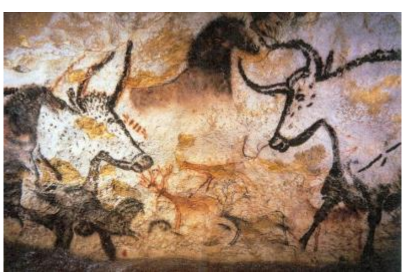
TEACHER BACKGROUND

Information theory enables a signal to be compressed (made smaller) and reconstructed at the other end without losing any of the message. For example, the Lempel-Ziv compression algorithm helps to enable the Internet. Information theory has moved cryptography way beyond the German enigma code to allow users to do secure transactions on the World Wide Web. The Web contains every sort of information that has ever been produced by humans – weather reports, poetry, financial records, videos, etc. The analogy between a web page and the page of a book is very inexact. However, it is interesting to note that Google estimates that there are about 6 billion web pages. If an average book is 600 pages, this would mean there is the equivalent of 10 million books online.

Information can be thought of as any fact or idea known by a person. Animals can communicate limited information to one another, such as when a bird's call warns another bird of danger. The idea that one person could fully learn what another person was actually thinking was one of the major factors that led to humans dominating the globe.

However, spoken language had several limitations. First, once spoken it was gone except in memory. Second, it could only travel so far. Humans tried to amplify their voices in many ways, such as cupping hands or using megaphone-like devices. In some places specialized sounds were developed that could travel farther that the regular voice, such as yodeling from mountain tops in the Alps. Instruments such as horns or drums could be made to produce even louder, farther-reaching sounds, and these sounds could be encoded with information as language was. But even with an ability to relay sounds from person to person, the use of sound for communicating information was very limited in space and in time. Spoken language could be enhanced by gestures but these, too, were temporary and local.

Since spoken language and musical sounds do not survive in the archaeological record, the existence of early human cognition and language is most evidenced by the rapid emergence of art as a human activity. Figural representation of the world and of human thoughts are everywhere associated with modern humans, but most strikingly in the famous cave paintings of Europe (the cave paintings are better preserved that art in Africa and elsewhere because the cold European climate caused the inhabitants to utilize caves rather than open rock faces).



One of the famous paintings from Lascaux Cave, France, dated to around 20,000 years ago and portraying bison and horses. Source: Wikipedia Commons. https://en.wikipedia.org/wiki/Lascaux#/media/File:Lascaux_painting.jpg

These images are clearly meant to convey information in some way, though exactly what information is hotly debated.

Such ability to communicate information had a profound impact on every aspect of society. Since abstract stories could be told, religion as we understand it today emerged (there is some evidence that Neanderthals may have had spiritual beliefs of some sort). Social relations could be expressed verbally, rather than through constant physical display, as in primates. Most importantly, it became easier to develop advanced technologies because processes could be described, taught, and handed down through generations. Neanderthals had improved stone-tool technology over those of earlier hominids, but Anatomically Modern Humans learned to use pressure rather than percussion to shape stone tools, to fire treat rocks, and to produce very specialized tools through long sequences of actions.

Bifacial spear points from South Africa, dated to over 70,000 years ago. Source: Wikipedia Commons. https://en.wikipedia.org/wiki/Blombos_Cave#/media/File:Blombos_point_white.JPG

By 20,000 years ago at the latest, the bow and arrow—the first complex technology—had been invented. For thousands of years, small human bands wandered across the countryside hunting large game. About 12,000 years ago, the global climate began to improve, and humans multiplied into a greater number of larger bands that could capitalize on a more rich and varied environment. Communication would have been a key part of this adaptation, with locations of resources both conveyed by scouts and also passed down through generations. Observations of the natural world, such as the flying patterns of birds, or the use of stars for navigation (see Early Navigation REACH unit) could be communicated.

When different human groups encountered each other, even if their languages had diverged, they could still find ways to communicate, thus enabling the exchange of goods – and also group members (inbreeding being a danger for small human populations). It was probably a relatively pleasant life, but having to constantly move across the countryside limited the population, the ability to accumulate goods, and the opportunity to develop certain new technologies.

