Chapter 1. **Plant Taxonomy: A scientific approach to the plant world**

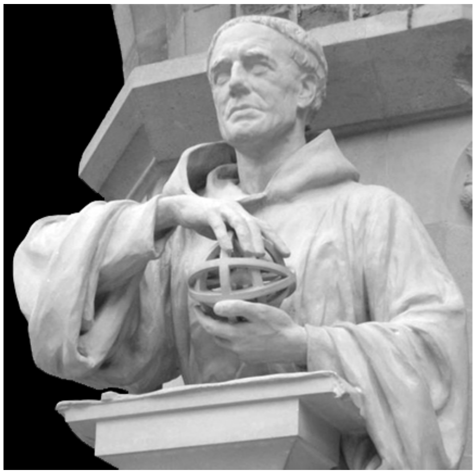
Plant taxonomy: The scientific classification of plants

We live from plants and of plants. We eat them, we use them for construction, we weave clothes with their fibers and we ferment them to make beverages. Through the process of photosynthesis, plants capture sunlight and atmospheric CO_2 to make organic molecules. Think about it: plants make living molecules, literally, out of thin air. Only light and carbon dioxide (and a little bit of water) are needed by plants to give us bread to eat, wine to drink, clothes to protect our bodies, fire wood to warm our houses, or mahogany to construct a violin. All the great civilizations in the world emerged, grew, and developed around agriculture: Mesopotamia, Egypt, China, India, the Horn of Africa, Mesoamerica, and the Andes, among many other regions of the world have given us the cornucopia of crops we use and feed on. We have co-evolved with plants and we have bred them into domestication, but plants have in some curious way also "domesticated" us, *Homo sapiens*. Our modern specialization of labor, our cities, our landscapes, our entire civilizations are a direct product of the way we have organized ourselves to obtain our crops and secure our timber.

Understanding the natural history of plants is not only an intellectual pursuit in theoretical science, it is the result of a deep basic need to understand our own history and to envision our own future. Feeding nine billion human beings in the world by 2050 while maintaining the ecosystem services and the biodiversity of life on earth will demand our best science, and a deep, profound understanding of the plants that make all life on earth possible. The scientific classification of plants, known as **plant taxonomy**, plays and will continue to play a central role in the viable future of our societies.

THE MEDIEVAL FOUNDATIONS OF MODERN SCIENCE

When was modern science founded? Although it is difficult to set a precise date because modern science is the result of the collective contributions of thousands of persons, two late-medieval thinkers and intellectual precursors of science have a large responsibility in the modern methods for the study of natural phenomena. The first one, **Roger Bacon** (1214–1294), an English philosopher and Franciscan friar who placed emphasis on the study of nature through empirical methods, is credited as one of the earliest European advocates of the modern scientific method. Inspired by Aristotle and by later scholars such as the Arab scientist Alhazen, Bacon was recognized by his intellectual brilliance. Called *Doctor Mirabilis* ("amazing teacher") by his pupils, Bacon believed that knowledge of the natural world advances through empirical experience, especially through systematic observation and through deliberate experimental trials. Natural phenomena, Bacon believed, have natural causes.

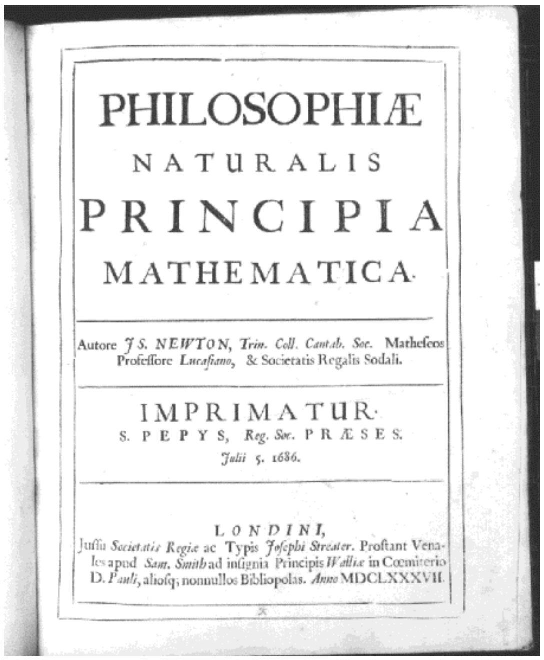


Roger Bacon, the "amazing teacher"

