Breakthroughs in Information and Communication Technologies

Part II

V Rajaraman

In Part 1 of this series of articles, I defined what is meant by a breakthrough in ICT, listed fourteen breakthroughs in chronological order, and described five breakthroughs. In this second part of the three-part series of articles on Breakthroughs in Information and Communication Technologies, I describe four more breakthroughs: Computer Graphics, Internet, Global Positioning Systems, and the World Wide Web. As in the last part, I will justify why I consider them as breakthroughs and briefly describe each of them.

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Keywords
Computer graphics, internet, global positioning systems, World Wide Web.

6. Computer Graphics

Computer graphics is concerned with the generation and display of digital data as pictures on a computer monitor. It includes simple two-dimensional (2D) illustrations such as engineering drawings, sophisticated realistically shaded three-dimensional (3D) objects such as automobiles, and videos such as animated movies. One of the most popular applications of computer graphics is in the design and development of interactive computer games. Another everyday use of computer graphics is as an aid for human-computer interaction (called a Graphical User Interface – GUI). GUI displays graphical icons on the screen of a monitor representing applications such as a browser, search engine, and word processor. The application is invoked by pointing to its icon using a device such as a mouse or a finger/stylus.

Even though it was realised early in the development of computers that giving the output of computation in a graphical form enhances human understanding of the result, no cost-effective

graphical output device that could be connected to a computer was available in the 1950s and 60s. Another constraining factor was that graphical output is useful only if it can be interactively used with a computer. For drawing pictures using a computer, it is necessary to have one-to-one interaction with the computer. Digital computers were too expensive in the 1950s and 60s to permit users this luxury. Computers were primarily used in a batch mode with many users sharing them. Research in computer graphics was hence restricted to well-funded institutions.

The first major breakthrough in computer graphics was the doctoral work of Ivan Sutherland at MIT in 1963. He wrote a program called 'Sketchpad' for the Lincoln TX-2 computer – a single user interactive computer – that had a Cathode Ray Tube (CRT) display. Sketchpad was a 2D drawing program. It had graphical objects such as lines, rectangles, ellipses, and circles. They could be manipulated using a device called a light pen that had a sensor to detect the light beam on a CRT screen. Sutherland wrote algorithms for geometric operations such as clip, zoom, and coalesce graphical objects for drawing useful 2D figures. Interestingly around the same time (1964) Douglas Engelbart, working at the Stanford Research Institute in the west coast of the USA, invented the 'mouse' that is widely used even today to move the cursor on a display unit of a computer. We have described some related work of Engelbart in Section 9 on the World Wide Web.

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PDP-1 computer was manufactured by the Digital Equipment Corporation in 1959 and was one of the first commercial transistorised computers with an architecture similar to Lincoln TX-2. It had a large CRT screen as an output device and became famous for history's first computer game called 'Space War' developed by Steve Russell in 1962 at MIT. This kindled interest in graphics for interactive game playing. IBM sold interactive computer graphics terminals for around USD 100,000 in 1965 which only major corporations could afford. These companies used the IBM graphics terminals for writing computer-aided design software to design complex structures (bridges, aircrafts, etc.) and for displaying the results of simulation of dynamic systems. The major

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problem in the 60s was the high cost of computers and graphics output devices. Progress was slow.

Academic research picked up when time-shared computers that allowed many users to simultaneously use a computer were introduced in early the 1970s. Even then graphics terminals were expensive. A significant development was the introduction of Direct-View Storage oscilloscope by Tektronix for USD 1500 that could be used as a graphics terminal with time-shared computers. This development enabled researchers in many academic institutions and research laboratories to develop graphics algorithms. In 1969, the Association for Computing Machinery (ACM), USA, established the Special Interests Group in Graphics (ACM SIGGRAPH) indicating the emergence of computer graphics as an important discipline in computer science. Among the academic institutions, the group established by David Evans at the University of Utah in 1966 contributed many important algorithms in computer graphics. In 1967 he invited Ivan Sutherland to join the department. They were frustrated by the non-availability of computer systems for graphics and started their own company – Evans and Sutherland – in 1968 to design and manufacture graphics workstations that were used in developing many innovative graphics programs. Several research students at the University of Utah designed important algorithms in computer graphics. In 1974 Edwin Catmull contributed to texture mapping in 3D modelling of objects. The group also developed algorithms for hidden surface removal in 3D modelling. In 1977 a group of 25 experts of the ACM SIGGRAPH developed the first standard for graphics called '3D core graphics system' that became the foundation for further developments in graphics. (This is the reason I picked 1977 as the breakthrough year for computer graphics).

