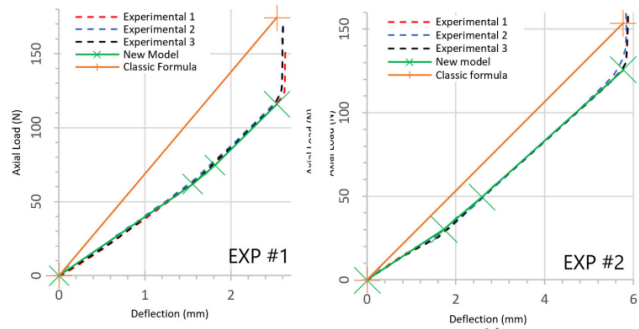


Fig. 23. Load-deflection curves of 2 helical cylindrical compression spring geometries from [261], comparing experimental data with the standard equation and the proposed analytical model.

in their technical journals or prestigious scientific publications. However, in 2018 [307], CGR International, a French spring manufacturer, in collaboration with the Clément Ader Institute and the National Institute of Applied Sciences of Toulouse, developed a research laboratory named STRAIN (Spring Technology ReseArch Institute). This laboratory bridges industrial spring challenges with academic resources and provides public access to the scientific discoveries and innovations it develops. As of 2024, STRAIN is the only known (semi-) academic laboratory in the world entirely dedicated to international spring research. We can also mention the Wire and Springs Research Group of the Ilmenau University of Technology [310], which often collaborates with the association of the German spring industry (VDFI). However, they usually publish in German, making scientific spread complex.

### 3 GEOMETRIES AND MATERIALS.

Mechanical springs today exist in three main forms: bar, helical, and flat (Figure 24). Bar springs are mainly found as torsion bars [311], but can also be used in bending or tension [310]. Flat springs encompass all geometries made from deformed or assembled thin sheets of metal, such as leaf springs, elliptical or bow springs, serpentine springs, no-sag springs, wave and crinkle springs, disc springs (or Belleville springs), spiral and constant-force springs, bellows springs, cantilever springs, meander springs, danto springs, membrane springs, and volute springs [310, 312–315]. These are generally stressed in bending. Helical springs, in the other hand, are divided into several categories based on their loading type (compression, tension, or torsion), wire geometry (circular, rectangular, ovoidal, stranded-wire, hollow, tapered wire) [139, 277, 316], winding axis curva-

Table 1. Analytical models computing helical compression spring stiffness, considering torsion (T), bending (B), shear (S) and axial tension/compression (A) within the wire, the number of coils (N), the curvature of the wire (C), the helix angle or the pitch (H) and the end coils (E).

Reference	T	B	S	A	N	C	H	E
1841 [124]	×				×			
1844 [125]	×	×			×		×	
1958 [291]	×				×	×	×	
1985 [292]	×	×	×	×	×	×		
1988 [293]	×	×			×	×	×	
1989 [268]	×				×			×
1990 [294]	×	×	×		×	×	×	
1992 [295]	×	×	×	×		×	×	
1995 [296]	×	×	×	×		×		
2005 [297]	×	×	×	×		×	×	
2009 [298]	×				×		×	
2016 [299]	×				×			×
2016 [300]	×	×	×		×	×	×	
2021 [261]	×	×	×	×	×	×	×	×
2023 [301]	×	×	×	×	×	×	×	×

ture (straight, arc springs, or canted coil garter springs) [317], coiling geometry (cylindrical, conical, barrel-shaped, hourglass-shaped, beehive-shaped, magazine-shaped, variable pitch) [318], or manufacturing process (coiled, molded, printed or machined) [319, 320]. Their wire is typically stressed in torsion or bending. The selection of a specific geometry depends on the application environment, available space, loading conditions, desired maximum deflection, and required stiffness characteristics. For example, helical springs with variable parameters such as wire diameter (tapered springs), mean diameter (conical, barrel, and hourglass springs), or pitch (variable pitch springs) result in variable stiffness, which is often lower for small deflections and increases with greater deflections [192, 321]. On the other hand, flat springs are easier to miniaturize due to their 2D characteristics [312–315].