In ancient Mesopotamia, by 5,500 years ago there is the appearance of clay objects whose shape or incising suggest that they were used as accounting tokens. The earliest visual (and tactile) recording systems are therefore based in the economic system and record both numerical data and qualitative data (the type of item being counted). By 5,000 years ago, these tokens had evolved into a script called cuneiform. Cuneiform was produced by pressing a wedge-shaped stylus into a wet clay tablet to produce a line (Cuneiform means wedge-shaped). The combinations of multiple horizontal and vertical lines revealed the meaning.

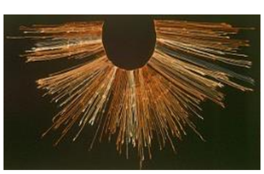
Because of the method of application, tablets were written and read top to bottom, right to left. Cuneiform was originally pictographic (also called logographic), meaning each symbol represented a word or number, rather than part of a word or number. Therefore, the earliest cuneiform systems had something like 1,500 signs! Among the complex Mesopotamian cultures with their many craft specialists, a new expert arose—the scribe. Because Mesopotamian states were theocratic, scribes were often priests, a pattern that will recur in history. Eventually, scribes realized that the symbols could also stand for sounds. This meant that they could also portray concepts. In English, “bear” is an animal but also means to carry or to have no clothes. So, a picture of a bear could mean the animal, or it could mean either of the concepts, determined by context. They then realized that since spoken language could be broken into syllables, each syllable could be represented with a symbol, reducing the necessary number of symbols to a few hundred. For a long while, symbolic and syllabic writing were used together.

Clay accounting tokens from Susa, dated to over 5,000 years ago. Source: Wikipedia Commons
https://commons.wikimedia.org/wiki/File:Clay_accounting_tokens_Susa_Louvre_n2.jpg

Sales contract in cuneiform. Shuruppak, circa 2600 BCE. Source: Wikipedia commons
https://en.wikipedia.org/wiki/Cuneiform#/media/File:Sales_contract_Shuruppak_Louvre_AO3766.jpg

In China, the earliest confirmed writing is from the Shang Dynasty, around 3,000 years ago. The Shang system, like cuneiform, uses a combination of symbolic and syllabic signs, so it was probably in development for some time. The earliest Shang writing is on oracle bones, which were used in divination, again showing the importance of religion to early communications. The Chinese also developed scribes as a professional class.

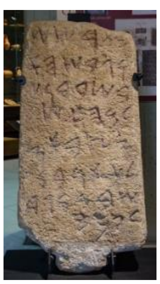
In Mexico, the Olmec civilization developed a pictographic writing system at least 3,000 years ago. Within several hundred years their successors, the Maya, had developed a syllabic system, and also employed a class of scribes. Again, the early use of writing was economic, but closely tied into the religious system. The exception to the pattern is the civilizations of the Andes. These never developed a true writing system. Instead, they develop a complicated system of knotted ropes, called quipu, that record the same sorts of information as early writing.



Quipu from the Inca Empire. Source Wikipedia Commons
https://en.wikipedia.org/wiki/Quipu#/media/File:Inca_Quipu.jpg

The most interesting fact to note, however, is that writing emerged independently in several locations, and in every case was a response to a need to record increasing amounts of information, both qualitative and, especially, quantitative. These independent systems evolved toward an idea of representing sounds rather than objects or words. Also interestingly, these ancient state-level societies tended to cause the spread of social complexity, either by expansion, competition, conquest, or just by example. In every case, they brought or transmitted their technologies, including writing. The final thing to note is that writing, once established, enables other forms of information to be recorded, not just accounting. It creates a feedback loop for the growth of information in society. Famously, soon after complex societies arose in Mesopotamia, a unique society arose in Egypt. Egypt eventually surpassed the other ancient civilizations in a number of areas such as monumental architecture (the Pyramids!) and metallurgy. They also developed a writing system—still a combination of logographs and syllabic elements—with several innovations. This system contains the famous Egyptian hieroglyphics.

Sometime around 2,800 years ago, the Phoenicians made a major invention—the vowel! That is, they realized that instead of each symbol representing a syllable (ba, be, bi, bo, bu, ca, ce, ci, co, cu, etc.), each individual sound could be represented by its own symbol, reducing the number of symbols from over 100 to just 22. This alphabet (from the name of the first two letters), spread like wildfire over western Asia, northern Africa, and Europe. It was adapted by the Greeks, another seafaring people that relied on trade. Ultimately, the Greeks established a vast trading empire throughout the Mediterranean, and later Greek was spread even further by the Macedonian (but Greek-speaking) conqueror Alexander the Great. He spread it to the Romans, who then, during their even greater conquests, spread it throughout Europe. Although civilizations of China and the Americas continued to effectively use older writing systems, those of Europe, western Asia and the Mediterranean world now had a more advanced technology for storing information – the Alphabet.