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Incidentally, several students who graduated from the computer graphics group of the University of Utah started some of the best-known companies that did pioneering work in computer graphics. Pixar, which specialised in realistic computer animation, was started by Catmull. Silicon Graphics that made workstations with excellent graphics programming features was started by Jim

Clark. Adobe Systems, famous for PostScript, Photoshop, and Portable Document Format (PDF), was started by John Warnock. Alan Kay working at Xerox Palo Alto Research Center (PARC) invented the GUI and object-oriented programming.

Researchers who had earlier worked at the Stanford Research Institute in Douglas Engelbart's group moved to Xerox PARC. This group developed a PC named 'Alto' in 1973. Alto had the first GUI consisting of windows, icons, menus, and a mouse developed by a group headed by Alan Kay. By 1975 the group also developed What-You-See-is-What-You-Get (WYSIWYG) software that allowed a user to cut and paste pictures in typed documents.

Graphical User Interface (GUI)

As I pointed out, in the 1960s and 70s computers were not interactive. Even when time-shared computers were introduced, graphics terminals were expensive and the input devices were tele-typewriters. The entire scenario changed with the advent of Personal Computers (PCs) in 1975. PCs were inexpensive, single user machines and had fairly large, 15" diagonal, raster scan display. Researchers who had earlier worked at the Stanford Research Institute in Douglas Engelbart's group moved to Xerox PARC. This group developed a PC named 'Alto' in 1973. Alto had the first GUI consisting of windows, icons, menus, and a mouse developed by a group headed by Alan Kay. By 1975 the group also developed What-You-See-is-What-You-Get (WYSIWYG) software that allowed a user to cut and paste pictures in typed documents. Alto was not introduced as a commercial product but was widely used in many Xerox laboratories and some universities. It greatly influenced the design of PCs in the decades to follow. Apple's Macintosh computer adopted Alto's GUI in 1984. By mid-1980s, PCs were widely used and Microsoft introduced the Windows Operating System (OS) in 1985 that had a good GUI. GUI provides easy human-computer interaction and is now standard in all PCs, greatly enhancing user productivity.

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Desktop Graphics Workstations

With the reduction of the cost of integrated circuits and the advent of fast microprocessors and co-processors for performing fast graphics oriented operations, computers that were much faster than PCs, called 'graphics workstations' appeared in the early 1980s. The typical workstations had to satisfy the so-called 3M criterion – a Megabyte memory, a Megapixel screen, and a Megaflop

(million floating point operations per second) speed. Workstations made by companies such as Sun, Apollo, DEC, Hewlett Packard, and Silicon Graphics had 19" to 21" monitors and used Unix OS. They were the workhorses of researchers as well as designers developing graphics and computer-aided design software in the 1980s. Many of the advances in graphics software occurred during this period. They catalysed the development of sophisticated interactive games that became a hit with the general public. Computer animation got an impetus.

Coming of Age of Computer Graphics

Starting early 90s, there was significant progress in 3D computer graphics. In 1992, a standard for generating 3D graphics, called openGL (Graphics Language), was released. OpenGL has a library of primitives that is machine and OS independent. It was quickly adopted by designers of diverse graphics programs such as computer-aided design, creators of realistic graphical scenes, and animation designers. Even game developers who used the most powerful computers (for quick interaction) used OpenGL.