Because springs are designed to store energy through

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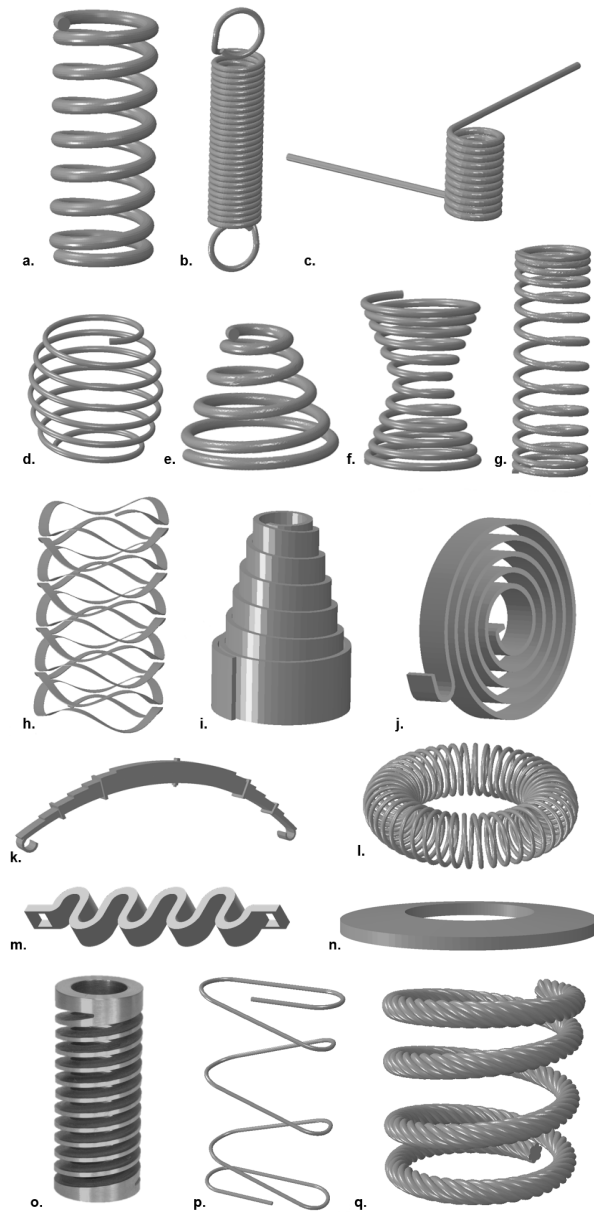


Fig. 24. Geometries of springs: helical compression (a), helical tension (b), helical torsion (c), barrel (d), conical (e), hourglass (f), variable pitch (g), wave (h), volute (i), spiral (j), leaf (k), garter (l), flat serpentine (m), Belleville (n), machined (o), magazine (p) and stranded-wire (q) -springs.

deformation, the material must possess high yield strength and fatigue resistance. However, material selection must also address several industrial challenges (availability, formability, low cost), quality considerations (low surface roughness, quiet operation, non-sparking properties, and defect-free surfaces), bulk concerns (low den-

sity), geometric factors (each spring shape has a preferred list of materials), physical and chemical properties (thermal and electrical conductivity, corrosion and oxidation resistance), and ecological factors (recyclability, low environmental impact) [2, 3, 253, 308, 322]. Y. Yamada [308] identified 88 criteria for spring material selection. Commonly, springs are made from steel [308], but for specific applications and research purposes, other materials can also be utilized, including:

1. Patented cold drawn unalloyed steels [237, 253]. High yield strength, works below 150°C, divided in five chemical compositions. For all applications.
2. Oil hardened and tempered steels [237, 253]. High yield strength, works below 170°C, less defects. For all applications.
3. Music wire (high quality, carbon hard drawn steel) [253, 308, 323]. High homogeneity and surface roughness. For small wire diameter applications.
4. Stainless steels [236]. High corrosion resistance, lower mechanical properties, cheaper, works below 300°C. For all applications, particularly medical, naval and chemical.
5. Aluminium alloys [324]. Lower mechanical properties, high thermal and electrical conductivity, non-magnetic. For energy applications.
6. Copper alloys (Phosphor bronze and Beryllium copper) [6, 253, 325]. High electrical conductivity, good corrosion resistance. For electrical and energy applications.
7. Chrome alloys [6, 253, 326]. Good thermal conductivity and resistance, works below 220°C, good fatigue resistance and shock absorption.
8. Nickel alloys (*Inconel*, *Hastelloy*) [6, 327]. High thermal resistance, works below 1000°C. For spatial or nuclear applications.
9. Titanium alloys [308, 328]. High yield strength over density ratio. For spatial and aeronautic applications.
10. Monel (Nickel-Copper) alloys [253, 308]. Good mechanical properties, high corrosion resistance, works below 260°C. For chemical and naval applications.
11. Cobalt alloys (*Elgiloy*) [329, 330]. High corrosion resistance, ductility and fatigue resistance, works below 500°C, non-magnetic. For watches and clocks applications.
12. Nickel-Silver alloys [253, 308]. A rare non-ferrous material with low electrical conductivity, good corrosion resistance.
13. Shape memory alloys (SMA) [191, 308, 331–333]. Able to find its initial shape back by temperature elevation, even loaded. Good mechanical properties. For hydraulic and spatial applications.

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14. Composite materials (carbon, kevlar, glass) [290, 308, 320, 334–340]. Best yield strength over density ratio, stress reduction by fiber-orientation optimization, anisotropic, complex to manufacture. Experimental.
  15. Natural fibers (plant, wood) [341–343]. Low density, poor mechanical properties, high recyclability, high availability, low cost, anisotropic, complex to manufacture. Experimental.
  16. Plastics [308, 344–346]. High availability, easy to manufacture (small series), flexible geometries, anisotropic, recyclable. Experimental or for toys applications.
  17. Ceramics [308, 347, 348]. Best thermal resistance, works above 1200°C, high oxidation resistance, high mechanical properties, complex to manufacture, low surface roughness. For spatial and energy applications.

