Sensors and Sensibilia: A Historical Survey

By Charles Berret

The history of sensors is humbling in its scope. Humans have always experienced the world through sensors like our eyes and ears, but we also use an array of tools to extend those basic capacities, to monitor our surroundings, and to track phenomena that are otherwise imperceptible.

These "tools" needn't even be high tech. The proverbial canary in the coal mine is a sensor for poisonous gases; a blind man's cane is a sensor for objects just ahead. Really, a sensor is anything that reacts predictably to the state of the world. Such a pat definition should raise a number of concerns about the construction of knowledge, and the authority embedded in what appears obvious, but this is a brief and broad survey of sensor technologies. It touches many cases, and regrettably skews toward Western ones, but hopefully this primer indicates the sheer scale of these instruments in the history of human sense-making.

Archaeological evidence shows that humans built sensors even in prehistory. Scales have been unearthed in the ruins of the earliest civilizations, as it was essential to weigh goods for trade and taxation. Agricultural needs also led people to track the cycles of heavenly bodies with monumental markers. Neolithic circles like Stonehenge and temple complexes like Abu Simbel were massive instruments built to watch the skies for signs of spring thaw and autumn harvest, among other things. Similarly, the area near present-day Cairo, where the Nile splits into its vast delta, has traditionally been the site where the river's annual flooding was measured by a variety of instruments known as nilometers. A reliable warning for the rising waters could mean the difference between a year of abundance and one of hardship.

It is worth noting that some of the earliest sensors were also aimed at supernatural forces. Oracles, charms, and portents were seemingly attuned to fates and spirits. Some holy figures specialized in reading animal bones and entrails to understand forces at work in the world, while throwing a supposed witch in a lake was once, it seems, considered a reliable sensor for the dark arts.

Yet some efforts at divination actually prompted the development of what we would now consider scientific sensors. The first magnetic compass was mainly used to tell fortunes when it was invented in China during the Han Dynasty, but it would not be used as a navigational tool either there or in the West until about the 12th century C.E.[1] Until then, travelers navigated by the stars, and of course the empirical study of astronomy was once highly entangled with the prophetic efforts of astrology. Indeed, it was the celestial circle of 12 zodiac signs that originated the geometric measure of 360 degrees, with each constellation assigned 30.

Many cultures tracked the movement of constellations not only to chart the year, but also to find their bearings by night. The Greek astronomer Hipparchus (190–120 B.C.E.) is credited with inventing both the astrolabe and the armillary sphere, instruments used to predict the movement of heavenly bodies, to navigate, and to tell time. Later, the sextant and alidade were added to astronomers' toolkits for measuring and charting the sky.

Several Greek astronomers tackled seemingly impenetrable problems even with these limited instruments. One of the cleverest of these experiments was organized by the Greek polymath Eratosthenes (276–195 B.C.E.), who

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1 C.E. is the abbreviation for Common Era, a scholarly alternative naming of the traditional calendar era, *Anno Domini* (A.D.). Similarly, B.C.E. is an abbreviation for Before Common Era.

estimated the circumference of the Earth through a single well-timed measurement. As the story goes, Eratosthenes learned that the sun would shine directly down a well in Aswan, Egypt, at noon on the Summer Solstice, meaning it was directly overhead—that is, roughly on the Tropic of Cancer, the closest point to the sun at that moment. So Eratosthenes measured the shadow of an obelisk in Alexandria at the same moment. Eratosthenes took the distance between Aswan and Alexandria, deduced the arc of the planet's curvature between those two points, and thereby calculated the planet's full circumference with remarkable accuracy.

Although Eratosthenes probably estimated that distance by having a slave count his steps through the whole journey, the ancients also developed several instruments to measure distance and speed more precisely. The architectural theorist Vitruvius (80 B.C.E.–15 C.E.) described the schematic for an odometer, which would count a mile each time a vehicle's wheels clicked through a certain number of turns. Nautical speed, on the other hand, was measured with a knotted length of rope attached to a plank of wood tossed overboard. As the ship moved, a sailor would count the number of knots to pass through his hands, and thus gauge the distance the ship had covered in a given span of time—often measured by an hourglass. This information helped the crew estimate its position in the voyage, however roughly, and steer the ship toward its port.

After the fall of the Roman Empire, the center of science and technology shifted to the Islamic world. Scholars at centers of learning like Baghdad and Damascus made many advances in astronomy, in particular, in order to schedule prayer times and to plot orientation toward Mecca. Islamic scientists were also accomplished chemists, and meticulously documented the properties and transformational potential of different substances in search of the alchemical shortcut to gold.