Computer graphics were used routinely by movie production houses to enhance movies such as Jurassic Park. A landmark was the release of Toy Story, a full-length movie in 1995, by Pixar Animation Studios under the leadership of Ed Catmull. The movie was entirely computer generated with no camera used. It was a hit and had many successors Toy Story 2, 3, etc. Hundreds of full-length movies are now being produced entirely using computer graphics without cameras and human actors.

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Computer Games

Computer graphics also ushered in the computer games market [2]. A company named Atari was a pioneer in this area in the early days of PCs. Real progress began in 1985 when Nintendo – a Japanese company – released a handheld device with multiple buttons (called a 'gaming console') that improved human-computer interaction for games. Sony PlayStation was very so-

phisticated and sold over 100 million units in 1995. Microsoft also entered the field of gaming hardware with a device called 'Xbox' in 1998. By 2010, more than 40% of homes in the USA had gaming consoles. Playing games required fast interaction and highly realistic graphics. As the number of people playing games increased to hundreds of millions, the market expanded. This influenced integrated circuit (IC) chip makers to design specialised graphics processing chips. Nvidia Corporation became a specialised graphics chip maker and manufactured a Graphics Processing Unit (GPU) used in real-time high-resolution 3D compute-intensive tasks. The internal architecture was fast enough to be used as general-purpose co-processors in current supercomputers.

Computer graphics and games have now moved to small hand-held mobile devices such as smartphones. Other developments are head-mounted displays that project 3D images in space giving an immersive experience called virtual reality.

Computer graphics is a breakthrough in ICT due to the following reasons:

- The idea that both 2D and 3D images can be generated by computer programs and displayed on a graphics output device is novel.
- The idea that the movement of a hand-held device (namely a mouse) on a desk can be translated to the movement of a pointer on the display screen is novel. This has immensely aided human-computer interaction.
- Results of computation displayed as 2D and 3D images aids our understanding of results of computation as opposed to reams of numbers printed on paper. Graphics has now become an essential aid for engineers, architects, and designers.
- Graphical User Interfaces greatly enhances our productivity in using computers. Windows, icons, menu, and pointing device are now standard on all computers. The importance of human-computer interaction has been realised and many new devices are appearing to improve our interaction with computers not only in computation but also in playing games with computers.

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- Computer games, besides spawning a new industry, has indirectly led to the development of fast computer chips that are now used in high-performance computers.

- Computer games have changed our society with millions of persons playing games with computers. Youngsters are not only innovating new games but also being glued to their computers for hours on end playing games. Games have now moved to smartphones with some game apps selling millions of copies.

- 3D graphics has led to the development of 3D printers that are now used in the computer-assisted manufacturing of objects. This has reduced the cost of many objects and has benefited our society.

7. Internet

Internet today has become an essential infrastructure in the world much like electricity. We depend on it for communicating with our friends, relatives, and organizations using email, disseminate and search for information, collaborate with colleagues anywhere in the world, listen to music, see videos, play a game with a remote opponent, hail a cab, and shop – to mention a few of our daily activities. It has been universally recognized as one of the greatest breakthroughs of the twentieth century.

As with many of the breakthroughs we have discussed in this article, it did not appear suddenly. The idea of such an infrastructure for social interactions using a network of computers was envisaged by JCR Licklider of MIT, in the early 1960s, when he wrote a paper proposing this idea. Subsequently, the Advanced Research Projects Agency (ARPA) of the US Department of Defence (DoD) appointed him to head the new Information Processing Technology Office (IPTO) with a mandate to further the research related to the Semi-Automatic Ground Environment

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(SAGE) program for protecting the USA against a space-based nuclear attack. Within IPTO Licklider evangelized the potential benefits of a country-wide computer communications network, influencing his successors to hire Lawrence Roberts, who was earlier at MIT, to implement his vision. Worldwide telephone networks existed in the 1960s. However, these networks were designed to carry conversations between two subscribers by establishing a circuit exclusively between them for the entire duration of the conversation. This method called circuit switching was wasteful and not suitable for carrying digital data between computers that is generated intermittently in bursts. This was pointed out by Leonard Kleinrock as a part of his doctoral work at MIT in 1961. He proposed that many independent messages could be transmitted between computers by breaking them into packets, each labelled with an identifier and interspersed and sent over a single communication path connecting them. The same idea was proposed independently by both Paul Baran at RAND Corporation, USA between 1961 and 1964, and by Donald Davies at the UK National Physical Laboratory in 1965.