#### 4 MODERN APPLICATIONS

This section is not intended to provide an exhaustive list of spring applications but rather to highlight the diversity of uses, environments, functions, and sizes of mechanical springs today. The various functions of springs are summarized and organized in Table 2.

##### 4.1 Automotive and railway sectors.

The main objectives of springs integrated in vehicles are to improve passengers comfort and safety and enhance vehicle's performances. As previously mentioned, vehicles suspension systems are made with leaf springs or helical springs with variable pitch or diameter [349], but cars, motorbikes, trucks and trains admits much more spring applications. It is possible to define four axis of spring applications in vehicles, including passenger compartment mechanisms, the engine system, the steering and braking system and the safety mechanisms.

In the passenger compartment, various mechanisms are present to assist passengers and enhance their comfort. For example, helical springs are utilized in all doors, hoods, trunk lids, glove boxes, and other hinged compartments, either clipping into a locked position or retaining the mobile parts in an open state [350–352]. In vehicle doors, a combination of torsion springs is used to create the locking system [353], while compression springs are implemented in the lifter plate assemblies for window regulators [354], ensuring smooth displacement of the windows. In vehicle seats, multiple no-sag, compression, torsion, and tension helical springs are integral to

the seat adjustment mechanisms [135, 355, 356], allowing passengers to tilt and move the seats effortlessly. Additionally, clip bins that enable the assembly of plastic components without screws or rivets, such as dashboards or door panels, can also be considered as spring mechanisms.

The engine mechanism consists of multiple moving components, resulting in complex connections between them. An efficient way to ensure proper positioning is to integrate springs, such as cushion or diaphragm springs in clutch mechanisms, which press the gears and clutch release bearings [357, 358]. Additionally, valve springs in automotive engines maintain correct engine timing and compression [359], while flat and helical springs in shift levers provide positioning feedback for the driver [360].

Within the steering and braking systems, conical springs assist in deactivating the brakes [361]. Torsion springs are also employed to return foot pedals to their initial position when released [362]. The anti-roll bar, also known as a sway bar or stabilizer bar, is a suspension component designed to improve stability and handling and can be considered a type of flat spring [363].

Springs are also an integral aspect of safety mechanisms in vehicles. The deployment mechanisms of airbag systems are triggered by compression springs [364–367], as are the horn mechanisms in steering wheels [365, 366]. If the seatbelt comfortably presses against the passenger's chest or retracts when released, it is due to a spiral constant force spring [368] located in the retractor mechanism. Furthermore, if the seatbelt latch plate is securely fixed to the buckle, it is thanks to flat springs within the buckle [369] that maintain the connection. Passenger safety is also enhanced by clear visibility, which is ensured by windshield wipers maintained in contact with the glass by tension springs [370]. Airless tires reduce the risk of accidents by integrating elastic springs within the rim, as demonstrated in Michelin's Unique Puncture-Proof Tyre System (the UPTIS wheel) [190], as shown in Figure 18.

In addition to the various spring mechanisms used in the automotive industry, harvesting and mining vehicles are characterized by their challenging work environments. Underground mining trucks are exposed to dust, toxic gases (such as methane and sulfur dioxide), high-temperature gradients, and hazardous or corrosive chemicals used in ore extraction (including cyanide and mercury). Harvesting vehicles, on the other hand, contend with dust, moisture, fertilizers, pesticides, herbicides, and other corrosive substances. Springs designed for these applications must be made from specific materials, partic-

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Table 2. Functions of mechanical springs in modern applications.

Main objective	Detailed objective	Examples
To cushion...	Weights	Mattress, upholstery
	Impacts	Vehicle suspension
	Vibrations	Vehicle suspension, building, laundry appliance, NES
	Noises	Car window regulator, robot, vibraphone
	Flows	Tidal energy device, bridge and offshore equipment
To maintain a contact	To conduct electricity	Electrical contactor, circuit breaker, switch
	To seal	Aerosol, tank, pipe, hypersonic engine
	To tighten	Clutch, brake
	To press	Valve, cam, stent, pantograph, tweezer
	To compensate	(from thermal expansion/contraction) Bridge, pipe
	To align	Shift lever, metrology, switch, lens implant
	To retain/counterbalance	Hinge, auto belay
	To clamp/lock	Clothespin, buckle, lock, freewheel
To release energy	To return	Cable retractor, syringe, foot pedal
	To oscillate	Clock, watch, NES
	To create sounds	Reco-reco, kalimba, spring guiro
	To measure	Metrology instruments, sensor, scale
	To trigger/ignite	Weapon, electric relay, switch, lighter, engine starter
	To propel/release	Sport equipment, spatial solar panel, inhaler, toys, toaster

ularly austenitic high-manganese steel, austenitic stainless steels, and carbide-free bainitic steels, or they may require specialized coatings [371, 372]. Furthermore, it is in these specific large carrying vehicles that the largest helical springs ever produced can be found.