The second one was **William of Occam** (1287–1347) also an English Franciscan friar and scholastic philosopher. Occam's most recognized contribution to modern science was a simple formula for efficient reasoning known as the principle of parsimony in explanation or "Occam's Razor." Occam's maxim states that if one can explain a phenomenon without assuming un-needed hypotheses, then there is no ground for assuming them. In other words, knowledge should always opt for explanations in terms of the fewest possible causes, factors, or variables. He turned this into a concern for intellectual simplicity; the principle says that one should not multiply explanations beyond necessity: "Do not explain with many what can be explained with few" (*frustra fit per plura quod potest fieri per pauciora*).

Jointly, the works of Bacon and Occam showed that, in order to understand the natural world, one should construct simple hypotheses on how things work, and then test these hypotheses against experiments and detailed examinations of the natural world. In 1919, the British mathematician Alfred North Whitehead brought back the deep meaning of Bacon's and Occam's method with the following phrase: "The aim of science is to seek the simplest explanations of complex facts. The guiding motto in the life of every natural philosopher should be, '**Seek simplicity and distrust it**.'" (*The Concept of Nature* 1919).

THE ENLIGHTENMENT


PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore *J S. NEWTON, Trin. Coll. Cantab. Soc.* Matheſeos Profeſſore *Lucaſiano*, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,
Juſſu *Societatis Regiæ* ac Typis *Joſephi Streater.* Proſtant Venales apud *Sam. Smith* ad inſignia Principis *Walliæ* in Cœmiterio D. *Pauli*, aliosq; nonnullos Bibliopolas. *Anno* MDCLXXXVII.

Newton's *Principia Mathematica*

It took four centuries for the rationalist ideas of Bacon and Occam to take root in Europe and North America during a period of intellectual explosion known as the **Enlightenment**. Known also as the *Siècle des Lumières* (the Century of Lights), the Enlightenment was a philosophical movement which dominated the world of ideas in Europe and the Americas in the 18th century. Centered on **reason** as the source of authority and legitimacy, the Enlightenment advanced ideals such as liberty, progress, tolerance, fraternity, constitutional government, and ending the abuses of established authorities. It emphasized individual liberty and intellectual tolerance as drivers of human progress, and the development of science was marked by increasing empiricism, scientific rigor, and rationalism, along with increased questioning of traditional beliefs. This period of history saw the intellectual revolutions of Newton and Descartes in physics, and Linnaeus, Humboldt, Darwin, and Mendel, among many others, in biology.

Perhaps the most important scientific legacy of the Enlightenment was **rationalism** — the basic principle that natural phenomena have objective causes that can be researched, interpreted, understood, and used to predict the way nature operates. It seems almost puerile today, but it took four full centuries, from Roger Bacon to Isaac Newton, for societies to fully accept that our everyday lives are not governed by undetermined supernatural causes but by simple, concrete factors that can be identified and tested through rigorous observations and experiments. The consequences of the Enlightenment in science were momentous. In medicine, for example, the period led to the breakthrough discoveries of Jenner, Koch, and Pasteur and, for the first time in history, Europe saw advances in health care as humankind had never seen before.

