Connected Knowledge
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12 January 2021

Introduction

The interconnectivity of living organisms and the planet is brought to light through the spread of knowledge and the development of digital intelligence. This lecture tells the story of how this started with early explorers and cartographers, to the emergence of theories based on careful observation, to early computing and models of how different species move around and inhabit different parts of the world, to the importance of chaos theory in understanding the dynamics of nature. Stories from the voyages of Darwin and other amateur scientists to today's new planetary science illustrate the different ways in which new knowledge is received by society and the impacts of open data, the semantic web and ontologies and open science are having on our lives.

Early Travellers and Knowledge

One of the most famous travellers of the 13th century was the Venetian Marco Polo. He learned the mercantile trade from his father and his uncle, Niccolò and Maffeo, who in 1269, embarked on an epic journey to Asia, exploring many places along the Silk Road until they reached Cathay (China). The Polo family appears to have been shrewd, alert, and courageous as they moved across vast distances, creating diplomatic and business links with leaders such as Berke Khan, sovereign of the western territories in the Mongol Empire, and the great Kublia Khan. They were received by the royal court of Kublai Khan, who was impressed by Marco's intelligence and humility. Marco was appointed to serve as Khan's foreign emissary and was sent on many diplomatic missions throughout the empire and Southeast Asia, such as in present-day Burma, India, Indonesia, Sri Lanka and Vietnam. As part of this appointment, Marco also travelled extensively inside China, living in the emperor's lands for 17 years and seeing many things that had previously been unknown to Europeans. They eventually returned to Europe, accompanying the Mongol princess Kököchin to Persia, as Kublia Khan's ambassadors, and carrying letters asking the pope to send him 100 intelligent men "acquainted with the Seven Arts". Arriving in Venice, after 24 years, they found the city at war with Genoa and Marco was imprisoned. There he dictated his stories to Rustichello da Pisa, a cellmate. These were published as *Il Millione*, which he intended as a vast cosmography based on first-hand experiences – better captured in its first title *Divisament dou monde*. It is a panoramic account viewed through a powerful wide-angle lens.

In the last millennium, the influence of individual books and maps on society's understanding of the world has been profound. Though Marco Polo was not the first European to reach China, he was the first to explore some parts of Asia and to leave a detailed chronicle of his experiences. His account of the Orient provided the Europeans with a clear picture of the East's geography and ethnic customs and was the first Western record of porcelain, coal, gunpowder, paper money, and some Asian plants and exotic animals. His book inspired Christopher Columbus and many other travellers, and a substantial literature based on Polo's writings grew up. Marco Polo also influenced European cartography, leading to the introduction of the *Fra Mauro* map.

Sampling the Natural World
As more and more individuals became interested in describing and documenting the living world, a world of scientific instruments began to emerge [1] Competition amongst instrument makers was fierce and ideas and prototypes were closely guarded. Edmund Wingate, who was a part of the inner circle of learned men, including Isaac Newton, and who came together under the auspices of Thomas Gresham and went on to found the Royal Society, is a case in point. He was mathematics tutor to Henrietta, the daughter of Henry IV of France and Maria de' Medici, before she was married to Charles 1. Whilst at the French court, Wingate designed a set of wooden measuring rods, based on Napier's logarithmic rods, that came together as a slide rule, and wrote about the principles of its use. However, he claimed that the instruments were stolen by a visitor and the idea subsequently "copied" by his contemporary 1622, William Oughtred of Cambridge, who combined two handheld Gunter rules to make a device that is recognizably a slide rule. It led to many acrimonious exchanges when Wingate returned to England to the court of Charles. Wingate went on to write *Of Natural and Artificiall Arithmetique* in 1630 in two parts. Part one was designed "onely as a key to open the secrets of the other, which treats of artificial arithmetique performed by logarithms". A second edition appeared in 1652 as Arithmetique made easie. The first book ran through many editions, with the expression natural arithmetic being discarded for that of common arithmetic. What I found interesting is that in this book Wingate showed farmers and landowners how to develop accounts for "off-book assets", the idea at the core of the banking collapse of 2008-9!

Scientific expeditions continued to play an important role throughout the sixteenth to nineteenth centuries in driving the development of scientific instruments. From the development of chronometers to a wide variety of measuring devices, exploration had always attracted many investors, patrons and prizes. The marine chronometer is just one such example. To determine a position on the Earth's surface, it is necessary and sufficient to know the latitude, longitude, and altitude. Altitude considerations can naturally be ignored for vessels operating at sea level. Until the mid-1750s, accurate navigation at sea out of sight of land was an unsolved problem due to the difficulty in calculating longitude. Navigators could determine their latitude by measuring the sun's angle at noon or, in the Northern Hemisphere, to measure the angle of Polaris from the horizon usually during twilight. To find their longitude, however, they needed a time standard that would work on board a ship. Observation of regular celestial motions, such as Galileo's method based on observing Jupiter's natural satellites, was usually not possible at sea due to the ship's motion.

The Dutch scientist Gemma Frisius was the first to propose the use of a chronometer to determine longitude in 1530. The purpose of a chronometer is to measure accurately the time of a known fixed location, for example Greenwich Mean Time (GMT). This is particularly important for navigation. Knowing GMT at local noon allows a navigator to use the time difference between the ship's position and the Greenwich Meridian to determine the ship's longitude. As the Earth rotates at a regular rate, the time difference between the chronometer and the ship's local time can be used to calculate the longitude of the ship relative to the Greenwich Meridian (defined as 0°) using spherical trigonometry. In modern practice, a nautical almanac and trigonometric sight-reduction tables permit navigators to measure the Sun, Moon, visible planets, or any of 57 selected stars for navigation at any time that the horizon is visible. But the creation of a timepiece which would work reliably at sea was difficult. The rolling of a ship at sea and the up to 0.2% variations in the gravity of Earth made a simple gravity-based pendulum useless both in theory and in practice.

Christiaan Huygens made the first attempt at a marine chronometer in 1673 in France, under the sponsorship of Jean-Baptiste Colbert. In 1675, Huygens, who was receiving a pension from Louis XIV, invented a chronometer that employed a balance wheel and a spiral spring for regulation, instead of a pendulum, opening the way to marine chronometers and modern pocket watches and wristwatches. He obtained a patent for his invention from Colbert, but his clock remained imprecise

[1] Hughes, D. 1983 Nature 306

at sea. In 1675 he tried to obtain an English patent from Charles II, but this stimulated Robert Hooke, who claimed to have conceived of a spring-driven clock years earlier, to attempt to produce one and patent it. During 1675 Huygens and Hooke each delivered two such devices to Charles, but none worked well and neither Huygens nor Hooke received an English patent.

Theoretical works on marine chronometers began to grow; in 1684 in Arcanum Navarchicum, a theoretical work by Kiel professor Matthias Wasmuth was followed by a further theoretical description of a chronometer in works published by English scientist William Derham in 1713 which proposed the use of vacuum sealing to ensure greater accuracy in the operation of clocks. Attempts to construct a working marine chronometer were begun by Jeremy Thacker in England in 1714, and by Henry Sully in France. Sully published his work in 1726 with Une Horloge inventée et executée par M. Sulli, but still neither his nor Thacker's models were able to resist the rolling of the seas and keep precise time while in shipboard conditions.

In 1714, the British government offered a longitude prize for a method of determining longitude at sea, with the awards ranging from £10,000 to £20,000 (£2 million to £4 million in 2021 terms) depending on accuracy. John Harrison, a Yorkshire carpenter, submitted a project in 1730, and in 1735 completed a clock based on a pair of counter-oscillating weighted beams connected by springs whose motion was not influenced by gravity or the motion of a ship. His first two sea timepieces H1 and H2 (completed in 1741) used this system, but he realised that they had a fundamental sensitivity to centrifugal force, which meant that they could never be accurate enough at sea. Construction of his third machine, designated H3, in 1759 included novel circular balances and the invention of the bi-metallic strip and caged roller bearings, inventions still widely used. However, H3's circular balances still proved too inaccurate and he eventually abandoned the large machines.