In the railway industry, flat springs are employed as non-rigid rail fastening systems [373], securing the connections even during thermal expansion or contraction. Tension springs are also implemented in pantographs to maintain electrical connections between the train and overhead lines [374]. Additionally, they are employed in the Shinkansen, the Japanese bullet train, in various applications including the oil controller mechanism, steam-trap device, bogie suspension, and emergency brake system [375–377].

#### 4.2 Aeronautics.

In aircraft, springs are employed in landing gears to absorb landing impacts and to lock the gears in position, utilizing helical or ring springs (admitting damping due to friction) [214, 215, 378], as well as leaf springs for small airplanes. These components are critical and must be appropriately sized and protected from hazards such as birds and tire debris, applicable to aircraft from the Boeing 767 to the Airbus A320 [378]. Similar to automotive vehicles, springs are present in seats, seat belts, and hinged components. Helical springs are also used in non-linear energy sinks (NES), which are devices designed to absorb and dissipate vibrational energy in a system while being lighter than oversized structures. NES devices are employed to reduce vibrations in critical structures like wings, fuselage, and jet engine mounts, thereby increasing safety and comfort [379, 380]. To ensure smooth

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and accurate adjustments and to provide the necessary torque for movement while maintaining stability during flight, ailerons, elevators, flaps, rudders, governors, and trims are spring-controlled [216–219]. Springs find applications in various systems, including instruments [199], jet engines [220–222], cabin pressurization, temperature control, and sealing systems [223, 381], de-icing mechanisms [381], emergency escape slide deployment, arming and release mechanisms [382–385], aerial refueling boom nozzles [386], and pre-joining fasteners for aircraft panels [387].

### 4.3 Spatial programs.

International and private space organizations value springs for their high precision and miniaturization capabilities. Springs serve as actuators for morphing and deployable structures, such as antennas, solar arrays, and landing gears, ensuring these components unfold or retract correctly. They can take various forms, including helical springs, molded springs, or tape springs [388, 389]. Due to the unique challenges posed by lunar or Martian surfaces, traditional pressurized tires are not reliable because of temperature and pressure variations. As a result, rover suspension systems differ significantly from those used in Earth vehicles. In these systems, wheels are directly linked to the chassis, with elastic connections integrated into the tire or wheel geometry. Examples include the elastic wheel of the former Soviet Lunokhod [390, 391], the spring-griddle net wheel used by the American Apollo lunar roving vehicle [390, 391], and the Chinese vane-spring-telescopic walking wheel [390]. Additionally, American shape memory alloy (SMA) spring tires are in development for NASA’s Martian and lunar rover vehicles [191]. These innovative tires can “remember” their original shape if damaged and consist of 684 interlaced helical springs per tire (as shown in Figure 18.x). Constant force springs are employed in Martian missions as cut cable retractors following spacecraft subsystems separation [392]. Canted coil springs are utilized as high-temperature seal devices in hypersonic engines, movable flaps, and reentry vehicle elevons [393]. Pusher springs ensure clean separation between the spacecraft and the launcher, minimizing debris [394]. Nonlinear energy sinks (NES) are implemented to protect rockets from dynamic load excitations across low, medium, and high-frequency bandwidths [379]. Lastly, bimetallic springs serve as mechanical heat switches, providing thermal protection for spacecraft by breaking contact between two critical systems under specified conditions [395].

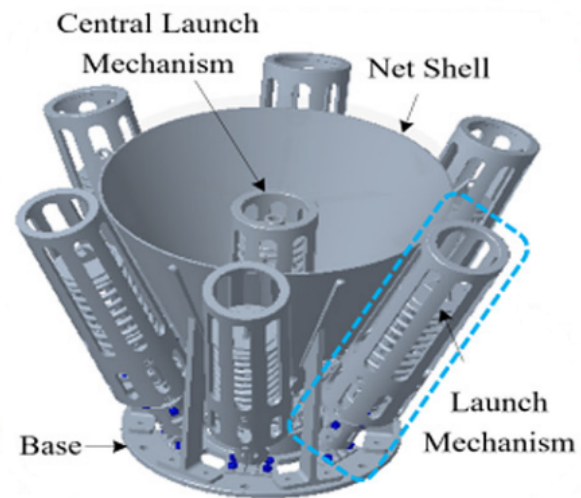


Fig. 25. Spring-propelled net in drone capture device. Adapted from [398].

### 4.4 Defense field.

As previously mentioned, springs are integral components in various military applications, including infantry weapons and grenades [209, 210], tanks [211–213], turret gun systems [211, 224], automatic firearms [242], intercontinental ballistic missiles [243], and submarine mines [246]. The functions of these springs are diverse, encompassing roles in triggering mechanisms, suspension systems, ammunition reloading devices, and propelling items. In addition to their roles in weapons systems, springs are also found in surveillance and reconnaissance equipment. For example, they are integrated in flapping-wing systems of micro-drones [396], which enable the drones to mimic the flight of birds and insects. Springs are also crucial in drone parachute deployment mechanisms [397], ensuring a reliable descent for the aircraft. Additionally, they are involved in drone capture propelling devices [398] (illustrated in Figure 25). Springs play a vital role in helicopters as well, particularly in emergency inflatable triggering mechanisms [385], which deploy inflatable systems during emergency situations. Furthermore, springs are used in deployable underwater sonar systems [399], allowing for effective underwater reconnaissance. They are also incorporated into cooling devices in helicopter weapon systems, which help prevent infrared tracking by ground-based artillery, as seen in the Comanche and Apache helicopters [400].