The Linnean Revolution

The Enlightenment coincided with a period of colonial expansion of the European nations around the world. In their accelerated growth, the countries of Europe started looking for resources abroad, which were vital for their long-term success. Strategically important rubber was imported from the Amazon; fibers for the cordage that moved the imperial fleets came from Indian hemp or Mexican sisal fibers; quinine, vital to treat the malarial infections that often afflicted the imperial armies in the tropical colonies, was obtained from the *Cinchona* trees in Peru; rosewood, mahogany, ebony, and many other precious timbers were imported from forests in Africa, southeast Asia, and Tropical America, while new foods such as potatoes, corn, chocolate, or vanilla were constantly being brought into Europe's farms and greenhouses. Strategic resources also demanded exploration to locate them, and for this reason the Enlightenment was also a time of exploration. England, France, and Spain were sending boats to all the corners of the earth to research the wealth of natural resources that the planet offered to colonial expansion. Museums and botanical gardens were being established in London, Paris, Berlin, or Madrid to showcase the extraordinary diversity of life on earth (and the imperial power of European nations).

In this context, understanding the complexity of nature and finding a robust system for the classification of living things was critically important. The old Aristotelian system of classification, which had reached a peak with Pliny the Elder's *Naturalis Historiae* at the height of the Roman Empire (77 AD), simply could not deal with the biological richness and the complexity of the newly discovered worlds.

Carl Linnaeus

Carl Linnaeus, a Swedish biologist (1707–1778), was the first one to tackle the challenge of plant classification by developing the modern **binomial system** for naming organisms. Published in a breakthrough book called *Systema Naturae*, Linnaeus grew his classification of living things from a slender 12-page volume in the first 1735 edition to a monumental multi-volume treatise for the 10th edition, containing the description and classification of 4,400 species of animals and 7,700 species of plants. The unwieldy and often confusing description of organisms used in pre-Linnean times was replaced by two words (the "binomial"), containing a generic noun (the species' "genus") followed by a descriptive adjective (the species' "epithet"). The generic name, or genus, is often shared with other species. For example, the genus *Quercus* includes all the oaks and the genus *Salix* includes all the willow trees. The epithet defines the particular species within that genus to which we are making reference: *Quercus suber* (literally, the "corky oak") refers to the Mediterranean cork tree; *Salix lanata* refers to the woolly willow of Scandinavia. Contrary to common belief, binomial nomenclature was commonly used in Europe before Linnaeus's time. Romans, for example, used it frequently to characterize plants and crop stocks. *Tritricum aestivum*, the spring wheat used to make bread, was known to be different from *Tritricum durum*, the hard-grain wheat used for stews and gruels. Linnaeus, however, was the first to use binomial nomenclature systematically throughout his work as part of a rigorous scientific method of classification.

The rise of the Comparative Method

Linnaeus's biggest contribution to science more than the binomial system itself was the approach behind his classification method. Before Linnaeus, the classifications of living things had been based mostly in organismic function. Animals, for example, were often classified according to the habitat where they lived into flying, walking, or swimming organisms. Plants were often classified according to their growth form into trees, shrubs, vines, and herbs, or according to their uses. Early in his career, Linnaeus realized that using function or use as a classification criterion could lead to big mistakes: dolphins were often classified as fish, or bats were classified as birds. Similarly, he realized that, for example, plants with very similar traits in flowers and fruits—and obviously closely related—could have herbaceous species and woody tall trees sharing the same reproductive and floral morphology. The Aristotelian system of classification simply did not work in the expanding frontiers of Europe during the Enlightenment.

To tackle this problem Linnaeus developed a system of comparative analysis of biological morphology known at present as the **Comparative Method**. Linnaeus realized that some traits, such as the growth habit of a plant, provided only evidence of a superficial similarity of function, imposed by "conditions of existence", while other traits provided evidence of a deep similarity derived from a common structure, or "unity of type". Doing careful anatomical comparisons, he was able to find traits that were indicative of a common structure while disregarding those that were indicative of a simple convergence in function. For example, the wing of the bats, when examined closely, has a bone structure that is quite different from that of birds but closely resembles the forelimb of other mammals, so although bats and birds share the ability to fly, the comparative analysis of deep commonalities shows that bats really belong with mammals. Similarly, Linnaeus realized that although the dwarf herbaceous arctic willow of northern Scandinavia looks very different from the tall, majestic willows of southern Europe, their leaves are quite similar and their flowers and fruits are almost identical, suggesting that, although one species might have become small and prostrate to survive the Arctic winters, their comparative morphology shows that they really belong in the same genus.