Nora Stone Phoenician inscription, 8th century BCE. Source: Biblical Archaeology *https://www.biblicalarchaeology.org/daily/biblical-artifacts/inscriptions/the-phoenician-alphabet-in-archaeology/*

As described above, the earliest writing was carved on wood, stone, or clay, or sometimes painted on these materials or on walls. There were many limitations to these substances, especially in terms of portability. What if a trader visited a faraway land, made a contract with a local, and then wanted to return a year later to follow up. Who would have the contract? Also, what if someone wanted to record information—a contract, perhaps, but also a personal letter, a story, a myth? Furthermore, as the early state-level societies grew into empires, it became necessary to communicate over greater and greater distances. Information is very useful to capture, store, and retrieve locally. But it is even more useful if it can be sent over long distances, that is, transmitted. Communication was critical to the evolution of people and early civilizations, but telecommunication was going to be even more important to the further development of empires, international trade, and, eventually, modern society.

Even from about 4,000 years ago, the Egyptians developed methods for writing on leather skins with dark minerals (this also involved adapting the hieroglyphic symbols to be more conducive to this new type of writing). As the Phoenician alphabet spread, the need to write on portable media grew as well. Somewhere in Asia Minor around 3,000 years ago, people learned how to prepare animal skins not for clothing, but for writing. Leather for clothing, which is tough and durable but also rough and uneven, is made by tanning the skin – treating it with chemical substances that stabilize the proteins of the animal hides. To create a writing surface, the ancient people soaked the hide in water and then in fermented vegetable matter to remove the hair. The skins were then stretched and scraped. The resulting material, called parchment, was perfect for writing with ink – pigments dissolved in a fatty base derived from plants or animals. Technically, parchment is from sheep or goats; a writing skin from cows is called vellum.

Various inks also evolved to keep pace with developing writing surfaces. As with many other inventions (see, for example, the magnetic compass explained in REACH Inquiry Unit on Early Maritime Navigation), the original ideas arose in China, but were transformed as they reached Europe. Around 3,000 years ago, the Chinese invented a powder ink made of fine soot that could be dissolved in water and applied. This substance spread to India (hence the name India Ink) and then to the west.

The existence of appropriate writing materials and surfaces meant that information could be condensed into small, relatively portable media. As mentioned before, when the ancient state-level societies evolved into large land empires, the need for telecommunication grew accordingly. Around 550 BCE, the Persian King Cyrus the Great devised a system of roads with waystations stocked with men and horses, so that written messages could be sent rapidly throughout his large empire. As the Greek historian Herodotus famously wrote, the messengers were not stopped by "snow nor rain nor heat nor darkness from accomplishing their appointed course with all speed." This set-up is considered to have been the first postal service. But note that telecommunication involved producing or recording a message, handing it to someone, and having that person (or persons through a relay) deliver the information to the recipient. The transmission may involve horses or ships. There were many opportunities for messages to be lost, or even intercepted if they were of a sensitive nature.

Another major communications invention from China was paper. From about as early as they were writing on parchment, the Egyptians began producing another writing surface called papyrus by mechanically flattening the papyrus plant that grows along the Nile. Papyrus, however, was prone to mold and decay – more problematic in Europe than in Egypt. In the second century CE, the Chinese learned to grind up appropriate plant materials, dissolve them in water, drain them through a screen, and dry and press the residue. This produced a smooth, white, durable writing surface. When it reached the west, it was called paper because of its resemblance to papyrus.

Parchment was generally sewn together into long strips, and rolled into scrolls. The Romans also used wax tablets held in folded wooden frames. About 2,000 years ago, the Romans realized that parchment or papyrus could be cut into sheets and bound in that way, and they created the *codex* – what we call the book, with a spine, covers, and pages in between. Over time, the advantages of the codex over the scroll caused it to become the main form of storing information. Scrolls continued to be used longer in China, and in various other places for specific applications (such as the Jewish ritual Torah scrolls).