Harrison solved the precision problems with his much smaller H4 chronometer design in 1761. H4 looked much like a large five-inch (12 cm) diameter pocket watch. In 1761, Harrison submitted H4 for the £20,000 longitude prize. His design used a fast-beating balance wheel controlled by a temperature-compensated spiral spring. These features remained in use until stable electronic oscillators allowed very accurate portable timepieces to be made at affordable cost. In 1767, the Board of Longitude published a description of his work in The Principles of Mr. Harrison's timekeeper and a French expedition under Charles-François-César Le Tellier de Montmirail performed the first measurement of longitude using marine chronometers aboard Aurore in 1767.

Beyond accurate measurement of time and space, the most important instrument that emerged at this time and which was crucial in transforming our knowledge about the connectedness of the living world was the microscope and the manufacture of powerful lenses. Antonie Philips van Leeuwenhoek was a Dutch businessman and scientist; a largely self-taught man in science, he is commonly known as "the Father of Microbiology", and one of the first microscopists and microbiologists. Raised in Delft, Dutch Republic, van Leeuwenhoek worked as a draper in his youth and founded his own shop in 1654. His interest in microscopes and a familiarity with glass processing led to one of the most significant, and simultaneously well-hidden, technical insights in the history of science: By placing the middle of a small rod of soda lime glass in a hot flame, van Leeuwenhoek could pull the hot section apart to create two long whiskers of glass. Then, by reinserting the end of one whisker into the flame, he could create a very small, high-quality glass sphere. These spheres became the lenses of his microscopes, with the smallest spheres providing the highest magnifications. He started to explore microbial life using single-lensed microscopes of his own design. He was the first to experiment with microbes, which he originally referred to as dierkens, diertgens or diertjes (Dutch for "small animals" translated into English as animalcules, from Latin animalculum = "tiny animal"). Through his experiments, he was the first to relatively determine their size. Most of the "animalcules" are now referred to as unicellular organisms, although he observed multicellular organisms in pond water. He was also the first to document microscopic observations of muscle fibres, bacteria, spermatozoa, red blood cells, crystals in gouty tophi, and blood flow in capillaries.

At first van Leeuwenhoek had been reluctant to publicize his findings, regarding himself as a businessman with little scientific, artistic, or writing background, but the prominent Dutch physician and friend Reiner de Graaf urged him to be more confident in his work. By the time van Leeuwenhoek died in 1723, he had written some 190 letters to the Royal Society, detailing his findings in a wide variety of fields, centered on his work in microscopy. He only wrote letters in his own colloquial Dutch; he never published a proper scientific paper in Latin, and strongly preferred to work alone, distrusting the sincerity of those who offered their assistance. The letters were translated into Latin or English by Henry Oldenburg, who had learned Dutch for this very purpose. He was also the first to use the word animalcules to translate the Dutch words that Leeuwenhoek used to describe microorganisms. Despite the initial success of van Leeuwenhoek's relationship with the Royal Society, soon relations became severely strained. His credibility was questioned when he sent the Royal Society a copy of his first observations of microscopic single-celled organisms dated 9 October 1676 - previously, the existence of single-celled organisms was entirely unknown. Thus, even with his established reputation with the Royal Society as a reliable observer, his observations of microscopic life were initially met with some scepticism. Eventually, in the face of van Leeuwenhoek's insistence, the Royal Society arranged for Alexander Petrie, minister to the English Reformed Church in Delft; Benedict Haan, at that time Lutheran minister at Delft; and Henrik Cordes, then Lutheran minister at the Hague, accompanied by Sir Robert Gordon and four others, to determine whether it was in fact van Leeuwenhoek's ability to observe and reason clearly, or perhaps, the Royal Society's theories of life that might require reform! In 1677, van Leeuwenhoek's observations were fully acknowledged by the Royal Society, and he was elected to the Royal Society in February 1680. Van Leeuwenhoek was "taken aback" by the nomination, which he considered a high honour, although he did not attend the induction ceremony in London, nor did he ever attend a Royal Society meeting.

Instrument makers became an essential part of the scientific landscape, allowing comparisons of phenomena to become an established methodology and the connectedness of nature to be made more visible. G.F.Brander (1713-1783), was one of the most important scientific instrument makers in Germany during the eighteenth century. Brander could produce glass scales on which the millimetre was divided into 30 equal parts; a considerable advance in the accuracy of measurement was thus generated. By 1780 the catalogue of Brander's workshop included 102 instruments covering the main areas of contemporary natural science: astronomy, mathematics, optics, meteorology, geodesy and physics. Another Munich personality was Joseph von Fraunhofer (1787-1826) –after which the Frauenhofer Institutes were named. It was through Fraunhofer's work that the scientific and industrial basis for the production of pure, defect free optical glass and its manufacture into lenses, achromatic lens combinations and prisms was created. The desire for a more accurate determination of the refractive indices of these glasses led to the discovery of the dark lines in the solar spectrum that bear his name. The small glass works at the Monastery of Benediktbeurn where Fraunhofer manufactured glass between 1807 and 1819 still exists.

In 1790 Guiseppe Piazzi, the first director of the Palermo Astronomical Observatory, Sicily, equipped the observatory with the most up-to-date instruments he could get. Many were obtained from the famous London instrument maker Jesse Ramsden, the two largest being a five-foot alt-azimuth circle and a transit instrument. A unique discovery was made by A. Brachner (Deutsches Museum) when in December 1982 he was contacted by the Benedictine Monastery of Ochsenhausen, Bavaria and asked for advice about the conservation of an astronomical instrument. Ongoing to the monastery he found their baroque observatory dome contained a beautiful example of a late 18th century, three-metre radius, azimuthal quadrant that had probably been used for teaching purposes.

The teaching aspects of scientific instrumentation was enhanced when J.H. Bennett introduced microscopy into the teaching curriculum for medicine at the University of Edinburgh in 1841. The work of Bennett and his colleagues also helped transform the microscope from a scientific “toy “into a first-rate research instrument. As Thomas Graham wrote in 1838 'It is curious how much the progress of science depends upon the invention and improvement of instruments.'

Detailed Observations of the Natural World

Natural history has been the cornerstone of data gathering. The change in scientific understanding really came however, when the systematisation of this knowledge began to take shape. Key figures in this transition were the curators of specimens of plants, birds and mammals, and the most important was Carl von Linnaeus. Born 1707, Linnaeus was a Swedish botanist, zoologist, taxonomist, and physician who formalised binomial nomenclature, the modern system of naming organisms. He is known as the "father of modern taxonomy". Many of his writings were in Latin, and his name is rendered in Latin as Carolus Linnæus (after 1761 Carolus a Linné).

Linnaeus rarely studied, often going to the countryside to look for plants. He reached the last year of the Lower School when he was fifteen, when he was introduced to a botanist, Rothman who broadened Linnaeus's interest in botany and helped him develop an interest in medicine. By the age of 17, Linnaeus had become well acquainted with the existing botanical literature. He remarks in his journal that he "read day and night, knowing like the back of my hand, Arvidh Månsson's *Rydaholm Book of Herbs*, Tillandz's Flora Åboensis, Palmberg's *Serta Florea Suecana, Bromelii Chloros Gothica and Rudbeckii Hortus Upsaliensis*". In 1729, Linnaeus wrote a thesis, *Praeludia Sponsaliorum Plantarum* on plant sexual reproduction. This attracted the attention of Rudbeck, and in May 1730, he selected Linnaeus to give lectures at the University although the young man was only a second-year student. His lectures were popular, and Linnaeus often addressed an audience of 300 people. He subsequently lived abroad between 1735 and 1738, where he studied and also published the first edition of his *Systema Naturae* in the Netherlands. He then returned to Sweden where he became professor of medicine and botany at Uppsala. In the 1740s, he was sent on several journeys through Sweden to find and classify plants and animals and continued to collect and classify animals, plants, and minerals, while publishing several volumes through the 1750s-60s. He was one of the most acclaimed scientists in Europe at the time of his death. Linnaeus has been called *Princeps botanicorum* (Prince of Botanists) and "The Pliny of the North" and is considered as one of the founders of modern ecology. Linnaeus's remains constitute the type specimen for the species *Homo sapiens* following the International Code of Zoological Nomenclature, since the sole specimen that he is known to have examined was himself!