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#### 4.5 Naval and submarine instruments.

Naturally, springs find extensive applications in boats and submarines, serving various functions in hinged doors, storage compartments, pumps, valves, and suspension systems of amphibious vehicles. One specific application involves drawbar springs, which are compression springs designed for mooring purposes. These springs implement two loop elements that pass through the center of the coils to connect to the opposite end coil [401]. In overload situations, drawbar springs prevent vehicle loss due to significant tide changes by reaching their solid length, at which point deflection stops, unlike tension springs that may continue to deflect until failure. In addition to mooring chains, drawbar springs can also be employed in safety nets or rigging cables. Springs play a crucial role in isolating the hull from vibrations caused by large marine machinery rafts [402], enhancing onboard comfort and safety. Furthermore, springs are utilized to release life rafts in emergency situations [385] and to seal submarine holes during dives [403], ensuring the integrity and operational effectiveness of these vessels in challenging maritime environments and pressure variation.

#### 4.6 Metrology equipment.

Highly valued for their ability to provide controlled force, maintain stability, and absorb or compensate for minor variations during measurement processes, springs are integrated into metrology equipment to ensure high precision in measurements. Various types of springs, including micro or nano membranes, Belleville springs, and flat springs [312], are used in a range of measurement devices. For instance, in dial indicators, springs keep the plunger in contact with the measured surface, leading to a maximal error of only 0.03% [313]. Similarly, in micrometers, springs apply consistent force when the spindle is turned, achieving an error margin of  $\pm 1\mu\text{m}$  [314]. Load cells use springs to convert measured deformation into an electrical signal, with a load estimation error of 0.1% [315]. In Coordinate Measuring Machines (CMMs), springs ensure that the probe maintains contact with the measured surface without applying excessive force, reducing the pressing load by a factor of 50 for the same stroke compared to motor-only operation [404]. Springs are also employed in seismometers [405] and serve as calibration devices in impact testing [406] or in micro-force probes [312]. The miniaturization of systems and the continuous pursuit of the highest precision have led to the size reduction of measuring devices. Fortunately, the strength of springs extends to the nano-scale, with cantilever nano-springs employed in atomic force microscopes [407] enabling measurements down to *1attogram*

( $10^{-18}g$ ). Additionally, spring-activated nano-measuring and nano-positioning machines or piezoresistive micro-probes showcase the versatile applications of springs in cutting-edge metrology technology [312].

#### 4.7 Robotics.

Springs act as muscles or tendons in robot actuated joints to ensure high-precision displacements. Indeed, robotic arms need to perform precise and complex tasks, such as assembling components or conducting delicate surgeries. Springs assist them in executing an accurate and smooth approach for grasping with reliable pressure (too low results in dropping the object, while too high can damage it) [408–410]. Robotic legs maintain system stability and balance while navigating potentially complex surfaces. Springs enable them to absorb the shock of steps and control the relative movements of the parts with high precision, ensuring that the robot does not fall [411, 412].

#### 4.8 Electronic devices.

Specific springs are known as electrical connectors and contactors [413], capable of simultaneously maintaining a position, facilitating the easy insertion or extraction of a device, and ensuring electrical conductivity. Well-known examples are the conical and flat springs that hold batteries [414, 415] (Figure 26). However, some less visible flat springs serve a similar purpose in SIM cards, circuit boards, RAM modules, headphones connectors or USB ports [416] and helical springs in electric motors, alternators and generators brushes [417], connecting electrical components together (either in static or with relative movement). Helical compression springs may also be involved in discharging mechanisms or circuit breakers [418], or in crocodile clips.

Another electronic application of springs is found in buttons, switches, and sticks. Beneath each key of vintage keyboards were buckling springs [419], which are elongated helical compression springs loaded in an unstable manner to decrease stiffness after a certain deflection, providing ergonomic feedback to users. Modern keyboards utilize the same spring technology as nearly all buttons and switches: flat springs. These flat springs are used extensively, from light switches to smartphone power and volume buttons, TV remotes, computer mice, and console controllers [169, 420–422]. In contrast, controller joysticks and triggers are activated by helical springs [423].