During the Renaissance, many new instruments and measures surfaced as Europe slowly emerged from the Dark Ages and saw, in certain pockets, the developing culture of the scientific laboratory. Among Leonardo da Vinci's

(1452–1519) hundreds of inventions, he designed a hygrometer to measure humidity and an anemometer to gauge wind speed. But perhaps the most noteworthy scientific advancements during the Renaissance resulted from precision optics for telescopes and microscopes. With these tools, scientists were able to observe phenomena beyond the normal limitations of vision. What was once invisible or imperceptible came into the realm of rational scrutiny through these new instruments and sensors. The first telescopes were invented in Holland for use on land and sea, but Galileo Galilei (1564–1642) adapted the design to observe the moon, stars, and planets. Galileo is also credited with the first thermometer, which he designed after noticing the regular expansion and contraction of some liquids in response to the ambient temperature. But the invention of the barometer by Galileo's friend Evangelista Torricelli (1608–1647) is an especially interesting case. Although changes in air pressure are largely undetectable to us, they are a useful indicator of approaching changes in the weather. Thus, the barometer is perhaps the first instrument that did not simply augment or quantify a basic human sense like sight or touch, but rather produced an entirely new capacity through the use of a tool. The philosopher Blaise Pascal (1623–1662) reputedly carried a barometer up the Puy-de-Dôme to demonstrate the drop in air pressure at higher altitudes.

During the political turmoil of the Reformation, when travel was not only dangerous but expensive, many scholars corresponded and collaborated by mail. The astronomer Tycho Brahe (1546–1601) was an especially active organizer of networked data gathering. From his castle observatory in Denmark, Tycho printed and mailed observation forms to a network of astronomers spanning all of Europe. His compiled results were the most accurate and comprehensive star maps of his time. The French astronomer Nicolas-Claude Fabri de Peiresc (1580–1637) also made effective use of the postal system to coordinate observation of eclipses by a dispersed group of scientists. The collected observations allowed Peiresc to determine more accurate lines of longitude and thus plot more accurate maps.

Determining longitude presented a far greater problem at sea, so the Royal Society of London established the Longitude Prize with a sizeable reward of £20,000 for anyone who could solve it. The answer turned to developing a clock small and rugged enough to carry aboard a ship, but still accurate enough to keep time with a central clock at a known location. The clockmaker John Harrison (1693–1776) claimed the prize with his invention of the marine chronometer. By synchronizing this clock to the one housed at the Greenwich Observatory, a sailor could check the position of the sun against the known time in Greenwich, which originated the Prime Meridian standard in international timekeeping.

Several other Enlightenment discoveries directly resulted from increasingly precise sensors. Joseph Priestley (1733–1804), the leading chemist of his time, believed that fire was caused by the release of a substance he called phlogiston—though no one had ever seen or even detected phlogiston. Antoine Lavoisier (1743–1794) finally discredited Priestley's theory using a scale accurate enough to show that matter does not become lighter upon burning—as one would expect if it had really released its phlogiston—but instead becomes slightly heavier through oxidation. For this feat Lavoisier is considered the father of modern chemistry, though he still lost his head during the French Revolution.

Another revolution, the industrial one, followed with a rush of inventions. Looking back on this period, the philosopher Alfred North Whitehead (1861–1947) once remarked that the greatest invention of the 19th century was really the method of invention itself. This was a muted critique of the relatively slow scientific progress amid the feverish technological push into modernity.

The domestication of electricity in the 19th century was particularly transformative, and it marks a turning point in the history of sensors for several reasons. For one, electricity is the basis of the telegraph, the first instantaneous communication medium. Electricity is, of course, also a source of power, enabling sensors to be automated. Finally, many sensors today operate through transduction, the conversion of a physical quantity like sound or temperature to energy, often in the form of an electrical signal. Many of the sensors discussed below, and many that we still use today, are reliant on electricity in a variety of ways.

The 19th century witnessed the arrival of technology that recorded images and sound. The first camera, which was unveiled to great fanfare in 1839, required long exposures for its chemical treatments to capture an image. But as inventors designed more sensitive film, the camera offered not only greater accuracy and detail than any drawing, but could also capture phenomena too fast and fleeting to be apprehended by the naked eye. Historians see this as the moment when mechanical sensors were first treated with greater credibility than the human observer, whose many biases and limitations could derail the objectivity of their findings.

The photographer Eadward Muybridge (1830–1904), for instance, built an elaborate array of cameras to photograph a horse at regular intervals through the course of its stride. The photos were commissioned by the industrialist Leland Stanford (1824–1893) to settle a bet over whether or not horses fully leave the ground as they gallop. The resulting series of images captured each stage of motion, conclusively showing that the horse does indeed lift into the air as it runs. Here, the unique capabilities of photography settled an otherwise intractable debate.

Likewise, the first sound recording technology enabled unforeseen possibilities to analyze, archive, and manipulate sound. Sound is so fleeting and inexpressible that we will never be certain what ancient languages and music were really like, thus the advent of recording it was a rather dramatic moment in the history of sensing. The first instrument that could record sound was Édouard-Léon Scott de Martinville's (1817–1879) phonautograph, which produced etches to represent a sound visibly, but could not reproduce it audibly. These etches must have been novel and evocative, but they were clearly static and limited. Thomas Edison's (1847–1931) phonograph, on the other hand, was the first to both create and play back brief recordings from a wax cylinder. In both cases, the air pressure of the sound waves would directly move a needle to inscribe its mark. With the invention of magnetic tape in 1928, audio could be recorded in multiple takes, with sounds overlapping other sounds, to create pieces more complicated than the phonograph's recording of a single moment.