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Roberts led the development of a computer network, based on this new idea of packet switching. A special computer called an Interface Message Processor was developed by a company, Bolt, Beranek, and Newman (BBN), in 1969 to provide a system-independent interface that could be used by any computer system to architecture a network using packet switching. This work was sponsored by ARPA and laid the foundation for designing a 'Wide Area Computer Network' (WAN) called the ARPANET. ARPANET went live in early October 1969. The first communication of packetized messages using the existing telephone network was between a computer in Kleinrock's laboratory at the University of California, Los Angeles, and a computer at the Stanford Research Institute at Palo Alto, near San Francisco. It was later expanded to connect computers at the University of California at Santa Barbara and the University of Utah. Gradually, many computers were connected using the existing telephone infrastructure. In 1972 the first email messaging system for com-

municating among researchers of the ARPANET was designed by Ray Tomlinson of BBN[1]. A file transfer protocol (FTP) to transfer files between computers connected to the ARPANET was designed by Abhay Bhushan of MIT in 1971 [3].

[1] Shiva Ayyadurai wrote an email software in 1978 when he was a 14-year-old student in the USA and registered a copyright in 1982 for the name EMAIL for his program.

Meanwhile, research in computer networking was also initiated in the UK by the National Physical Laboratory and in France by IRIA (now called INRIA). The French network was called the 'Cyclades'.

The first networking protocol used on the ARPANET was called the 'Network Control Program' (NCP). This was used to architecture larger national computer networks with mainframes as nodes. In the late 1970s, PCs began to proliferate and Ethernet for connecting them to a LAN was invented by Robert Metcalfe. LANs grew rapidly and an interconnection system was required to connect them. It required a new protocol to succeed the Network Control Program. This protocol was designed to satisfy the following four criteria.

(i) Each network should be considered as an independent entity.

(ii) The communication was to be "best effort". In other words, if a packet was lost in transit, it should be detected by the receiver and the sender requested to resend it.

(iii) Routers were designed to control the transmission of packets between networks.

(iv) There was no global control of communication.

These four principles made it possible to create the Internet as a network of networks spread throughout the USA and across the Atlantic. The protocol to interconnect computer networks was called the 'Transmission Control Protocol/Internet Protocol' (TCP/IP). It was invented by Robert Kahn of BBN and Vinton Cerf of Stanford University in 1983, borrowing ideas from the Cyclades network designed by Louis Pouzin in France. This quickly became the most widely used network protocol in the world and led to the development of many networks supported

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by ARPA as well as those in other parts of the world. TCP/IP is a two-layered protocol. Given a message to be sent to a computer B from computer A, TCP disassembles the message from A into small 'data packets' called datagrams that are then transmitted over the network to be reassembled by B's TCP into the message's original form. TCP also ensures the recovery of lost packets and the reordering of packets received out of order. IP is a unique address assigned to each computer (or device) connected to the Internet. As a datagram travels from one device to the next, IP address of the destination is checked by every device in the network which ensures that the datagram reaches the correct destination address. TCP/IP protocol ensures error-free transmission of messages between computers connected to the Internet. Each request for transmitting a message is new and unrelated to all previous requests. This allows the paths in the network to be used continuously [4].

In 1990, the ARPANET was transferred to the National Science Foundation of the USA and named the NSFNET. A Computer Science Network (CSNET) connecting universities in North America had also been formed. The NSFNET was connected to the CSNET. A network called EUnet connected research facilities in Europe. The North American net was connected to EUnet making it a large international network allowing collaboration among scientists across the Atlantic.