In the Comparative Method, deep similarities of structure are known as "homologies" while superficial similarities, or similarities of function, are known as "analogies". The wing of bats and the wing of birds are really analogous structures; they have the same function but different origins. In contrast, the grasping hand of primates and the wing of bats are homologous; they may have different functions but share a common origin. For plants in particular, Linnaeus realized that floral morphology is much more constant than size or growth habit, and that homologies of taxonomic importance should be searched chiefly in flowers and fruits: Some willows are herbaceous while others are woody trees, but their flowers are very alike. Similarly, some legumes such as the common beans are short-liver herbs, while others, such as the desert ironwood, are woody trees that can live for thousands of years, but their almost-identical flowers betray a common origin. Linnaeus realized they belong in the same family.

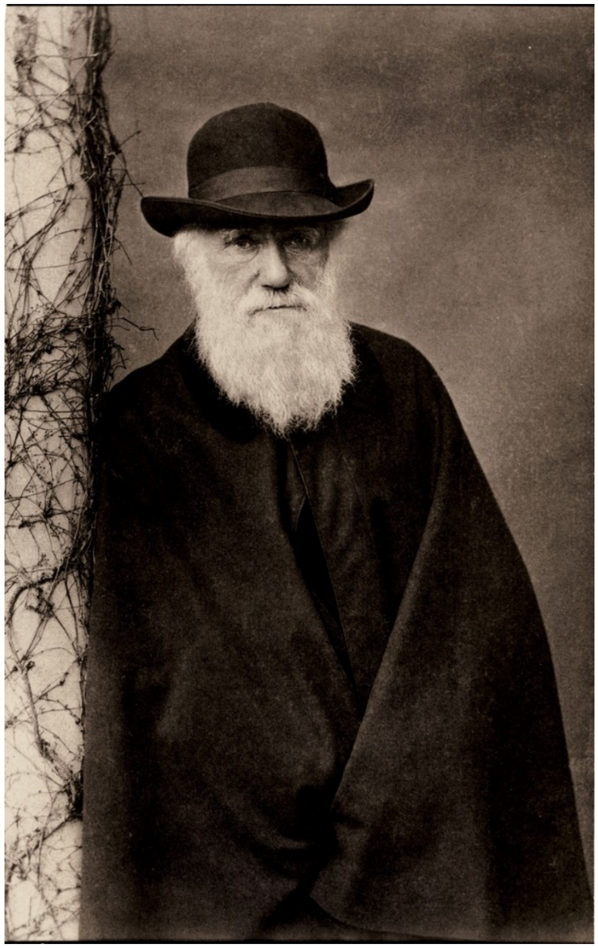
Linnaeus's approach to understanding the classification of living things spread rapidly into other fields of science, such as linguistics, archaeology, anthropology, or geology. Using the comparative method linguists started to understand the evolution of human language, and geologists started comparing the composition of rocks to unravel the deep history of the earth's surface. During the vibrant intellectual times of the Enlightenment, the comparative method brought a true revolution in the study of nature and triggered a debate about the deep causes of biological richness and species formation. For the first time in history, scientists became interested in understanding how living things have changed in a deep time scale and what were the origins of biological lineages.

The Comparative Method flourished during the Enlightenment with the intellectual explosion of rationalism. Scientists, as well as explorers in the most remote corners of the earth, used comparative science to illuminate the search for predictive patterns or "laws of nature". This revolutionary approach led to the serious questioning of solidly established paradigms, such as the true age of the earth or the changeable nature of biological species. Lastly, rationalism and the comparative method also demolished the anthropocentric view of the universe, by simply placing *Homo sapiens* as yet another species in nature's tree of life.