The advent of paper and ink improved the codex further, but each page still had to be copied painstakingly by hand. In China, they realized that paper and ink allowed one to carve a picture or even words in reverse in a medium such as wood or stone, and then make multiple copies by inking the image and pressing paper evenly on top of it. Hand-copying a page could take all day, but here, once the initial labor was invested in the carving, dozens of copies could be made in a single day. Although this was an improvement over hand-copied pages, the spread of information was still limited in a large empire with millions of inhabitants. These limitations were overcome with the invention of moveable type. First developed in China in the 11th century, moveable type became a mainstay of European printing.

In 15th century Germany, a goldsmith named Johannes Gutenberg made two important complementary innovations. His family's involvement in the wine business led him to perfect a screw press for inking paper. His own metallurgical skill led him to invent metal moveable type. Letters were placed in a matrix to form text, rather than carved all together. Letters made from lead alloys could be easily and quickly cast meaning that the printer did not need to know in advance which letters were needed. Note that, like the Chinese, the Koreans had experimented with moveable type before Gutenberg, but their symbolic writing systems, involved many, many letters. The Latin-derived alphabet – one of the many to descend from the original Phoenician invention – was ideally suited to this new form. Gutenberg could turn out thousands of pages in a day. (For the full story of the Printing Press, see the IEEE REACH Printing Press Inquiry Unit.)

Illustration: Replica of Gutenberg's Workshop, Gutenberg-Museum Mainz, http://4.bp.blogspot.com/-IcF1U_vWgI8/UKHU5oOJfGI/AAAAAAAAS10/DzSnDHnt-4c/s1600/Gutenberg-Museum-Printing-Press.jpg (Accessed: 17 June 2016)

For the first time, information could be "mass produced" and "broadcast – that is, distributed widely. Earlier writing was used to "broadcast" only if was carved onto monumental architecture – the equivalent of the modern billboard. If the information was to be shared more broadly, then a letter, such as a royal proclamation would have to be read aloud. Quickly in Renaissance Venice – and soon throughout Europe – the idea arose of printing a single sheet folded to form four pages and used to convey current news – this was the beginning of the modern newspaper.

The Printing Press had many impacts on society. As printed material became more common, it was used more widely and literacy rates rose. More diverse types of information were printed and distributed. These and other developments in the late Medieval and Renaissance eras helped lead Europe toward the Enlightenment and the Scientific Revolution. What scientists discovered was that visible light – used in all of the visual telecommunication technologies discussed above – is just one kind of light. Light is an electromagnetic wave, and it exists in a continuum of frequencies, many not visible to the human eye. Early scientists were intrigued by the phenomena of electricity and magnetism, and studied them intensely. In 1799, Alessandro Volta of Italy invented the battery, meaning that electricity could easily be supplied in the laboratory. By 1820, Hans Christian Ørsted in Denmark was able to demonstrate that electricity and magnetism were linked, and that one could cause the other. Soon James Faraday in the

UK demonstrated how electricity passed through a wire coil around a metal could produce a magnet, which could then exert force on other objects.

Since electricity passed easily along wires almost instantaneously (at the speed of light, we now know), scientists and engineers realized it could be used as a form of telecommunication with a potential to transform economies and societies. One could insert an electric signal at one end and the signal would travel along a wire. At the other end, the electric signal could be converted to magnetic field that could move a piece of metal. In the UK, William Fothergill Cooke and Charles Wheatstone developed a successful telegraph where the input and output were a series of needles pointing to a letter. This system required six wires to operate the five needles.

Cooke and Wheatstone telegraph, 1837. The five needles were controlled by six wires, and the intersection of the needles that moved indicated the letter. Source Wikipedia Commons (https://en.wikipedia.org/wiki/Telegraphy#/media/File:Cooke_and_Wheatstone_electric_telegraph.jpg)

In the United States, Samuel Morse was also working on an electric telegraph. He was aware of the work of Enlightenment mathematicians on binary mathematics, where all numbers could be represented by a combination of ones and zeroes. He and his partner Albert Vail reasoned that a combination of long and short symbols (called dashes and dots) and long and short pauses (short pauses between symbols in a letter and long pauses between letters) could be used to represent all the letters. This system needed only one wire connecting the transmitter and receiver. The different sound of a dot vs a dash meant that a trained telegrapher could transcribe a message without having to look up at a chart, as with the Wheatstone-Cooke telegraph. Morse successfully demonstrated his system in 1844, and Morse Code came to dominate telegraphy. By 1852, there were 37,000 km (23,000 miles) of telegraph lines in the United States alone. By 1866, and undersea transatlantic cable allowed telegraphic communication between the Old and New Worlds.