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The groundwork was thus completed to create the Internet as a worldwide communication infrastructure for computers to communicate with one another. In due course, all the computer networks in countries all over the world were connected using the TCP/IP protocol. Once the infrastructure was in place many applications could be built over this infrastructure.

The major issues of management of such a worldwide infrastructure and commercial use of the infrastructure that was primarily built for academic use remained. Those have been resolved to a reasonable extent and now the Internet is a stable, well managed, infrastructure.

Internet is a breakthrough in ICT due to the following reasons:

- The idea of transforming a worldwide telephone network that carried continuous audio signals between people using circuit switching, to one that carries digital signals between computers using packet switching, is novel.
- The idea of the TCP/IP protocol that allows orderly communication among computers using different operating systems connected to diverse networks is novel.
- This Internet spawned many other breakthroughs including the World Wide Web, search engines, and cloud computing that we will discuss in what follows.
- The Internet is an infrastructure that has completely changed the way computers are used. In addition to data processing, it is now used as a communication system to send and receive mail, make video calls, search for information, buy items from e-shops, and a myriad of other applications. It has now become as vital to our daily life as electricity and tapped water.
- Applications built on the Internet infrastructure have brought in societal changes in the form of social networks.Politicians and celebrities, among many, use tweets to communicate their ideas. Facebook has enriched the nature of social interactions. Blogs allow people to disseminate their ideas quickly and widely.
- The Internet has tremendously increased our efficiency by enabling quick communication, searching for information, and getting advice from experts on various issues.
- A number of new industries have emerged due to the availability of the Internet. E-commerce platforms such as Flipkart, search engine companies such as Google, cloud computing companies such as Amazon Web Services, software as a service companies such as Salesforce, social networking companies such as Facebook, and companies such as Dropbox providing cloud storage owe their existence to the Internet.
- Internet of Things (IoT) is an emerging technology that would connect, using the Internet infrastructure, all the gadgets we use

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and enable us to control them from anywhere at any time. This will be a big new industry.

8. Global Positioning Systen (GPS)

Throughout human history, navigation has been an important activity. In the early days, the position of the stars was used to approximately detect one's location and this was used by sailors. The emergence of a compass that depended on the Earth's magnetic field was an important breakthrough in navigation. The next technology that was used for navigation emerged with the invention of wireless transmission over long distances by Marconi 1901 [2] Low-frequency radio beacons transmitted by fixed land-based stations were used by ships during the 1970s and 80s to navigate employing a system called Loran-C. The biggest breakthrough that occurred in the twentieth century was the launch of the first artificial satellite, Sputnik, by the Soviet Union in 1957. It was soon realised that time signals sent from satellites could be used to determine the position of an object anywhere in the world accurately within a few metres. This was of great strategic importance to defence during the cold war between the USA and the Soviet Union.

[2] Sir J C Bose invented the mercury coherer (together with the telephone receiver) used by Marconi.

A meeting of the heads of the armed forces of the USA was held in 1973 when the first concrete steps were taken to create a satellite-based global navigation system. The system to be developed was called NAVSTAR (Navigation Satellite Timing and Ranging) Global Positioning System (GPS). The system was planned to have a constellation of 24 satellites of which the first was launched in 1974. As in all breakthroughs we describe in this article, the fruition of the idea of using satellites to detect the position of an object anywhere on the earth's surface, that was conceptualised in 1973, became operational with the launch of all 24 satellites (and 3 spare satellites to substitute if one or more satellite failed) in 1995 [6].

Originally GPS was intended only for the use of the defence forces of the USA. When a civilian Korean Airlines plane strayed into the Soviet airspace in 1983, due to poor navigation instruments, and was shot down by the Soviet Union leading to the death of 269 innocent people, President Reagan of the USA decided to allow GPS to be used by anyone in the world free of charge.