THE SCIENCE OF PLANT TAXONOMY

Linnaeus died in 1778 surrounded by a well-earned fame. His ideas became widespread, and a group of scientists in London created the **Linnean Society**, one of the first scientific societies in the world, to disseminate Linnaeus ideas and the comparative method. Many scientists realized that Linnaeus concept of homology or deep similarities was in effect making reference to commonality of origin in living things. The idea that groups of species that share common traits descend from a common lineage was implicitly present in Linnaeus taxonomy, which grouped similar species into Families, making clear allusion to evolutionary relatedness. Indeed, the idea that groups of related species shared a common ancestry became widespread during the Enlightenment, and many top scientists embraced it, including **Erasmus Darwin**, one of the most active members of the Linnean Society. But the question remained, if similar species descend from a common ancestor, how do species split apart to form new species?

Taxonomy and evolution


Charles Darwin in his old age

It was Erasmus Darwin's grandson, **Charles Darwin** (1809–1882), who came with an answer to this perplexing question and in doing so gave a new and more rigorous perspective to Linnean taxonomy and the comparative method. Darwin, a Cambridge-trained scientist and an acute observer of nature who had travelled around the globe in the HMS Beagle as a naturalist for the British Navy, was able to elucidate through careful observation how species form. Like his grandfather, he embraced the idea that all species have descended over time from common ancestors, but went one step further. In a joint publication with Alfred Russel Wallace he introduced the idea that this branching pattern of evolution resulted from a process that he called **natural selection**, in which different populations of the same species gradually drift apart in form and function as a result of differential survival and fecundity. He figured out that, in the same way that selective breeding by farmers produces starkly different varieties of a species, isolated populations of a species will gradually change to adapt to local conditions, eventually differing so much from their ancestral lineage as to form an entirely new species.

Darwin published his complete theory of evolution in his 1859 book *On the Origin of Species*, overcoming earlier concepts of transmutation of species that had met serious criticism by the scientific establishment. However, although he knew from plant breeding and animal husbandry studies that biological traits are passed from parents to offspring, Darwin did not know how biological traits were inherited or the mechanism of inheritance.

After Linnaeus and before Darwin: Early evolutionists


Lamarck

Looking at the diversity of life on earth, and comparing the shared anatomy of species, many scientists reached the conclusion that species were related by common lineages. Linnaeus' idea of "commonality of origin" clearly contained the idea of evolutionary and genetic relatedness. In France, Jean-Baptiste de Lamarck (1744 1829), a French naturalist, was an early proponent of the idea that evolution occurred in nature and proceeded in accordance with natural laws. Building on Linnaeus's theory of common origins, he developed the first truly cohesive theory of evolution, in which environmental forces adapted organisms to local environments through use and disuse of traits, differentiating them from other organisms.

In England, Erasmus Darwin also formulated a formal theory of evolution. He discussed how life evolved from a single common ancestor, forming "one living filament". Adding to Lamarck's theory of evolution through acquired traits from use and function, Erasmus Darwin also talked about how competition and sexual selection could cause changes in species: "The final course of this contest among males seems to be, that the strongest and most active animal should propagate the species which should thus be improved".

Erasmus Darwin was a respected English physician, as well a well-known poet, philosopher, botanist, and naturalist. In true aristocratic Victorian eccentricity, he often presented his evolutionary ideas in verse, in particular in the poem *The Temple of Nature* (1802):

Organic life beneath the shoreless waves
was born and nurs'd in ocean's pearly caves;
first forms minute, unseen by spheric glass,
move on the mud, or pierce the watery mass;
these, as successive generations bloom,
new powers acquire and larger limbs assume;
whence countless groups of vegetation spring,
and breathing realms of fin and feet and wing.