The turning point for Linneaus happened when he undertook explorations of Lappland. Rudbeck had made the journey in 1695, but the detailed results of his exploration were lost in a fire seven years afterwards. Linnaeus's hope was to find new plants, animals and possibly valuable minerals. He was also curious about the customs of the native Sami people, reindeer-herding nomads who wandered Scandinavia's vast tundras. In April 1732, Linnaeus was awarded a grant from the Royal Society of Sciences in Uppsala for his journey. Linnaeus began his expedition from Uppsala on 12 May 1732, just before he turned 25. He travelled on foot and horse, bringing with him his journal, botanical and ornithological manuscripts and sheets of paper for pressing plants. Near Gävle he found great quantities of *Campanula serpyllifolia*, later known as Linnaea borealis, the twinflower that would become his favourite. He sometimes dismounted on the way to examine a flower or rock and was particularly interested in mosses and lichens, the latter a main part of the diet of the reindeer, a common and economically important animal in Lapland. He travelled clockwise around the coast of the Gulf of Bothnia, making major inland incursions from Umeå, Luleå and Tornio. He returned from his six-month-long, over 2,000 kilometres (1,200 mi) expedition in October, having gathered and observed many plants, birds and rocks. Although Lapland was a region with limited biodiversity, Linnaeus described about 100 previously unidentified plants. These became the basis of his book Flora Lapponica.

It was also during this expedition that Linnaeus had a flash of insight regarding the classification of mammals. Upon observing the lower jawbone of a horse at the side of a road he was travelling, Linnaeus remarked: "If I only knew how many teeth and of what kind every animal had, how many teats and where they were placed, I should perhaps be able to work out a perfectly natural system for the arrangement of all quadrupeds." It was thus in Flora Lapponica that Linnaeus's ideas about nomenclature and classification were first used in a practical way, making this the first proto-modern Flora. The account covered 534 species, used the Linnaean binomial classification system and included, for the described species, geographical distribution and taxonomic notes.

Gazetting the Natural World

With the Linnean classification widely accepted, scientific expeditions and explorations of new lands had a comparative basis upon which to describe the natural world. The Comte de Buffon was one of my favourite taxonomists, as he described many fishes which I was studying as part of my PhD. Buffon was a French naturalist, mathematician, cosmologist, and encyclopédiste. His works influenced the next two generations of naturalists, including two prominent French scientists Jean-Baptiste Lamarck and Georges Cuvier. Buffon published thirty-six quarto volumes of his *Histoire Naturelle* during his lifetime, with additional volumes based on his notes and further research being published in the two decades following his death. Ernst Mayr, a famous twentieth evolutionary biologist wrote that "Truly, Buffon was the father of all thought in natural history in the second half of the 18th century".

In 1732 he moved to Paris, where he made the acquaintance of Voltaire and other intellectuals. He first made his mark in the field of mathematics and, in his *Sur le jeu de franc-carreau* (On the game of fair-square), introduced differential and integral calculus into probability theory; the problem of Buffon's needle in probability theory is named after him, and in 1734 he was admitted to the French Academy of Sciences. During this period, he corresponded with the Swiss mathematician Gabriel Cramer. In 1739 he was appointed head of the Parisian Jardin du Roi with the help of Maurepas his protector and was instrumental in transforming the Jardin du Roi into a major research centre and museum. He enlarged it, arranging the purchase of adjoining plots of land and acquiring new botanical and zoological specimens from all over the world.

In the course of his examination of the animal world, Buffon noted that despite similar environments, different regions have distinct plants and animals, a concept later known as Buffon's Law. This is considered to be the first principle of biogeography. He made the suggestion that species may have both "improved" and "degenerated" after dispersing from a centre of creation. He argued that all the world's quadrupeds had developed from an original set of just thirty-eight quadrupeds. On this basis, he is sometimes considered a "transformist" and a precursor of Darwin. He also asserted that climate change may have facilitated the worldwide spread of species from their centres of origin.

Charles Darwin wrote in the fourth edition of On the Origin of Species that "the first author who in modern times has treated it [evolution] in a scientific spirit was Buffon. But as his opinions fluctuated greatly at different periods, and as he does not enter on the causes or means of the transformation of species, I need not here enter on details". The paradox of Buffon is that, according to Ernst Mayr, he was not an evolutionary biologist, yet he was the father of evolutionism. He was the first person to discuss a large number of evolutionary problems, problems that before Buffon had not been raised by anybody ... he brought them to the attention of the scientific world. Except for Aristotle and Darwin, no other student of organisms has had as far-reaching an influence.

He brought the idea of evolution into the realm of science. He developed a concept of the "unity of type", a precursor of comparative anatomy. More than anyone else, he was responsible for the acceptance of a long-time scale for the history of the earth. He was one of the first to imply that you get inheritance from your parents, in a description based on similarities between elephants and mammoths. But he hindered evolution by his frequent endorsement of the immutability of species., whilst writing about the concept of struggle for existence. He developed a system of heredity which was similar to Darwin's hypothesis of pangenesis. Commenting on Buffon's views, Darwin stated, "If Buffon had assumed that his organic molecules had been formed by each separate unit throughout the body, his view and mine would have been very closely similar. But there was no doubting the importance of his Histoire Naturelle.

One of Linneaus' students was Daniel Solander; he learned and mastered Linnaeus's new naming system. Scientists elsewhere in the world were keen to apply it too, so in 1759 the professor sent his protégé to England as an emissary. In 1762 he was appointed Assistant Librarian at the British Museum, cataloguing the natural history collections. These would become some of the founding collections of the Natural History Museum, over a century later. His work allowed him to further promote the Linnaean system. But it was a pivotal moment in 1764 when the botanist met landowner Joseph Banks, with whom he became a close friend and colleague. Influenced by Solander, Banks had planned to study with Linnaeus at Uppsala, but he ultimately joined James Cook aboard HMS Endeavour, departing for Tahiti in 1768, and invited Solander to accompany him. The two scientists spent the expedition studying the natural history of the areas they visited and collected around 30,000 specimens from 1768 to 1771, with 1300 new to Western science, using the eponymous Solander slips on which to write notes. Post-Endeavour, in 1773, Solander returned to the British Museum as Assistant Keeper and continued to work with the collections until his death in 1782, his legacy, that of Solander and their artists' work captured in the 34-volume Banks' Florilegium – published in was finally published in the 1980s over 200 years after the expedition.

Scientific Explorations

The era of scientific explorations had really taken off by the mid eighteenth century; yet still many parts of the terrestrial world remained unexplored even up to the early twentieth century. This was the time of great journeys of Darwin and Wallace, of Lewis and Clark in the United States, Livingstone and Stanley in Africa, Nansen, Amundsen and Shackleton in the polar regions, and many more committed to describing the world through a scientific lens and in search of discovering the workings of the planet. No unexplored region in the nineteenth century, neither the heights of the Himalayas, the Antarctic wastes nor even the hidden side of the moon has excited quite the same fascination as the mystery of the sources of the Nile. Barely 150 years ago the matter had become the greatest geographical secret after the discovery of America, and a matter of endless speculation amongst geographers. China became known to Europe, America and Australia were discovered and the land masses mapped, but still in the mid nineteenth century the centre of Africa remained an enigma. Then in 1848, Johann Rebmann reported that he had travelled from the coast of east Africa and seen a vast mountain called Kilimanjaro, with snow on the summit. Johamm Krapf followed this up with his observation of another snow-capped peak, Mount Kenya. Lake Ujiji and Nyanza were also spoken about. The question was whether the lakes were the same, and how did the mountains fit into the pattern of the Nile? It was to answer these questions that Burton and Speke set off for Africa in 1856, deciding to strike out westward from Zanzibar into the "dark interior" where no white man had ever been before. With this new expedition, the age of the Central African exploration began.