They can also ensure smooth and accurate movements, a required capacity when manipulating fragile,

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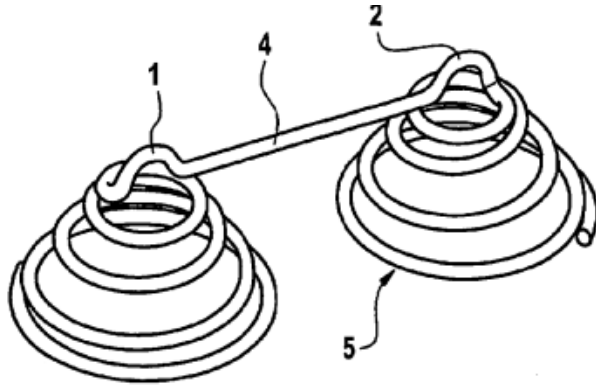


Fig. 26. Conical springs used as battery holders and electrical contactors [415].

conductive, and/or micro- elements. Torsion springs keep foldable smartphones or laptops open [424], while helical springs support adjustable mounting systems for televisions [425]. LCD apparatuses in TV screens are gently maintained by compression springs [426], VFD ones from video cassette recorders, car radios, and microwave ovens are made of filaments tensioned by flat springs [427], whereas camera shutter and lens aperture mechanisms are driven by a combination of tension, compression, and torsion helical springs [428, 429]. Gyroscope sensors in smartphones utilize ring springs as tilting sensors [430], and gaming controllers employ helical springs for their vibration mechanisms [431]. Finally, a complex combination of leaf and helical springs is implemented in the reading and ejecting mechanisms of CD players in gaming consoles and computers [432–434].

#### 4.9 Medical uses.

Because of its versatility and many favorable properties as a material, stainless steel is ideally suited for applications in numerous industries. Its biocompatibility and hygienic characteristics provide the necessary properties for use as a spring material in medical and pharmaceutical applications. Springs offer adjustable and accurately controlled force and movement, which is essential in surgical instruments [435], control valves for respiratory devices [436], syringes [437], diagnostic devices [438], artificial limbs [439], and drug delivery systems [437]. They are also attractive for their miniaturization; micro-springs are used in auxetic intravascular stents [440] ( $d \approx 0.05\text{mm}$  and  $D = 2.1\text{mm}$ , Figure 27), active coronary stents with drug-loaded surfaces [441] (i.e., the spring serves directly as medicine), or in micro-endoscopes [442] ( $d \approx 0.1\text{mm}$  and  $D \approx 0.7\text{mm}$ ). Springs can store energy to release fluid quickly, as in inhalers [443], insulin pens

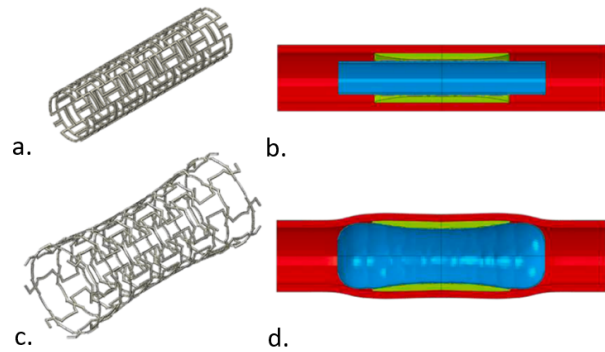


Fig. 27. Spring stent in initial shape (a) in the artery before deployment (b), and in deformed shape (c) in the artery after deployment (d) [440].

[444], pacemakers, or implantable cardioverter defibrillators [445]. Their flexibility is also advantageous for protecting and guiding fibers and long instruments like colonoscopes [446], endo-periscopes [447], gastroscopes [447], and bronchoscopes [442], or for blocking canals such as Essure devices, female sterilization devices that are placed into each fallopian tube [448], and inferior vena cava filters, which spread inside the vein to prevent blood clots from reaching the lungs [449]. Springs are also exploited to maintain in position, as seen in orthodontic devices [450], cataract lens implants [451], and orthotic braces [452].

#### 4.10 Civil structures and energy facilities.

Springs are used in civil engineering for safety measures, ensuring the integrity of structures despite thermal expansions or contractions, urban vibrations (from traffic, coordinated footsteps, or machinery), wave shocks, river cyclic loading, wind forces, and seismic activity. These phenomenon can be devastating for energy facilities such as nuclear plants, hydroelectric dams or wind turbines. To mitigate these effects, engineers can either optimize the shape of the structures, increase localized stiffness in the buildings, or install vibration absorbers. These absorbers are often designed as either elastomeric bearings or pre-stressed helical springs (with additional dampers or integrated into NES) [379, 380, 453, 454].

In scientific literature, spring suspensions are utilized in various applications, including a water tower suspended foundation [455], a pier column support [456], buildings subjected to earthquakes [457, 458], a 120m span aircraft hangar [459], and skyscrapers and towers such as Toronto's CN Tower (535m high) and Taipei 101 Tower (504m) in Taiwan [460, 461]. They are also imple-

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mented in concert halls and TV studios [462], dance and ballet floors [463], a metro trestle [462], nuclear power plants [461, 464], refinery chimneys [461], wind generators [461], offshore floating wind turbines [465], thermal power plants [461], offshore platforms [466], cable-suspended bridges [467], column bridges [468], semi-through bridges [469], and wind-excited support structures for traffic signals [470].