Taxonomy and genetics

It was until a few years after Darwin published *The Origin of Species* when **Gregor Mendel** (1822–1884), a German scientist and friar, solved the conundrum. Working with pea plants, Mendel showed that when a yellow pea and a green pea were bred together their offspring plant was always yellow. However, in the next generation of plants, the green peas reappeared at a ratio of 1:3. Mendel realized that inheritance is driven by discrete trait-transmitting units called "**genes**", and that organisms have two sets of genes or **alleles**—one inherited from the mother and another one from the father—for each transmissible trait. He also realized that when an organism has two different alleles one of them is usually expressed over the other. He called these alleles "dominant" and "recessive", as in the pea's yellow and green colors. Mendel's pea plant experiments established the basic rules of heredity, now referred to as the laws of Mendelian inheritance.


Gregor Mendel

Although Mendel published his studies in 1866, the profound significance of his work was not recognized by the scientific establishment until the turn of the 20th century, more than three decades later, ushering-in the modern age of genetics. With modern genetics, finally the mechanism of natural selection became clear: When a population of a species grows in isolation from the rest of its lineage, natural selection will favor the transmission of those genes that make the individuals more apt to survive and reproduce successfully. And those that do survive and reproduce will leave behind abundant progeny with their very own, locally successful genes. After a few generations, the local population will have adapted to its environment and will differ from the rest of its lineage. A new species has been produced.

Science and non-science

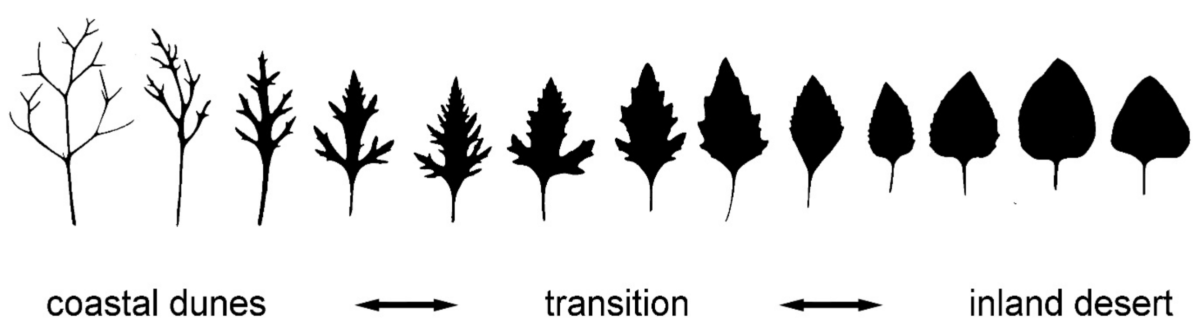
Science is both a body of knowledge and a process. It is a system of knowledge acquisition and discovery designed and perfected for the understanding of the natural world. Science allows us to link isolated facts into a coherent and comprehensive understanding of the natural world. As envisioned by Bacon and Occam over six centuries ago, science works by postulating hypotheses on how things work, and then by testing these hypotheses against experiments and detailed examinations of the natural world. A scientific hypothesis has to be observable, testable, and based on natural causes. In order to accept a hypothesis, the results of observations and experiments concerning a naturally occurring event should be similar when performed repeatedly, so that the inferred cause-and-effect mechanism can be used to make specific predictions. Scientific theories are not immutable, they are not “carved in stone”. Rather, they are subject to constant revision and correction. Scientific ideas are under constant scrutiny, they can be proved wrong, and if they do they have to be modified or discarded, in order to consistently explain observations of naturally occurring events.