Livingstone was only fifty-two when he set out on his last journey in 1865. His previous expeditions, whilst successful in terms of discoveries, had been a disaster for his companions. Livingstone was a nomad and a traveller first and foremost, and so he set out once again in an effort to clear up the question of the Nile and to suppress the slave-trade. His books had made him the most famous of all African explorers and he had enough money from royalties to take up the invitation form the Royal Geographical Society to carry on his life's work and resolve finally the enigma of the lake and river system in the centre of the continent. Livingstone's plan was to go directly inland towards the unexplored country south of Lake Tanganyika. Never can there have been a journey founded upon so many misassumptions – the search for the source of a river in a region where it did not exist; it was an anti-slavery expedition that had no power and it was the march of a man, who believed that he alone, unarmed and unsupported could pass through Africa. But this was the point – these issues were all resolved not by Livingstone himself but because he inspired others to go off in other directions!

For several years, Livingstone's whereabouts had been a perennial mystery; when word got back that he was alive apathy took over. So, it was an odd moment when the most assiduous, foreign correspondent – Stanley - pushed through the crowds in Ujiji, it was his own admitted cowardice that made him approach Livingstone formally instead of embracing him and say, "Dr Livingstone I presume?", to which he replied "Yes" and lifted his cap. At the outset of his journey Livingstone had been for Stanley another assignment. But Livingstone needed medicine and news of the outside world and the young Stanley needed kudos; soon they had fallen into a plan to journey together to settle the question of the Rusizi River and confirm Livingstone's belief that the Lualaba was the Nile. So it seemed inevitable that on discovering that the Ruisizi flowed into and not out of Lake Tanganyika, that Livingstone would stay whilst Stanley set off to the coast and Zanzibar, carrying with him the treasures of Livingstone's journals, his notes and his first book *How I Found Livingstone* and most critically a letter to the New York Herald from Livingstone describing a slave massacre at Nyangwere and the terrible Ujijian slavery, a letter which led to the suppression of the East Coast slave-trade. Stanley was met on his way back by a new expedition which the Royal Geographic Society had sent to find the 'lost man'; and so, it was Stanley who in 1872 caused a sensation throughout the world with his description of the Ujiji meeting with Livingstone. After he died, an almost impossible journey was undertaken to return his body to England, where it remained overnight at the Royal Geographic Society and was then interred in Westminster Abbey. Even before his death, Livingstone's great power over people's minds had reached out from Central Africa. The sources of the Nile eluded him, but the description of the massacre at Ngangwe raised such a storm that the Sultan of Zanzibar was forced to close the slave market forever.

Geography Matters

In northern Kenya, a new chapter in our understanding of the connectedness of life on the planet was opening. The year 1888 marked the arrival of the first European explorers in the Lake Turkana (Rudolf as it was then called) region. They found a multifarious collection of nomadic tribes, cultures, languages and economic systems mostly based on pastoralism. The first explorers were Count Teleki and Lieutenant von Höhnel, who were trudging northwards to find the mysterious lake which had been reported lying somewhere in the last blank space on the map of east Africa. They did not meet the fearsome Laikiak Maasai, who had tenaciously obstructed Joseph Thompson's trail blazing march to Mount Kenya five years earlier. After an extreme two-year trek, they found themselves on the shores of Lake Rudolf and surrounded by an area of active volcanoes. Some five months later they arrived in Vienna carrying bales of rare and valuable specimens for the Imperial Natural History Museum, that kept curators busy for months as they worked through the thousands of scientific specimens so diligently collected.

Why was the discovery of Lake Rudolf, the world's largest permanent desert lake, so important?

First it catalysed a series of expeditions up to 1899 to all its shores; it established the basis for an alien but fundamentally well-intentioned Protectorate and yet it's greatest secrets remained undiscovered until 1972 when hominin fossils of some of the earliest human ancestors were found the Turkana Basin. Richard Leakey, now synonymous with the work on hominids begun by his parents, and his wife Margaret, undertook an expedition to Allia Bay on Lake Turkana, having seen sediments around the Lake shore during a flight to avoid a storm. They established the Koobi Fora camp. In 1969 the discovery of a cranium of *Paranthropus boisei* caused great excitement. A *Homo rudolfensis* skull (KNM ER 1470) and a *Homo erectus* skull (KNM ER 3733), discovered in 1972 and 1975, respectively, were among the most significant finds of Leakey's earlier expeditions. In 1978 an intact cranium of *Homo erectus* (KNM ER 3883) was discovered.

Skull 1407 was originally thought to be *Homo habilis*, but the scientific name *Homo rudolfensis*, was proposed in 1986 by V. P. Alexeev. *Homo rudolfensis* is a species of archaic human from the Early Pleistocene of East Africa about 2 million years ago (mya). Because H. rudolfensis coexisted with several other hominins, it is debated which specimens can be confidently assigned to this species beyond the lectotype skull 1470 and other partial skull aspects. No bodily remains are definitively assigned to *H. rudolfensis*. Consequently, both its generic classification and validity are debated without any wide consensus, with some recommending the species to actually belong to the genus *Australopithecus* as *A. rudolfensis* or *Kenyanthropus* as *K. rudolfensis*, or that it is synonymous with the contemporaneous and anatomically similar *H. habilis*. *Australopithecus anamensis* fossils were discovered by Meave Leakey in 1994 date to around 4 million years ago. In 1984, the Turkana Boy, a nearly complete skeleton of a *Homo ergaster* juvenile, was discovered by Kamoya Kimeu. Meave Leakey then discovered a 3.5-million-year-old skull there, designated *Kenyanthropus platyops* ("the flat-faced man of Kenya"). Early *Homo* species exhibit marked brain growth compared to Australopithecus predecessors, which is typically explained as a change in diet with a calorie-rich food source, namely meat. Though not associated with tools, dental anatomy suggests some processing of plant or meat fibre before consumption, though the mouth could still effectively chew through mechanically challenging food, indicating tool use did not greatly affect diet.

Further to the south in the Olduvai Gorge or Oldupai Gorge in Tanzania, is one of the most important paleoanthropological sites in the world; it has proven invaluable in furthering understanding of early human evolution. A steep-sided ravine in the Great Rift Valley that stretches across East Africa, it is located in the eastern Serengeti Plains within the Ngorongoro Conservation Area in the Arusha Region, about 45 kilometres from Laetoli, another important archaeological site of early human occupation. The British/Kenyan paleoanthropologist-archaeologist team Mary and Louis Leakey established and developed the excavation and research programs at Olduvai Gorge which achieved great advances of human knowledge and world-renowned status. The gorge takes its name from the Maasai word oldupai which means "the place of the wild sisal" as the East African wild sisal (*Sansevieria ehrenbergii*) grows abundantly throughout the gorge area. Twenty-five kilometres downstream of Lake Ndutu and Lake Masek, the gorge cuts into Pleistocene lakebed sediments up to a depth of 90 m. A side gorge, originating from Lemagrut Mountain, joins the main gorge 8 km from the mouth. This side gorge follows the shoreline of a prehistoric lake, rich in fossils and early man sites. Periodic flows of volcanic ash from Olmoti and Kerimasi helped to ensure preservation of the fossils in the gorge.

The site is significant in showing the increasing developmental and social complexities in the earliest humans, or hominins, largely revealed in the production and use of stone tools. Prior to tools, evidence of scavenging and hunting can be noted—highlighted by the presence of gnaw marks that predate cut marks—and of the ratio of meat versus plant material in the early hominin diet. The collecting of tools and animal remains in a centralised area is evidence of developing social interaction and communal activity. All these factors indicate an increase in cognitive capacities at the beginning of the period of hominids transitioning to hominin—that is, to human—form and behaviour. Just as in Lake Turkana, *Homo habilis* occupied Olduvai Gorge approximately 1.9 million years ago (mya); then came a contemporary australopithecine, *Paranthropus boisei*, 1.8 mya, followed by *Homo erectus*, 1.2 mya. *Homo sapiens*, which is estimated to have emerged roughly 300,000 years ago, is dated to have occupied the site 17,000 years ago.