Morse telegraph key. Source, Smithsonian Institution (https://americanhistory.si.edu/collections/search/object/nmah_1096762)

The important concept to note is that information had been becoming more widely available. With widespread literacy, anyone could write a letter, or a poem, or a book, and anyone could read it. To print the material required special knowledge and special equipment, but the information was not processed in any additional way. The printed letters could be read as easily (more easily, in fact) that the written manuscript submitted to the printer. The invention of the typewriter in 1865 further blurred the line between writing and printing. But with the Morse Code system, the information had to be processed. The sender wrote out or spoke the message, but a trained telegrapher had to translate it into Morse Code and send it over the wire. At the other end, a trained telegrapher had to translate the message back into an alphabet (later, printing telegraphs were developed). The message then had to be delivered or picked up at a telegraph office. So, in a way, this was a step back from the democratization of information. In 1876, Alexander Graham Bell figured out how to turn sound into electrical impulses that could travel along the wire and then be reverted to sound, and the telephone ("sound over a distance") was born, and anyone could speak to anyone else over distance (though telephones remained rare and expensive for some time).

However, the telegraph as the main medium of telecommunication was going to be threatened in turn. In the 1860s, James Clerk Maxwell in the UK determined a set of equations that described exactly how electromagnetic waves propagated themselves through space, analogous to ocean waves speeding through water. This meant that theoretically wires were not needed Waves have a distance between peaks, called a wavelength, and a rate at which they pass a fixed point, called the frequency. The wavelength multiplied by the frequency therefore gives the speed of the wave, which for electromagnetic waves is always the speed of light. The longer the wavelength of an electromagnetic wave, the lower the frequency, and the less energetic they are, meaning the less they interact with physical material. Maxwell predicted that radio waves, with long wavelengths between 1 millimeter and 10,000 kilometers, should be propagating through air constantly. In 1887 the German physicist Heinrich Hertz was able to produce, transmit and detect radio waves in his laboratory.

As with transmission through wire, scientists and engineers realized that they were at the border of a new frontier. Wire for the telegraph or telephone was expensive and difficult to install, and subject to damage. If a signal could be sent wirelessly over the air, it would be a huge breakthrough. [See the REACH Radio Inquiry Unit for more about the history of radio]. It was Guglielmo Marconi who first developed a system that could send electromagnetic signals and receive them across the ocean. His signal was not precise enough to send voice, so he used Morse Code. This technology was therefore called wireless telegraphy. Marconi became wealthy establishing a system of transmitting and receiving stations, so that telegrams could be send almost instantaneously over great distances.

Marconi Station, Wellfleet, Massachusetts, 1905. Source, Smithsonian Institution (https://americanhistory.si.edu/collections/search/object/NMAH.AC.0055_ref2402)

Then, in 1904, John Ambrose Fleming invented a glass tube with two leads that only allowed a current to flow in one direction, with the amount of current controlled by the voltage across the tube. This meant that such a tube could detect and amplify radio waves. It was quickly improved by American Lee De Forest who, in 1906, added a third lead to create the triode or Audion vacuum tube (these tubes, based on Edison's lightbulb, had to be emptied of air to function properly). Such tubes are deemed electronic, rather than simply electric, and a new industry was born.

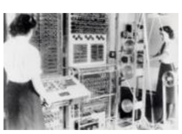
De Forest Audion, 1906. Source Smithsonian Institution (https://americanhistory.si.edu/collections/search?edan_local=1&edan_q=audion&edan_fq%5B0%5D=online_visual_material%3Atrue)

Sound could now be sent over radio waves by sending a carrier wave and modifying it with the information, that is, the voice. This was called wireless telephony, or, as it came to be known, radio. Because it was the amplitude (wave height) of the carrier wave that was modified, this type of radio is called AM (Amplitude Modulation).