Nonscience is the other sphere of human knowledge. Unfortunately, the term might seem derogatory as the "non" in nonscience almost implies some value judgment, but nonscientific areas of knowledge are as creative as science and of great importance for human knowledge. The term “nonscience” (not to be confused with pseudoscience or bogus-science) simply refers to ideas, concepts, and hypotheses that cannot be put to a scientific test. Nonscience involves religions, ethical beliefs, moral precepts, ideologies, and philosophical ideals. It often deals with ultimate causes and ethical or metaphysical questions. These kinds of ideas answer for us questions about the world, but, unlike scientific answers, they cannot be put to a test as they are based upon moral convictions, ethics, faith, belief, or ideology. They are not open to testing; they can be discussed, questioned, and sometimes changed, but, when they are, it is not through any sort of experimentation or observational testing but rather through abstract, philosophical analyses. Nonscientific ideas are of great importance to humans. They provide us with a moral compass, they show us how to use scientific knowledge in an ethical manner. They tell us what our values and our subjective relationship should be with the world around us and with each other, and they address questions for which we have no scientific response.

Vegetative traits can be misleading: Natural selection and morphological variation

Linnaeus realized early in his work on plant taxonomy that vegetative characters were often highly variable under different environmental conditions, and based his approach to plant taxonomy mostly on sexual characters, which he realized were less variable and tended to be more constant within taxa. Darwin realized that these contrasting changes in form were often the result of natural selection in different environments, and Mendelian genetics explained how environmental pressure may select different genotypes with genes expressing the most adaptive characters for each set of environmental conditions.

An extraordinary example of this can be observed in the California brittlebushes (genus *Encelia*, in the family Asteraceae) in the Vizcaíno Desert of Baja California (Kyhos, D., et al. 1981. *Systematic Botany* 6(4): 399–411). One species, *Encelia ventorum*, lives in the coastal dunes and has compound leaves with thread-like (filiform) folioles. A second species, *Encelia palmeri*, lives in the inland deserts and has entire leaves covered with dense hairs that protect them from excessive radiation and water loss. In the transition between the dunes and desert hybrid plants appear with intermediate characteristics, following the coast-to-desert gradient with a correlative gradient in leaf form. Although the leaves show a wide range of variation, the flowers are strikingly similar, indicating that, despite the immense leaf variation, the two species are very closely related within a common taxonomic lineage.



(Modified from Kyhos et al. 1981)

Modern Plant Taxonomy

With the synthesis of Darwinian evolution and Mendelian genetics, the system of plant taxonomy developed by Linnaeus evolved into a rigorous science. **Plant taxonomy**, also known as "**plant systematics**", studies the relationships between plant lineages and their evolution. The scientific principles of genetics and evolution brought a new significance to Linnaeus's concept of homology, or deep similarities between species. The hypotheses to be tested in plant taxonomy are about the taxonomic similarity of species. The classification of biological species using the barrage of tools that modern science provides, such as molecular biology, electron microscopy, geographic information systems, computer modelling and databasing is called **integrative** taxonomy.

Indeed, in modern science taxonomic similarity is measured in genetic and evolutionary terms. If two species with similar traits share common genes, then they must be closely related and share a common origin. If, on the contrary, two species with externally similar traits do not share common genes, then we must conclude that the morphological resemblance is only superficial and the species belong to different lineages. The rule can be applied not only to species but to any higher-order **taxon**, or lineage in the taxonomic tree. A good example of this can be found in the cacti of the New World (i.e., the Americas) and the succulent euphorbias of Africa. At a distance both **taxa** look extraordinarily similar, with leafless, spiny, green succulent stems clearly adapted to survive drought in arid environments. But external appearances can be deceitful: they really belong to two widely separated lineages that evolved in two different continents in response to increasing aridity. Their unrelated nature becomes evident when we look at their strikingly different flowers, for example, or when their DNA is sequenced. In these two taxa, the shared trait of succulence is an analogy, in Linnaeus terms, or a case of **convergent evolution**, in Darwinian terms. Their similarity, as striking as it may be, is only skin-deep.

The goals of modern plant taxonomy are the **description**, **identification**, and **classification** of plants:

Plant description is a formal description of a newly discovered species published in the form of a scientific paper. The author describing a new species will name the plant using a Latin binomial, such as Linnaeus originally proposed. The name of this new species is then registered on the International Plant Names Index, an online database that can be consulted by researchers all over the world.