The Theatre of the World

Many scientific expeditions were linked to mapping and charting new areas, and as such cartographers were often considered essential members of the team. Charts and maps carefully reproduced became a source of knowledge that enabled scientists to connect patterns of distributions with geographic and ecological conditions, as Buffon had been able to show. Today, many of the drawings of older maps look obscure and caricatures of what we have become used to seeing. The development of geographic projections has been a crucial element in helping natural scientists locate specimens, describe biomes and develop an understanding of our planet. Without a strong and consistent cartographic projection, data become unlocatable and difficult to use in theories and models.

The 16th-century Flemish surveyor and cartographer Gerardus Mercator (Gerhard de Cremer) understood this, when he published his collection of maps of northern Europe in 1595. The first collection of maps of the world, *Epitome of the Theatre of the World* (1570), was produced by Mercator's contemporary, the Belgian cartographer Abraham Ortelius.

Mercator is widely considered the most notable figure of Netherlandish school of cartography in its golden age (approximately 1570s–1670s). He was notable as maker of globes and scientific instruments and had interests in theology, philosophy, history, mathematics and geomagnetism. He was also an accomplished engraver and calligrapher. Unlike other great scholars of the age he travelled little and his knowledge of geography came from his library of over one thousand books and maps, from his visitors and from his vast correspondence (in six languages) with other scholars, statesmen, travellers, merchants and seamen. Mercator's early maps were in large formats suitable for wall mounting but in the second half of his life, he produced over 100 new regional maps in a smaller format suitable for binding into his Atlas of 1595. This was the first appearance of the word Atlas in reference to a book of maps. However, Mercator used it as a neologism for a treatise (Cosmologia) on the creation, history and description of the universe, not simply a collection of maps. He chose the word as a commemoration of the Titan Atlas, "King of Mauretania", whom he considered to be the first great geographer. A large part of Mercator's income came from sales of his terrestrial and celestial globes. For sixty years they were considered the finest in the world and were sold in such great numbers that there are many surviving examples. This was a substantial enterprise involving the manufacture of the spheres, printing the gores, building substantial stands, packing and distributing all over Europe. He was also renowned for his scientific instruments, particularly his astrolabes and astronomical rings used to study the geometry of astronomy and astrology.

In cartography, a map projection is a way to flatten a globe's surface into a plane in order to make a map. This requires a systematic transformation of the latitudes and longitudes of locations from the surface of the globe into locations on a plane. All projections of a sphere on a plane necessarily distort the surface in some way and to some extent. The study of map projections is the characterization of the distortions. Projections are a subject of several pure mathematical fields, including differential geometry, projective geometry, and manifolds. However, "map projection" refers specifically to a cartographic projection.

Today, we can see a range of projections used in mapping and in emblems. For example, the United Nations uses an Azimuthal equidistant projection for its emblem, which was created by Abu Rayhan al-Biruni I c 1000, whilst Google Earth uses a Mercator projection.

Observations and Theories

Knowing where you are is a key aspect of connecting knowledge; however, making and interpreting observations requires quite another skill. Some the most contentious debates in science have arisen because of the way that observations have been interpreted. One of the most famous scientific debates was the Oxford Evolution debate at the British Association annual meeting of 1890 between the evolutionists versus creationists following the publication of The Origin of Species, by Charles Darwin. Thomas Huxley was supporting evolutionary thinking and Bishop Wilberforce creationism.

The debate is best remembered today for the heated exchange in which Wilberforce supposedly asked Huxley whether it was through his grandfather or his grandmother that he claimed his descent from a monkey. Huxley is said to have replied that he would not be ashamed to have a monkey for his ancestor, but he would be ashamed to be connected with a man who used his great gifts to obscure the truth.

One eyewitness suggests that Wilberforce's question to Huxley may have been "whether, in the vast shaky state of the law of development, as laid down by Darwin, anyone can be so enamoured of this so-called law, or hypothesis, as to go into jubilation for his great grandfather having been an ape or a gorilla?", whereas another suggests he may have said that "it was of little consequence to himself whether or not his grandfather might be called a monkey or not."

Rather than being a formal debate between the two, it was actually an animated discussion that occurred after the presentation of a paper by John William Draper of New York University, on the intellectual development of Europe with relation to Darwin's theory (one of a number of scientific papers presented during the week as part of the British Association's annual meeting). Although Huxley and Wilberforce were not the only participants in the discussion, they were reported to be the two dominant parties.

The debate came about because at the British Association for the Advancement of Science meeting at Oxford in May 1847, the Bishop of Oxford Samuel Wilberforce used his Sunday sermon at St. Mary's Church to critique the anonymous publication *Vestiges of the Natural History of Creation* in 1844 which had brought a storm of controversy but attracted a wide readership and became a bestseller. Wilberforce talked about the "the wrong way of doing science" and delivered a stinging attack obviously aimed at its author, Robert Chambers, in a church "crowded to suffocation" with geologists, astronomers and zoologists. The scientific establishment also remained sceptical, but the book had converted a vast popular audience.

Subsequently, Charles Darwin's *On the Origin of Species* was published in 1859 to wide debate and controversy. The influential biologist Richard Owen wrote a negative anonymous review of the book in the Edinburgh Review, and coached Wilberforce, who also wrote an anonymous 17,000-word review in the Quarterly Review.

Thomas Huxley, one of the small group with whom Darwin had shared his theory before publication, emerged as the main public champion of evolution. He wrote a favourable review of "Origin" in The Times in December 1859, along with several other articles and a lecture delivered at the Royal Institution in February 1860. The reaction of many orthodox churchmen was hostile, but their attention was diverted in February 1860 by a much greater furore over the publication of Essays and Reviews by seven liberal theologians. Amongst them, the Reverend Baden Powell had already praised evolutionary ideas, and in his essay, he commended "Mr. Darwin's masterly volume" for substantiating "the grand principle of the self-evolving powers of nature".

Earlier in the week, Charles Daubeny read a paper "On the final causes of the sexuality in plants, with particular reference to Mr. Darwin's work ..." Owen and Huxley were both in attendance, and a debate erupted over Darwin's theory. Owen spoke of facts which would enable the public to "come to some conclusions ... of the truth of Mr. Darwin's theory" and repeated an anatomical argument which he had first presented in 1857, that "the brain of the gorilla was more different from that of man than from that of the lowest primate particularly because only man had a posterior lobe, a posterior horn, and a hippocampus minor." Huxley was convinced this was incorrect and had researched its errors. For the first time he spoke publicly on this point, and "denied altogether that the difference between the brain of the gorilla and man was so great" in a "direct and unqualified contradiction" of Owen, citing previous studies as well as promising to provide detailed support for his position.

Wilberforce agreed to address the meeting on Saturday morning, and there was expectation that he would repeat his success at scourging evolutionary ideas as at the 1847 meeting. Huxley was initially reluctant to engage Wilberforce in a public debate about evolution, but, in a chance encounter, Robert Chambers persuaded him not to desert the cause. The Reverend Baden Powell would have been on the platform, but he had just died of a heart attack.

Word spread that Bishop Samuel Wilberforce, known as "Soapy Sam", would speak against Darwin's theory; he was one of the greatest public speakers of his day and, according to Bryson, "more than a thousand people crowded into the chamber; hundreds more were turned away." Darwin himself was too sick to attend. The discussion was chaired by John Stevens Henslow, Darwin's former mentor from Cambridge. It has been suggested that Owen arranged for Henslow to chair the discussion "hoping to make the expected defeat of Darwin the more complete". The main focus of the meeting was supposed to be a lecture by New York University's John William Draper, "On the Intellectual Development of Europe, considered with reference to the views of Mr. Darwin and others, that the progression of organisms is determined by law". After Draper had finished, Henslow called on several other speakers, including Benjamin Brodie, the President of the Royal Society, before it was Wilberforce's turn.