Springs are also employed in mobile civil structures and energy facilities, such as elevator mechanisms [471], penstock valve mechanisms in hydroelectric dams for regulating water flow [472], and blowout preventers for gas extraction, serving as high-pressure seals [473]. They are used in control valves of separation gas tanks to prevent over-pressure and manage flow control [474], as well as in blade pitch control systems of wind turbines [475]. Additionally, springs play a role in the braking systems of wind turbines to control the system during high winds or maintenance periods [476] and in tidal energy systems to smooth out flow impacts [477].

#### 4.11 Sport practice.

Springs in all forms help athletes improve their performance, comfort, and safety. Springs can be designed as propelling or bouncing devices. To achieve greater distances, athletes can rely on helical springs in golf club heads to restore more energy to the golf ball [478, 479], helical springs in adjustable body-played shuttlecocks [480], or tension springs with pulley-augmented strength in modern compound bows [481]. When it comes to increasing jumping performance, notable examples include double-leaf springs in bouncing shoes for higher jumps [482], conical compression springs in gymnastics springboards [483], tension springs and spring beds in gymnastics trampolines [484], and vaulting poles acting as bow springs [485]. At the intersection of bouncing devices and shock absorbers, helical and leaf springs are also found in the heels of athletic shoes [486–488], in the curvature of ski bends acting as composite leaf springs [489], and in prosthetics for disabled athletes acting as composite flat springs [490] (Figure 28). However, shock absorbers are more distinctly characterized by the use of helical and leaf springs in bicycle suspension systems [146, 189, 491].

Springs can also ensure the safety and comfort of athletes by serving as retaining and resisting components. For example, fitness equipment incorporates resisting springs [492, 493], while rock and gym climbers benefit from spring-loaded camming devices, spring-retractor auto belays, and spring carabiners for safety [494–496]. Torsion helical springs in bicycle brake systems keep the

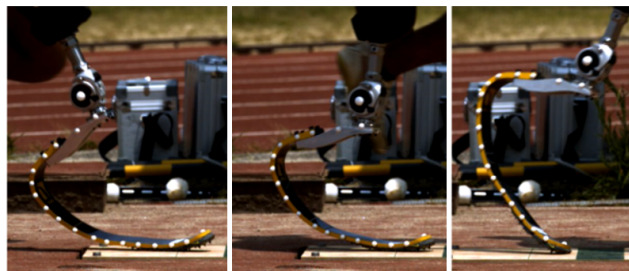


Fig. 28. States of the deformation of the leaf-spring-shaped prosthesis foot at the time of takeoff action [490].

brake shoes open when the associated handle is released [146, 497], while helical and flat springs in bicycle derailleur systems facilitate the pulling or pushing of the chain to the desired gear [146, 498].

By extension, any sport ball gas, any protective gear polymer, any racket strings act also as springs, but exit the scope of this review.

#### 4.12 Domestic mechanisms.

In addition to the previously mentioned mattresses, upholstered furniture, pens, lighters, clocks, watches, locks, and tweezers, a variety of springs are included in garden tools, such as volute springs in secateurs and averuncators [499], office items like paper clips, safety pins, and staplers [500, 501], general plumbing as bathroom taps or kitchen faucet spring spout [502], and household clamps, including clothespins, hair clamps, and mouse traps [503]. Springs are also employed in toys to create motion without electrical energy, such as in spring-propelled cars [504], slinkies [505, 506] (Figure 29), pop-up toys (jack-in-the-box) [507], slap bracelets (bi-stable ribbon springs) [508], automaton wind-up toys [509], firing foam guns [506], and playground spring-riders [510]. Notably, the longest spring ever created is a slinky measuring 91.4m long and 1.2m wide, produced in 2017 by artist A.W. Jessee [511].

In musical instruments, small coil springs are used in action mechanisms after a note is played to assist in the rapid return of hammers and keys in pianos, keyboards, and accordions [512], as well as foot pedals in pianos, drum kits, hi-hat cymbals, and vibraphones [513], and piston valves in wind instruments [514]. Springs are also used directly to produce sound in percussion instruments, such as flat springs in cog-wheel rattles [515], Jew's harps, acme clickers [513], flexatone [516], kalimba and marimbula [516]. Helical tension and compression springs are directly scratched in spring guiro and

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Fig. 29. Slinky in an arch configuration [505].

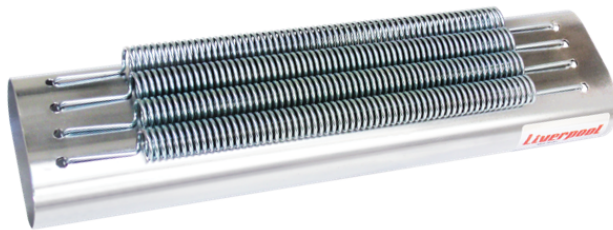


Fig. 30. Brazilian metal reco-reco made of 4 helical tension springs [517].

reco-reco (Figure 30) to create sounds [516, 517], while helical or spiral springs are located beneath snare drums [513] to make sharper sounds. In electric guitars, tremolo systems incorporate tension springs to provide pitch modulation [518].