At the same time, medical instruments invented in the 19th century gave physicians the ability to monitor a patient's pulse, respiratory rate, temperature, and blood pressure. The physician René Laennec (1781–1826) developed the stethoscope after watching children tap sounds to each other through a long block of wood. Ludwig Traube (1818–1876) realized that a patient's fever corresponded to the trajectory of illness and recovery, so thermometer readings became a regular component of diagnosis and treatment. With Scipione Riva-Rocci's (1863–1937) invention of the sphygmomanometer in 1896, blood pressure became the fourth vital sign monitored by physicians. Later, Willem Einthoven (1860–1927) was awarded the Nobel Prize for inventing the electrocardiogram to measure the heart's electrical activity through a string galvometer.

The first bedside monitor was used by the surgeons Aaron Himmelstein and Martin Scheiner in 1950 to simultaneously monitor a patient's heart rate and electrocardiogram during an operation. Vital signs were plotted as waveforms on an oscilloscope, and alarms would sound if either one reached a dangerous level. These monitors were common by the 1960s, and soon their range of sensors expanded to blood pressure, respiratory rate, and body temperature, among others measurements.

In the first half of the 20th century, astronomers too were probing for signals that we cannot detect naturally. Telescopes sensitive to radio waves, microwaves, or x-rays could scan and map energy from the distant reaches of the universe. NASA's Search for Extraterrestrial Intelligence (SETI) famously distributed the vast scans of its radio telescopes to volunteers whose home computers would crunch data when they were not in use.

Astronomers have also used spectrometers to analyze the light emitted by celestial bodies. Subtle shifts in the color of stars, for instance, could reveal a great deal about their composition and activity. Edwin Hubble (1889–1953) reasoned that the red shift of some stars indicates that they are moving away from earth due to the continual expansion of the universe since the Big Bang. Likewise, the gravitational red shift of Mercury when we observe it from the opposite side of the Sun provided some of the first empirical evidence for Einstein's theory of general relativity.

Meteorology also benefited dramatically from the technology that emerged in the 19th century. In 1843, when many cities kept local weather data, Elias Loomis compiled that information to draft the first synoptic weather map depicting pressure fronts, wind movements, and weather conditions for the entire eastern United States on a single day. But this had been compiled from past data. He could only gather the data by post. But when the telegraph network began to link American cities two years later, current weather data could be gathered from a widely dispersed network of weather readings, and the first broad picture of weather systems could be stitched together from regular, recent data. In 1849, the Smithsonian Institution began gathering weather reports from a dispersed network of 140 volunteers, and by 1856 it had compiled and displayed a daily weather map of the country.

As weather networks grew, meteorologists set up small, remote boxes called weather stations to shelter sensors like thermometers and barometers as they collected readings. For aerial readings, multi-purpose sensors called meteorographs were mounted to kites or hot air balloons. In the 1920s, the U.S. Weather Bureau dispatched a fleet of airplanes to gather weather data across the country. In 1928, the first radiosonde, an unmanned weather balloon, gathered high-altitude weather data and transmitted it back home via radio. And in the late 1930s, meteorologists began using doppler radar to map precipitation over entire regions.

In fact, the invention of radar and radio broadcasting are closely tied to weather experiments. Following Heinrich Herz's (1857–1894) pioneering work on radio waves, the physicist Alexander Popov (1859–1906) inadvertently invented radar while he was trying to build a lightning sensor using radio waves. Popov noticed that each of the ships he used to gather readings were blocking each other's measurements, but that this offered an oddly effective way to locate the other barges. Building on these findings, Gugliemo Marconi (1874–1937) invented the first radio communication system as a means to send telegraph messages wirelessly. The same pings that we associate with a radar screen would, in this case, beat to the rhythm of Morse code and send the message out over the air.

In this way, Marconi's wireless telegraph was strangely kindred to the wi-fi and cell phone transmissions we still receive on the radio spectrum. The staccato volleys of telegraph tones were quite literally digital, and they share many qualities with the languages and encodings that circulate through today's electronics.

Given the many uses we still have for the radio spectrum, it is worth recalling that old technologies rarely go away. Weather vanes still perch on roofs to tell the direction of the wind, mercury thermometers can detect a fever in a pinch, and the magnetic compass is still an effective navigational tool. Digital instruments are more common today, and in many ways more useful for data analysis, but the story of sensors is vastly historical.

Although this section stops well short of the present day, it should illustrate that sensors have played a massive role in human history. Much of what we know about the world, we know through sensors that extend and quantify our natural capacities. We can say with certainty if it was warmer yesterday than it is today. We can reckon when it is midnight in Delhi. We have heard the voice of Winston Churchill.

Sensors are also at the heart of communications media that enable us to gather and distribute information. Many of the researchers discussed above were only able to make progress in their work once they could gather data from a dispersed group of collaborators. Sensors enable us to investigate what we simply cannot see, hear, or touch. These instruments have quite literally provided us with new senses, and they are, as a result, the most difficult to scrutinize.