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ments, and was shot down by the Soviet Union leading to the death of 269 innocent people, President Reagan of the USA decided to allow GPS to be used by anyone in the world free of charge. The positional accuracy for civilian use was reduced to about 100 metres initially. This restriction was removed by President Clinton in 2000, and a positional accuracy of around 5 metres was made available to the public. Even though GPS is freely available now for all to use, it is controlled by the U.S. Department of Defence [7].

Many countries are not comfortable with this situation as the US government can unilaterally blackout GPS in any part of the world if it desires, and it has done so in the past. Many countries have therefore developed their own systems for use in their countries and the surrounding regions. Russia has a global navigation system called GLONASS that has 24 satellites in orbit with 3 spares and covers the whole world. The European Union has a system called Galileo. Indian Space Research Organization (ISRO) has developed its own system IRNSS (Indian Regional Navigation Satellite System) that has 7 satellites in geosynchronous orbit. IRNSS can provide positional information for the whole of India and the surrounding areas to an accuracy of 20 metres for the public. China has a system called BeiDou. Japan and France are also developing their own systems. GPS development cost is extremely high and no private institution would have taken up the project. It was undertaken by the USA mainly for its defence. Fortunately, the cold war ended and it has now become a boon for all.

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The main idea behind GPS is to use the signals transmitted by satellites. These signals specify the time and position of the satellite when it transmitted a signal. When a receiver on Earth detects this signal, it knows how far it is from the satellite, as electromagnetic signals from the satellite travel at the speed of light. Signals from at least four different satellites are required to detect the position, namely latitude, longitude, and altitude of the receiver using triangulation. Altitude data is required by aircraft. In order that at least four satellites are visible from anywhere on

A GPS receiver fitted to a car or a truck to find its position costs around rupees 5000. Apps are available on mobile phones at no cost or a few hundred rupees depending on the features of the app to detect the position of the mobile phone using GPS.

Earth, a constellation of 24 satellites is required. These satellites are placed in six different orbits that are tightly controlled. These orbits are in planes inclined at around 55 degrees to the equatorial plane. Each orbit has four satellites. This disposition of satellites ensures that a receiver at any place in the globe will be able to receive signals from between 5–8 of these satellites. Three more satellites were launched to ensure that in case one or more satellites fail, at least 24 operational satellites are available. GPS receivers on the ground are inexpensive. A GPS receiver fitted to a car or a truck to find its position costs around rupees 5000. Apps are available on mobile phones at no cost or a few hundred rupees depending on the features of the app to detect the position of the mobile phone using GPS. This position information is shown on maps provided by companies such as Google to find out the street address of the location of a mobile phone or that of a car fitted with a receiver. In fact, some of the recent apps in mobile phones have a voice guidance system that tells the driver the route from a location A to a location B while he/she drives the car.

GPS is a breakthrough in ICT due to the following reasons:

- The idea of using timing signals from satellites to accurately find the position and altitude of objects anywhere on Earth is novel.
- Even though GPS was developed at very high costs for defence purposes by various governments, its release for civilian use has led to many useful applications and innovations.

GPS is of great assistance to navigate ships, sailing boats, and aircraft. Coupled with weather maps, ships/sailing boats/aircraft can avoid areas where there are storms brewing. Fishing boats can avoid straying into the territorial waters of other countries.

- Navigation that is vital for travel by road, sea or air, has become very simple after the advent of GPS as accurate location and altitude information is given by the system. Nowadays when one travels by road, a smartphone is used to find the location of the vehicle using the signals emanating from GPS satellites. Apps are available in smartphones to guide a person to travel to any given destination.
- GPS is of great assistance to navigate ships, sailing boats, and aircraft. Coupled with weather maps, ships/sailing boats/aircraft can avoid areas where there are storms brewing. Fishing boats can avoid straying into the territorial waters of other countries.