Wilberforce criticised Darwin's theory on ostensibly scientific grounds, arguing that it was not supported by the facts, and he noted that the greatest names in science were opposed to the theory. Nonetheless, Wilberforce's speech is generally only remembered today for his inquiry as to whether it was through his grandmother or his grandfather that Huxley considered himself descended from a monkey. Huxley's own contemporary account makes no mention of this remark.

Huxley rose to defend Darwin's theory, finishing his speech with the now-legendary assertion that he was not ashamed to have a monkey for his ancestor, but he would be ashamed to be connected with a man who used great gifts to obscure the truth, a statement had a tremendous effect on the audience, and Lady Brewster is said to have fainted!

Next, Henslow called upon Admiral Robert FitzRoy, who had been Darwin's captain and companion on the voyage of the Beagle twenty-five years earlier. FitzRoy denounced Darwin's book and, "lifting an immense Bible first with both hands and afterwards with one hand over his head, solemnly implored the audience to believe God rather than man". He was believed to have said: "I believe that this is the Truth, and had I known then what I know now, I would not have taken him [Darwin] aboard the Beagle." The last speaker of the day was Hooker. According to his own account, it was he and not Huxley who delivered the most effective reply to Wilberforce's arguments.

Notably, all three major participants felt they had had the best of the debate. Wilberforce wrote that, "On Saturday Professor Henslow ... called on me by name to address the Section on Darwin's theory. So, I could not escape and had quite a long fight with Huxley. I think I thoroughly beat him." Huxley claimed "[I was] the most popular man in Oxford for a full four and twenty hours afterwards." Hooker wrote that "I have been congratulated and thanked by the blackest coats and whitest stocks in Oxford." Wilberforce and Darwin remained on good terms after the debate.

The overall sense was that "everybody enjoyed himself immensely and all went cheerfully off to dinner together afterwards"!

Darwin's Fishes – Spirits of Wine

The observations that had caused Darwin to draw up his theory of evolution were far-ranging and derived in large part from his observations during the expeditions he undertook whilst on the voyage of HMS Beagle, which Admiral Fitzroy referred to in the Oxford debate. So much has been written about iconic species such as the finches on the Galapagos Islands that it is not for this lecture to go into the details. Suffice to say that the quantity of observations is extraordinary, and points to the intensity of Darwin's daily efforts.

My own reading of Darwin's works has led to immense admiration for his powers of observation and concise nature of the descriptions, especially those set out in his Zoological notebooks and diaries, which are kept in the University of Cambridge Library. In the late 1980s, I worked on transcribing these as part of a publication on Darwin's Fishes and looking at the specimen collections in the Natural History Museum and the Museum at Cambridge University. The experience was fascinating, first because of the serendipitous nature of why the opportunity came about – Darwin's handwriting was often made up of indecipherable lines with occasional dots –very characteristic of many in the medical profession and exactly as my father's had been. I was also trained as an ichthyologist and taxonomist, so working on the fishes described in Spirits of Wine was a delight. What immediately struck me was that, despite not being an ichthyologist (Darwin's own admission), his detailed descriptions were so accurate that it was possible to identify the specimens without looking at them. This was just as well, because as the Curator in the British Museum Jenkyns remarked, Darwin's skills in preserving fish specimens were not very good - most jars arrived in London as a mush of alcohol, tissues and bones.

Darwin's notebooks and diaries also contained interesting information about how he was building up his ideas of classification and evolution. The famous diagram of a phylogenetic tree was already included as were anecdotes. What I found captivating was a sketch of a woman's breasts as two simple U shapes with nipples, which Darwin had initially called "titties" and then struck out to call mammary glands- as if he was already sensing that others might read his notebooks and diaries. Sadly, the Notebook with the evolutionary tree diagram has gone missing, most probably stolen, from the library in Cambridge and there is a call out for its return. Let's hope that this happens.

Wallace's Birds and Butterflies – Father of Biogeography

At more or the less the same time as Darwin was engaged with on HMS Beagle and his subsequent research at Down House, Alfred Russell Wallace a British naturalist, explorer, geographer, anthropologist, biologist and illustrator was engaged in extensive field work. First in the Amazon River basin, and then in the Malay Archipelago, where he identified the faunal divide now termed the Wallace Line, which separates the Indonesian archipelago into two distinct parts: a western portion in which the animals are largely of Asian origin, and an eastern portion where the fauna reflects Australasia.

Wallace is best known for independently conceiving the theory of evolution through natural selection; his paper on the subject was jointly published with some of Charles Darwin's writings in 1858, which prompted Darwin to publish *On the Origin of Species*.

More crucially, Wallace was considered the 19th century's leading expert on the geographical distribution of animal species and is sometimes called the "father of biogeography, a worthy successor to Buffon. Wallace was one of the leading evolutionary thinkers of the 19th century and made many other contributions to the development of evolutionary theory besides being co-discoverer of natural selection. These included the concepts of warning colouration in animals, and reinforcement (sometimes known as the Wallace effect), a hypothesis on how natural selection could contribute to speciation by encouraging the development of barriers against hybridisation.

Wallace was attracted to unconventional ideas such as evolution, which sometimes strained his relationship with the scientific community. His 1904 book *Man's Place in the Universe* was the first serious attempt by a biologist to evaluate the likelihood of life on other planets. He was also one of the first scientists to write a serious exploration of the subject of whether there was life on Mars.

Apart from his extremely perceptive views on biogeography, Wallace was one of the first prominent scientists to raise concerns over the environmental impact of human activity. He was also a prolific author who wrote on both scientific and social issues; his account of his adventures and observations during his explorations in Singapore, Indonesia and Malaysia, *The Malay Archipelago*, was both popular and highly regarded. Since its publication in 1869, it has never been out of print.

Unfortunately, unlike Darwin and Lyell, Wallace had no family wealth to support himself, no regular income and no long-term salaried position. As a result, he had financial difficulties throughout much of his life. His Amazon and Far Eastern trips were supported by the sale of specimens he collected and, after he lost most of the considerable money he made from those sales in unsuccessful investments, he had to support himself mostly from the publications he produced until he was awarded a small government pension, through Darwin's efforts, in 1881.

I firmly believe that the co-development of evolutionary theory by Darwin and Wallace, coming from two separate but comparable sources of data, is an excellent example of strong arguments for the scientific method as well as the essential role of collaboration in research.

<u>Close Observers of Nature</u>

Alongside naturalists and scientists, the close, patient observation of Nature by writers and diarists has also given us a rich source of knowledge. The calendar of nature, letters and poems written by Reverend Gilbert White on the *Natural History and Antiquities of Selbourne*, Henry D.Thoreau's *Walden: on Life in the Woods* by and Pullitzer Prize winner Annie Dillard*'s Pilgrim at Tinker Creek* have each had a significant impact on the literary but also on scientific understanding. By using allegorical and simple, or non-technical language have they provide a bridge between the worlds of science and literature.

Darwin was said to have been influenced by White's writings. Rather than studying dead specimens, White observed live birds and animals in their own habitats over many years, creating a 'new kind of zoology, scientific, precise and based on the steady accumulation of detail'. The Natural History represents a shift to holistic, evidence-based engagement warmed by empathy. From nearly 40 years of observations, White recognised that birds and animals have inner lives. He based his work on accurate (although haphazard) recording of events, classifying, measuring, analysing data, making deductions from observations, and experimenting. His 1783–84 diary corroborates the dramatic climatic impacts of the volcanic 'Laki haze' that spread from Iceland with lethal consequences across Europe. Together with William Markwick he collected records of the dates of emergence of more than 400 plant and animal species in Hampshire and Markwick in Sussex between 1768 and 1793. These data, summarised as the earliest and latest dates for each event over the 25-year period, are among the earliest examples of modern phenology.

White did not have grand theories, plan experiments and replicate them as a modern scientist would: he was more freewheeling and, arguably, as a consequence more appealing as a writer. He was one of the first writers to show that it was possible to write of the natural world with a fresh and intensely personal vision without in any way sacrificing precision:

> *'during this lovely weather the congregating flocks of house martins on the Church and tower were very beautiful and very amusing! When they flew off all together from the*

roof, on any alarm, they quite swarmed in the air. But they soon settled again in heaps on the shingles; where preening their feathers to admit the rays of the sun, they seemed highly to enjoy the warm situation.'