Morse was not the only one who realized the power of a binary number system. In 1854, British mathematician George Boole detailed a logic system where algebraic formulas could be implemented using only true/false as the possible values. By the early 20th century electromechanical and relay switches—which are either off or on—were being used for a wide range of activities. In his MIT master's thesis in 1937, Claude Shannon (more on him below!) proved that relay systems could be designed according to Boolean logic, greatly simplifying and regularizing them. This led to the idea that computers capable of doing complicated mathematics could be built out of electromechanical or electronic circuits. Instead of working in base 10, a computer could theoretically convert everything to base 2 and conduct every conceivable calculation. Other information, such as words, could be encoded in the same way.

With the outbreak of World War II—the first truly technoscientific war – calculation became critical. Powerful calculations were needed for ballistics, to develop the atom bomb in the Manhattan project, and for codebreaking.

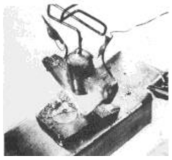
Since radio was the most important communication medium for all sides of World War II, and since radio waves can be overheard easily, coding once again became a critical element of human communication. The Germans developed an electromagnetic coding machine called Enigma that was supposed to produce unbreakable code. In response, the British built a machine, Colossus – considered one of the world's first digital computers – that successfully broke that code. Electronics had now become a major medium for storing and processing information.



Colossus being programmed. Source Wikipedia Commons (https://en.wikipedia.org/wiki/Colossus_computer#/media/File:Colossus.jpg)

After the war, improvements in digital computers continued rapidly. In 1945, the visionary American engineer Vannevar Bush proposed that someday everyone would have on their desk a device that could store all information and share it with the devices of others. Computers at that time, however, needed large numbers of electronic tubes, which took up a lot of space and power, and the tubes tended to overheat and fail.

Then, in 1948, several amazing things happened. First, researchers at AT&T's Bell Labs discovered how to grow a crystal so that it had the electronic characteristics of an electronic tube. They named this "solid-state" (all solid, no separate vacuum chamber) device the transistor. With further development, there was now a way to create electronic devices that were small (and got continually smaller over the years with inventions such as the integrated circuit), low power, and did not tend to fail at the rate that tubes did. So, it opened up the possibility of vastly increased computing power. But what would that power be used for?



First transistor. Source Engineering & Technology History Wiki (https://ethw.org/File:ACenturyofElectricals_Page_34-1.jpg)

Claude Shannon, who already had contributed so much with his master's thesis, was also working at Bell Labs that year, and he published a paper called "A Mathematical Theory of Communication." In it, he argued that human communication could be generalized into a system. Information (called a message) is produced by a source and is sent out by a transmitter as a signal. The signal goes through a channel and comes to a receiver, which then turns the signal back into the message for the destination. In a telephone, for example, the human voice is the message. The microphone (transmitter) turns it into an electromagnetic signal that travels down the wire (channel) to the earpiece (receiver) on another phone that turns it back into a voice message.

This is an interesting theoretical qualitative concept, enabling one to think about any sort of communication in an analytical way. Shannon, however, went further and quantified it. He proved that if the signal is a digital signal, then the capacity in bits per second (the bit is the 1 or 0 of a digital signal) equals the bandwidth times the logarithm (base 2) of the signal-to-noise ratio plus 1. Without getting into the mathematics, engineers now had a tool to calculate how fast they could send information over a signal, given information about the signal and the noise. At the same time, Shannon published a paper with two colleagues arguing that information could be sent over radio waves by coding it as binary pulses rather than a continuous signal. So, in addition to AM and FM, there was now PCM (Pulse-code modulation).

There would clearly be advantages to this new system, but one might think that digital signals would be subject to the same potential errors as analog signals. However, also in 1948, Richard Hamming invented error-correcting codes. He demonstrated that if one encoded a message in blocks of binary digits, with each block satisfying certain algebraic equations, if an error occurred (a 1 turned to a 0 or vice versa), the error could be detected and corrected by the receiver. Thus, with sufficient computing power to code and decode the signal, messages could be sent quickly, efficiently, and error free. A new field, with implications for almost all of the major fields of electrical and electronic engineering (broadcast, signal processing, communication) was born—Information Theory. That is why many historians feel that the year 1948 can be referred to as the beginning of the Information Age.