- A new industry that designs, manufactures, and markets inexpensive computer-based devices that could be mounted on a motor vehicle that assist the driver with oral commands to travel to a specified destination has emerged due to the availability of GPS.
- The low cost of GPS-based systems has enabled local transport companies to track buses/trains and give accurate information to commuters about the current schedules real-time status allowing them to plan their trips. Large truck-operating companies track their trucks using GPS and optimise their movement.
- New cab hailing mobile apps that depend on GPS have disrupted the old local taxi services. The emergence of companies such as Uber, Lyft, and Ola has made commuting in cities convenient and cost-effective. A despatching program that uses GPS has the location of taxis and customers at all times. It allows optimal despatch of taxis, saving fuel for the taxis and the waiting time of customers.
- The new emerging industry of driverless cars depends on GPS besides light imaging, detection, and ranging (LIDAR) system.

9. World Wide Web

Vannevar Bush conceptualised in 1945 the idea that the information stored in the repositories of individuals and organizations, usually as typewritten, handwritten or printed documents, if made available to everyone in an easily accessible form, will enhance the knowledge base of all. He wrote an article titled 'As We May Think' in the Atlantic Monthly expressing this idea. Digital technology was not available then. He proposed an electromechanical device called MEMEX that would use documents photographed in microfilms, indexed, connected via a network of 'links' and 'associative trails'. This article foresaw the idea of hypertext to link documents and using the links to search and retrieve relevant documents.

The next big step was taken by Doug Engelbart in 1960 by inventing the computer mouse as a tool to point at a desired object displayed on a video screen. He showed how it could be used to edit documents. Soon it became an indispensable part of desktop

Doug Engelbart gave a presentation in 1968, now legendary (available on YouTube), in which he demonstrated the use of a mouse to navigate documents displayed on a video screen. He also demonstrated in that presentation, teleconferencing, word processing, file creation, file maintenance, hypertext, hypermedia, and collaborative real-time editing of documents.

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Berners-Lee noticed that even though CERN was an international laboratory with a large number of scientists who were expected to collaborate, their research reports were stored in their own computers and it was not easy for other scientists to access these reports in spite of their computers being networked. He got the idea that he could enable the sharing of files among scientists at CERN and also with other scientists working elsewhere in the world as the Internet connected all computers and allowed easy communication between them.

Tim Berners-Lee, a graduate from Oxford University joined CERN, the large particle physics laboratory near Geneva, Switzerland, in 1980 for a few months as a contract employee during which he built a prototype system named ENQUIRE to share and update the reports written by scientists in CERN. He came back to CERN as a programmer in 1989. By this time, networking and Internet were ripe for implementing novel applications. Berners-Lee noticed that even though CERN was an international laboratory with a large number of scientists who were expected to collaborate, their research reports were stored in their own computers and it was not easy for other scientists to access these reports in spite of their computers being networked. He got the idea that he could enable the sharing of files among scientists at CERN and also with other scientists working elsewhere in the world as the Internet connected all computers and allowed easy communication between them. He wrote a proposal titled '*Information Management: A Proposal*' that outlined his idea of structuring documents with embedded links that would point to other related documents that may be located in any connected computer. The proposal was not initially accepted by his manager Mike Sendall but he changed his mind in October 1990 and allowed Berners-Lee to proceed with the project using a desktop computer NeXT that had been recently bought and networked with other comput-

ers. NeXT had many good features to aid in the development of the software. In order to link the documents stored in different computers, Berners-Lee realised that the documents must have symbols added to them which assign special meanings to the documents. These symbols are called 'markups'. He suggested that documents be written using a special language called the 'Hypertext Markup Language', abbreviated HTML. HTML describes the structure and contents of a document and how it is to be linked to other documents. The links are important as they allow traversing from a document to all related documents. HTML has gradually become the basis for the creation of a web of documents.

These innovations that describe what a document contains, how it is related to other documents, where these documents are stored, and how to access them, laid the groundwork for the World Wide Web.