American nature writer, Donald C. Peattie, writes in The Road of a Naturalist about White's contribution to the public interest in birds: "The bird census, now so widely promulgated by the Audubon Society, was the invention of Gilbert White; he was the original exponent, as far as I know, of the close seasonal observation of Nature, a branch of science known to the pedantic as phenology. He was the first to perceive the value in the study of migration (then a disputed fact) and of banding or ringing birds, though it was Audubon who first performed the experiment. No professional ornithologist ever did so much to widen interest in birds; from White's pages they cock a friendly eye at us and hop out of his leaves right over our thresholds."

White's other contributions to the field of natural history are impressive, for example, his close observation and recording of events over time led him to develop the idea of the 'food chain', laying the foundations for the modern study of ecology; he discovered a distinction between three species of leaf warblers based on their different songs; he pioneered modern theories on bird territory and its effects on their population. Even today, most naturalists will have read Gilbert White's book and often refer to his work for its insights and investigative achievements.

Henry Thoreau's Walden is a reflection upon simple living in natural surroundings. The work is part personal declaration of independence, social experiment, voyage of spiritual discovery, satire, and—to some degree—a manual for self-reliance. Walden details Thoreau's experiences over the course of two years, two months, and two days in a cabin he built near Walden Pond amidst woodland owned by his friend and mentor Ralph Waldo Emerson, near Concord, Massachusetts.

Thoreau makes precise scientific observations of nature as well as metaphorical and poetic uses of natural phenomena. He identifies many plants and animals by both their popular and scientific names, records in detail the colour and clarity of different bodies of water, precisely dates and describes the freezing and thawing of the pond and recounts his experiments to measure the depth and shape of the bottom of the supposedly "bottomless" Walden Pond. By immersing himself in nature, Thoreau hoped to gain a more objective understanding of society through personal introspection.

In a similar vein, Annie Dillard's beautiful chronicle of a year spent at Tinker Creek is a nonfiction narrative, told from a first-person point of view. It details explorations and various contemplations on nature and life. The title refers to Tinker Creek, which is outside Roanoke in Virginia's Blue Ridge Mountains. Dillard began writing Pilgrim in the spring of 1973, using her personal journals as inspiration. Separated into four sections that signify each of the seasons, the narrative takes place over the period of one year. Thoughts on solitude, writing and religion are captured alongside scientific observations on the flora and fauna that she encounters. It captures theodicy and the inherent "cruelty" of the natural world. It is analogous to Walden, deeming her Thoreau's true heir. Dillard won the 1975 Pulitzer Prize for General Non-fiction at the age of 25; the jury said in its nomination that "Miss Dillard is an expert observer in whom science has not etiolated a sense of awe... Her book is a blend of observation and introspection, mystery and knowledge. We unanimously recommend it for the prize.

<u>Lorenz, Chaos and the Butterfly Effect</u>

In February 2015, the Obama Administration committed USD 3.2 million toward saving the monarch butterfly. Environmental activists, deeply concerned by the monarch's alarming decline, applauded the move. The bookish among them may have also noticed a literary echo in the encouraging news: the totemic orange-and-black North American butterfly is the cause célèbre of Barbara Kingsolver's

2012 novel, “Flight Behavior,” which happens to feature a tall, thin, Harvard-educated, African American scientist named Ovid Byron, who bears a striking resemblance to the President, down to his inverted initials.

In the book, Ovid Byron is a world-renowned entomologist who flies from New Mexico to Tennessee to study the huge flocks of monarchs that have suddenly shown up in a South Appalachian forest hollow, leaving the local population—rural, poor, and very religious—at once unnerved and amazed. Having never seen anything so spectacular as this orange rapture in the valley, the people of Feathertown are inclined to think of it as a “burning bush,” a miracle sent by God to light up their threadbare lives. The butterflies become a magnet, attracting television crews, day-trippers in S.U.V.s, and a lumpy group of knitters determined to immortalize the beauty of the butterflies with their needles and recycled orange wool.

But beauty can be deceptive: the butterflies are climate refugees. They have abandoned their flight path from Canada to their usual winter habitat, a sunny hillside in Mexico where they have been overwintering safely for generations, but which has been ravaged by logging and landslides. Their mysterious flight behaviour is a symptom of an overheated Earth, calving glaciers, and a disintegrating Arctic. This Appalachian roosting is fictional—the monarchs continue to overwinter in Mexico—but the mudslides and logging wrecking their habitat are not.

The link between climate change and the Monarch butterfly has also taken shape through the immensely influential research undertaken by Ed Lorenz on chaos and the metaphorical butterfly effect - the sensitive dependence on initial conditions in which a small change in one state of a deterministic nonlinear system can result in large differences in a later state.

Edward Lorenz used the metaphorical example of the details of a tornado, the exact time of its formation and exact path taken, being influenced by minor perturbations such as a distant butterfly flapping its wings several weeks earlier. Lorenz discovered the effect when he observed runs of his weather model with initial condition data that were rounded in a seemingly inconsequential manner. He noted that the model would fail to reproduce the results of runs with the unrounded initial condition data. A very small change in initial conditions had created a significantly different outcome.

The idea that small causes can have large effects was earlier recognized by French mathematician and engineer Henri Poincaré. Edward Lorenz's work placed the concept of *instability* of the Earth's atmosphere onto a quantitative base and linked the concept of instability to the properties of large classes of dynamic systems which are undergoing nonlinear dynamics and deterministic chaos. It not only set the stage for ensemble forecasting for the weather and eventually the likely impacts of climate change but also captured the public’s imagination and raised awareness that predictability about the natural world is inherently limited.

Open Science, Open Data and Omics

As knowledge about the natural world has grown, so too have the underpinning data and publications. Before the advent of scientific journals, scientists had little to gain and much to lose by publicizing scientific discoveries. Many scientists, including Galileo, Kepler, Isaac Newton, Christiaan Huygens and Robert Hooke, made claim to their discoveries by describing them in papers coded in anagrams or cyphers and then distributing the coded text. Their intent was to develop their discovery into something from which they could profit, then reveal their discovery to prove ownership when they were prepared to make a claim on it.

The system of not publicizing discoveries caused problems because discoveries were not shared quickly and because it was difficult for the discoverer to prove priority. Recall Wingate and Oughtred and the invention of the slide rule. Newton and Gottfried Leibniz both claimed priority in discovering calculus. Newton said that he wrote about calculus in the 1660s and 1670s, but did not publish until 1693. Leibniz published *Nova Methodus pro Maximis et Minimis*, a treatise on calculus, in 1684. Debates over priority are inherent in systems where science is not published openly, and this was problematic for scientists who wanted to benefit from priority.

These cases are representative of a system of aristocratic patronage in which scientists received funding to develop either immediately useful things or to entertain. In this sense, funding of science gave prestige to the patron in the same way that funding of artists, writers, architects, and philosophers did. Because of this, scientists were under pressure to satisfy the desires of their patrons, and discouraged from being open with research which would bring prestige to persons other than their patrons.

But as individual patronage system ceased to provide the scientific output which society began to demand there was a trend to pool research by multiple scientists into an academy funded by multiple patrons. In 1660 England established the Royal Society and in 1666 the French established the French Academy of Sciences. Between the 1660s and 1793, governments gave official recognition to 70 other scientific organizations modelled after those two academies. In 1665, Henry Oldenburg became the editor of Philosophical Transactions of the Royal Society, the first academic journal devoted to science, and the foundation for the growth of scientific publishing. By 1699 there were 30 scientific journals; by 1790 there were 1052. Today many academies have pressured researchers at publicly funded universities and research institutions to engage in a mix of sharing research and making some technological developments proprietary. And whilst it is difficult to predict the potential pay-outs of technology or to assess the costs of withholding it, there is general agreement that the benefit to any single institution of holding technology is not as great as the cost of withholding it from all other research institutions.