Finally, household mechanics encompass kitchen and laundry appliances. Each hinged and locked door of these appliances incorporates several sets of springs [519]. Additionally, washing machines, clothes dryers, and dishwashers utilize compression springs in suspension systems to absorb vibrations and shocks, thereby reducing noise and improving performance [520]. Springs can also be found in the ejection mechanism of toasters [521], in the spark ignition mechanism of gas ovens [522], in the thermostats of refrigerators and freezers [523], and in the alignment mechanism of coffee makers [524].

#### 4.13 Chemical industry.

They ensure the safety of liquids, gases, and their containers. Compression springs are employed in locking mechanisms in spring-actuated devices such as aerosols,

sprays, and push-button dispensers [525], as well as in emergency locking mechanisms for valve deficiencies [526], effectively sealing the desired region. Additionally, they are utilized in evaporative emissions control systems of gas tanks and in pressure relief devices [527]. Compression springs also serve as retaining springs in pipe support systems, preventing failure during thermal expansion or contraction [528], in valve mechanisms that allow them to open under specific pressure conditions [529], in seals to prevent leaks in piping systems [530], and as return springs in pneumatic and hydraulic actuators [531].

## 5 CONCLUSION

The history of springs is a fascinating narrative that spans from primitive uses to sophisticated applications in modern engineering, shaped by technological advancements, military necessities, and material innovations.

Initially, proto-springs were crafted from bent wooden branches and bones for hunting purposes by our ancestors during the Stone Age (bows, snares and traps). Bronze Age saw the early uses of metals, considered more malleable and durable than wood or bones. Egyptians, Scandinavians, Europeans and Mesopotamians all developed metallurgy, and started to create small metallic devices, and started to create small metallic tools and weapons, such as race chariots suspension systems and composite bows in Europe, West-Asia and Africa. As for China, they develop the first spring-loaded locks, which would not appear in Europe until centuries later.

During Classical Antiquity, Greco-Romans, Archimedes in particular, developed spring-propelled siege engines to overwhelm enemy cities and extend their empires. The catapults, ballistae and onagers torsion springs were twisted fiber bundle made from horse or human hair, while Chinese crossbows were similar technology to bows. Middle Ages saw not only the enhancement of spring-propelled weapons into arbalests, mangonels and springalds, but also the improvement in wire drawing and forging processes brought by the use of powerful water- and windmills. These developments enabled Villard de Honnecourt to create several spring-loaded mechanisms, such as sawing and turning devices.

With the development of heat treatment and foundry techniques, as well as the mining and trading of resources from Africa and the Americas, Renaissance manufacturing processes enabled the production of the first spiral

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springs: the clocks' mainspring. These springs were independent and cheaper, lighter, smaller and more accurate than their weight- and pendulum-driven counterparts. Through Leonardo da Vinci creativity and engineering expertise, springs are considered in many devices as motion conversion mechanisms. The 15th century is also marked with the apparition of the first firearms, where springs play the role of ignition, trigger and release mechanisms in the form of elliptical flat springs, while being more efficient and less hazardous than the previously used matchlock mechanisms. Enlightenment saw the greatest scientific advances in mechanical and material engineering, including the works of Robert Hooke, Leonhard Euler and Thomas Young, pioneers in the spring knowledge. The first modern helical springs came into existence during the same period, with tension springs described in 1660 by Hooke and compression springs by Venturus Mandey in 1702.

Along with the Industrial Revolution and steam engines, valve springs and cam springs became ubiquitous in mechanical engineering. The growing knowledge and technology surrounding springs led to the development of various new spring forms, implemented into mattresses (hourglass springs), upholstery (no-sag springs), carriage and wagon suspensions (leaf springs). In 1841, Carlo Ignazio Giulio develop for the first time the stiffness equation of the helical springs, still learnt to all spring engineers and manufacturers today. The 20th century, influenced heavily by the World Wars and international conflicts, accelerated mechanical research funding, resulting in advancements in industrial manufacturing processes, such as thin-wire coiling process, hot coiling process and CNC machines. These innovations facilitated the production of springs in diverse shapes and sizes, cementing their role as essential components across various industries, highly valued for their ability to store and release energy without any external power source.

Today, springs play a vital role across a diverse range of applications, characterized by their various geometries, materials, and functions. From ensuring vehicle passengers safety and comfort, facilitating the operation of household appliances and enhancing athletic performances, to performing precise and delicate surgeries, deploying solar panels on satellites and preventing high-risk building from collapsing from earthquakes, springs are integral to modern daily life and technology. Their adaptability allows them to be designed in numerous forms and size, each tailored for specific tasks, from nano-cantilever springs for metrology and micro-stents for medicine to the several-meters-high helical springs for mining vehicles. The selection of materials, such as steel, plastic, ce-

ramic and composites, further expands their applicability and durability in different environments, such as space, with extreme pressure and temperature gradients; harvest fields, where corrosive substances are present; mining operations, where hazardous and flammable gases exist; marine settings, with corrosive saltwater; medical applications involving sensitive tissues; and electronic devices with specific magnetic and electrical characteristics. As innovation continues, the versatility of springs ensures their continued relevance and importance in both existing and emerging technologies.

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