Plant identification is the determination of the identity of an unknown plant by comparison with previously collected specimens or with the aid of books or identification manuals. The process of identification connects the specimen with a published scientific name. Once a plant specimen has been identified, its name and properties are known and can be compared with previously published descriptions.

Plant classification is the placing of known plants into the evolutionary tree of life, by organizing species into groups or categories based on inferred lineage relationships. Scientific classification follows a system of rules that systematically groups taxa into a hierarchy of Genera, Families, Orders, Classes, and Kingdoms. The classification of plants results in an organized system for the naming and cataloging of specimens based on the most rigorous evidence on the inter-relationships between plant lineages.

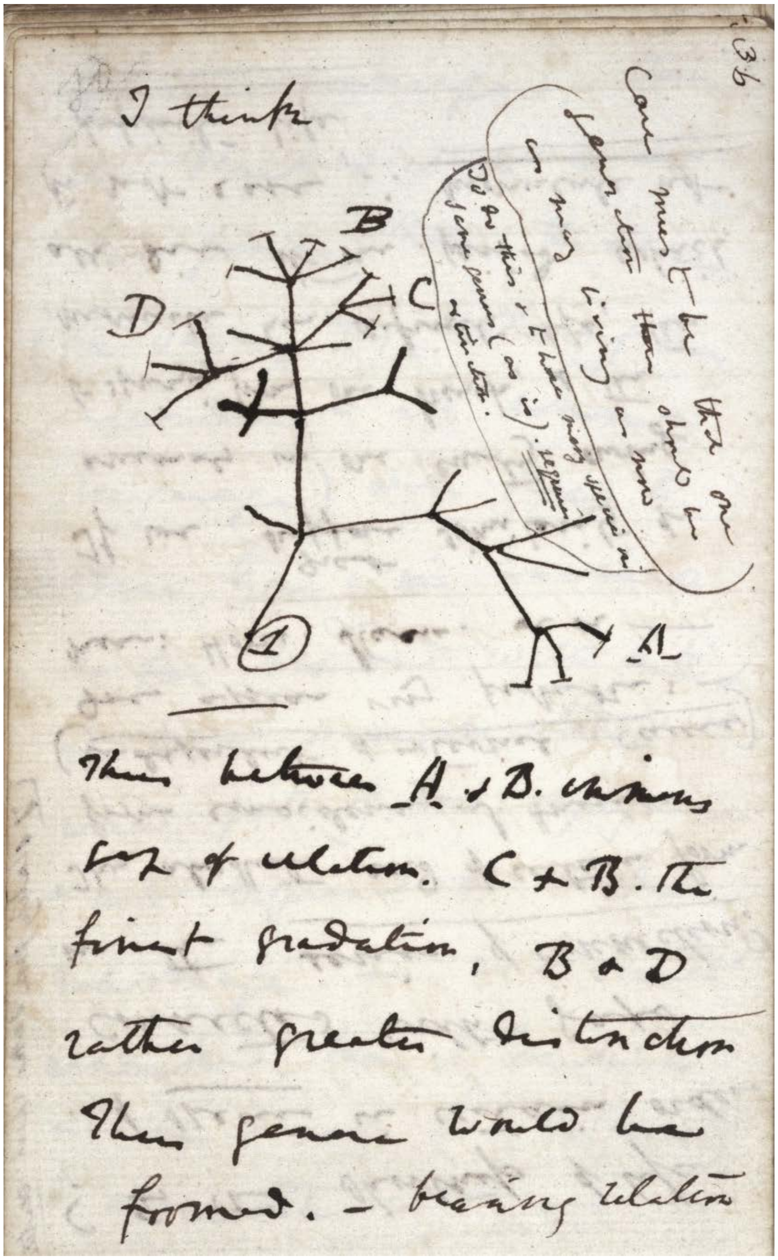


Figure 1.5. Darwin's "*I think…*" diagram — The first taxonomic tree