Open science, a term coined by Steve Mann in 1998, is the movement to make scientific research (including publications, data, physical samples, and software) and its dissemination accessible to all levels of an inquiring society, amateur or professional. It can be seen as a continuation of practices begun in the 17th century with the advent of the academic journal, when the societal demand for access to scientific knowledge reached a point at which it became necessary for groups of scientists to share resources with each other so that they could collectively do their work. The conflict that led to the Open Science movement is between the desire of scientists to have access to shared resources versus the desire of individual entities to profit when other entities partake of their resources.

Open science is transparent and accessible knowledge is shared and developed through collaborative networks. It encompasses practices such as publishing open research, campaigning for open access, encouraging scientists to practice open-notebook science, and generally making it easier to publish and communicate scientific knowledge. There is currently no global normative framework covering all aspects of Open Science. In 2019, UNESCO was tasked by its 193 Member States, to identify globally agreed norms and to create a standard-setting instrument for Open Science. Two UN frameworks set out some common global standards for application of Open Science and closely related concepts: the UNESCO Recommendation on Science and Scientific Researchers and the UNESCO Strategy on Open Access to scientific information and research.

Examples of Open Science continue to grow. The Darwin Tree of Life Project at the Wellcome Sanger Centre aims to sequence the genomes of all 60,000 species of eukaryotic organisms in Britain and Ireland. It is a collaboration between biodiversity, genomics and analysis partners to transform the way we do biology, conservation and biotechnology. Genomic data can be used to understand the evolution of the diversity of life, to explore the biology of organisms and ecosystems, to aid conservation efforts and to provide new tools for medicine and biotechnology. The Darwin Tree of Life Project is just one of several initiatives across the globe working towards the ultimate goal of sequencing all complex life on Earth, in a venture known as the Earth BioGenome Project. The organisms that live in and around Britain and Ireland constitute what is probably the best known and most deeply studied biota in the world, explored during centuries of observation and research.

The wide applicability of earth observation is another domain where Open Science has become the norm; sharing and working on vast data streams, has led to discoveries about our climate and just how much human habitation has altered the face of our planet. And for open data, we have monitoring systems to tell us just how well countries are doing in making available and accessible publicly funded data collection and information activities.

Ontologies, Metaphysics and AI

Open science would not be possible without the world wide web, which has given scientists and the public greater access to science and publications and reports, and the semantic web, which enables humans to use reasoning and computers to recognise and use a wide array of information contained in text, numbers, images, videos etc. The growth of knowledge about our planet and its dynamics is extraordinary and with it has come a need to rethink how we organise our knowledge and engineer solutions to accessing it in an efficient manner. For this we need to turn to ontologies. Ontology is the branch of philosophy known as metaphysics, that studies concepts such as existence, being, becoming, and reality. It includes the questions of how entities are grouped into basic categories and which of these entities exist on the most fundamental level. Parmenides, a pre-Socratic philosopher, was among the first to propose an ontological characterization of the fundamental nature of reality. Through history, many leading thinkers have been involved in developing ontologies - Plato, Aristotle, Descartes, Spinoza, Kant, Schopenhauer, Derrida, Foucault, Nietzsche, Heidegger, Carnap, Quine and Whitehead. Today, there are thousands of ontology engineers supporting the development of fields such as genomics, geography, chemistry, and the environment.

In computer science, information science and systems engineering, ontology engineering is a field which studies the methods and methodologies for building ontologies. It comprises formal representations of a set of concepts within a domain and the relationships between those concepts. In a broader sense, this field also includes a knowledge construction of the domain using formal ontology representations such as OWL/RDF/RDFS (Web Ontology Language/Resource Description Framework. RDF is a family of World Wide Web Consortium (W3C) specifications originally designed as a metadata data model. A large-scale representation of abstract concepts such as actions, time, physical objects and beliefs would be an example of ontological engineering. Ontology engineering is central to conceptual modelling.

Key to managing large databases containing knowledge about our planet, including the human genome and earth observations from the multiple satellite platforms, is the structuring of relationships for automated processing of information not interpretable by software agents. This processing can be improved by adding rich semantics to the corresponding resources, such as video files, through a formal conceptualization of represented knowledge domains using machine-interpretable ontologies to provide structured data in, or based on, RDF, RDFS, and OWL. Ontologies can contain more than just the list of terms (controlled vocabulary); they contain terminological, assertional, and relational axioms to define concepts (classes), individuals, and roles (properties). Key to the success of ontologies is the idea that terms and knowledge graphs are curated within only one ontology group; this requires significant levels of collaboration and open access to science and knowledge.

A common way to provide the logical underpinning of ontologies is to formalize the axioms with description logics, rules and definitions which can be mapped to any kind of resource or resource segment, such as images, videos, and regions of interest, to annotate objects, persons, etc., and interlink them with related resources across knowledge bases, ontologies, and linked datasets. This information, based on human experience and knowledge, is valuable for reasoners for the automated interpretation of sophisticated and ambiguous contents, such as the visual content of multimedia resources. In the first instance, ontology-based reasoning was used for information retrieval, automated scene interpretation, and knowledge discovery. Whilst building the databases for the Sustainable Development Goals, I led a team to create a meta-ontology – to removing word-sense disambiguation. For example, the word access is used in goals and targets relating to education, health care, information and clean water; each has a different meaning and underlying ontology.

Artificial intelligence and its branches such as machine learning, deep learning, which function on extracting relevant information and generating insights from data to find sustainable and decisive solutions, also benefit from ontologies, for example to help communications with diverse users, track and analyse trends, and determine if the collected data is actually of any help or simply a waste of a effort! Having an ontology consisting of the relevant terms and connections from a specific domain, the process of identifying core concepts, improving classification results, and unifying data to collate critical information can help streamline research and actions. Ontological Modelling can also help the cognitive AI or machine learning model by broadening its' scope to include unstructured, semi-structured, or structured data format, and enabling smoother data integration.

Additionally, ontologies also help to improve the data quality, provide more coherent and easy navigation as users move from one concept to another in the ontology structure and use a set of individual facts to create a knowledge graph. This is a collection of entities, where nodes and edges between these nodes express the types and the relationships between them.

<u>Gene Ontology – Cross-scale Translation of Knowledge</u>

Ontologies are a flourishing part of the life sciences, with biologists using them to make sense of their experiments, ontologies have to be structured optimally against the knowledge base they represent. The structure of an ontology needs to be changed continuously so that it is an accurate representation of the underlying domain. Recently, an automated method was introduced for engineering ontologies in life sciences such as Gene Ontology (GO), one of the most successful and widely used biomedical ontology. Based on information theory, it restructures ontologies so that the levels represent the desired specificity of the concepts. Similar information theoretic approaches have also been used for optimal partition of Gene Ontology. Given the mathematical nature of such engineering algorithms, these optimizations can be automated to produce a principled and scalable architecture to restructure ontologies such as GO. The Open Biomedical Ontologies (OBO), established in 2006, provides a common 'foundry' for the various ontology initiatives, including the Gene Ontology consortium, the Sequence Ontology, and the Plant Ontology consortium.

<u>Open Research and COVID-19</u>

The COVID-19 pandemic has shown the power of open science and open data, and domain-specific ontologies combined with AI-driven tools for data analytics which has supported an international collaborative effort to sift through the relevant data and uncover new data patterns and trends. We quickly converged on the dashboard developed by John Hopkins and supported by the WHO and data flows coming in from every country worldwide. Without open science and data, it is likely that the significant efforts which countries have taken to control the spread of the disease would not have been nearly as effective. Sharing knowledge about the gene sequence of the virus, its source and epidemiology such as its demographic impacts and rates of transmission, has enabled people to be alerted very quickly, for example about new variants, changes in the spike proteins and transmissibility.

Future of Knowledge

As we have seen from the global response to COVID-19, we are entering a new era of scientific research and knowledge, one which has underlined the importance of open science and open data. This era presages a future where public knowledge about planet Earth will be radically transformed based on our ability to access, analyse, simulate and combine large and complex data sets from a dazzling array of instruments, satellites, interdisciplinary research programmes and a growing number of citizen scientists.