The next important innovation was to design a protocol that would allow a computer to retrieve related documents from another computer connected to it. This was called the 'Hypertext Transfer Protocol (HTTP). This protocol is used to access HTML pages. The third important step was to assign a unique address specifying the computer where the required document resides. This was originally called Universal Resource Indicator by Berners-Lee and is now called 'Universal Resource Locator' (URL). (The Internet already had a 'Domain Name System' (DNS) that responded with the IP address of the server that hosted the website which facilitated assigning a URL). These innovations that describe what a document contains, how it is related to other documents, where these documents are stored, and how to access them, laid the groundwork for the World Wide Web. This basic idea and the relevant software were essential but not sufficient to allow easy retrieval of documents scattered in computers all over the world connected by the Internet. A crucial step was needed to easily navigate the web of documents. Even though a rudimentary navigation software to explore the web was developed by the team at CERN in 1991, it was not easy to use. A software called 'Hypertext Browser' was developed by Marc Andreessen and his team of programmers at the National Centre for Supercomputing Applications at the University of Illinois USA. It was called the 'Mosaic browser' and was launched in 1993. Using

A crucial step was needed to easily navigate the web of documents. A software called 'Hypertext Browser' was developed by Marc Andreessen and his team of programmers at the National Centre for Supercomputing Applications at the University of Illinois USA. It was called the 'Mosaic browser' and was launched in 1993. It allowed easy navigation of the web.

this browser one can retrieve, for example, a document by typing in the address bar, the URL of the document that has the format: `http://www.xcollege.ac.in/admission-rules.html`, where `http` stands for hypertext transfer protocol, `://` link, `www.xcollege.ac.in`, the address of the server of the college where the document is stored, followed by the path to the desired document, namely, admission-rules, which is in HTML format. The World Wide Web became usable with the availability of Mosaic browser as it had an intuitive user interface and could display graphics. Since then many browsers, such as Netscape, Internet Explorer, Firefox, Opera, Safari, and Chrome were developed. Nowadays, a browser is an essential software in any computer, and many free, feature-rich, browsers are available [8, 9].

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Tim Berners-Lee was far-sighted and wanted the World Wide Web technology to spread widely and be used extensively. In order to achieve this, certain principles were enunciated by him and his team.

(i) The web technology was made non-exclusive and available to anyone.

(ii) No central authority controlled it.

(iii) The web was designed to be non-discriminatory, that is, no one was given preference and better quality of service on payment.

A World Wide Web Consortium (abbreviated W3C) was formed as the main international standards organization for the World Wide Web under the leadership of Tim Berners-Lee. Besides standardisation, W3C conducts training programmes, develops software, and coordinates an open forum for discussions about the web and its future.

These principles pioneered the philosophy of 'open source' and 'open access' to allow many interested and qualified people to contribute towards the improvement of the World Wide Web. A World Wide Web Consortium (abbreviated W3C) was formed as the main international standards organization for the World Wide Web under the leadership of Tim Berners-Lee. Besides standardisation, W3C conducts training programmes, develops software, and coordinates an open forum for discussions about the web and its future.

The World Wide Web technology is a breakthrough in ICT due to the following reasons:

- The idea of organizing documents using a hypertext markup language that enables the linking of these documents stored in interconnected computers across the world is novel.
- The World Wide Web enabled the underlying Internet infrastructure to be useful to the public by allowing anyone to easily access billions of documents stored in computers spread all over the world.
- It made it essential for every organization and even individual to have a 'web presence' in order to be noticed. Every organization now creates a website giving details about it and places it in a publicly available web server, and updates it frequently.
- Many useful documents such as government rules and regulations, judgements delivered by courts, telephone directories, and stock prices are now available on the web.
- Website designing and maintenance has emerged as a new profession. Today a number of companies all over the world employ millions of persons to design websites for large corporations as well as individuals.
- Entirely new mode of commerce (e-commerce) has developed by allowing companies to create websites with a catalogue of items with prices that customers can search and order from anywhere in the world.

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In the next concluding part of this series, I describe search engines, digitization and compression, mobile computers, cloud computing, and deep learning.

Suggested Reading

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