The Magic Inside Your Cell Phone and Its Broad Societal Impact[1]

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It is a pleasure to be here with all of you today. I must note that in my normal introduction, I suggest that the audience turn on their cell phones, since it's much better for our business, but please do follow the local instructions.

The preceding talks have been most interesting. I was especially taken with the "Future of the Professions" talk by Richard and Daniel Susskind on artificial intelligence (AI) and, in particular, with the question of whether artificial intelligence is capable of proposing an innovative idea at a level similar to or surpassing human intelligence. Recalling the first time I thought of using code division multiple access (CDMA) technology for mobile communications, I have wondered whether a properly trained deep learning network might propose such a solution. I believe that at some time in the future the answer will be yes, and might include consideration of the advantages, risks, costs, time to market, and potential competition—the entire range of aspects that enter into a business decision. Indeed, a deep learning study might now be under way, with training based on entering many business cases together with the personal backgrounds of the innovators.

On that note, I will touch on my own personal history. As an undergraduate at Cornell University, I experienced early technical magic as part of my senior thesis project, leading a group of students to build an operating digital differential analyzer, a digital version of an analog computer. The components we used were from an IBM 650 computer, state-of-the-art in 1956. The digital memory stored approximately 20 kilobytes on a physically large magnetic drum, spinning at high speed and using many magnetic heads to read and write data at a useful rate. The logic unit employed a vacuum tube to implement just two logic elements, requiring considerable power and space.

1 This paper, presented as the Herman Heine Goldstine Lecture, was read 28 April 2017.

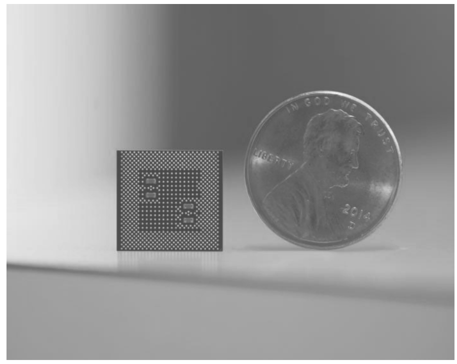

FIGURE 1. Integrated circuit (IC) chip with over 1 billion gates. Photo courtesy of Qualcomm.

It's interesting to view what has been achieved in the interim, enabling today's magic in our cell phones. Rather than 20 kilobytes, a flash drive, like the one I used to transfer this presentation, can store 256 gigabytes (256 billion bytes) at a cost of about $40, several orders of magnitude below that of the drum, while delivering much greater reliability. Rather than two logic elements per component, implemented using one vacuum tube, we now achieve over 1 billion logic elements per IC (Figure 1) implemented using over 6 billion transistors. Clearly, the technology we have available has improved dramatically, and it has been great fun over the years anticipating and exploiting new capabilities.

When I entered the Massachusetts Institute of Technology (MIT) in 1956, I was uncertain which area to pursue for graduate work. Luckily for my choice of future career, Claude Shannon joined the MIT faculty that year, inspiring many in electrical engineering to think more deeply about information theory. Interestingly, as a graduate student, he had worked on Vannevar Bush's analog differential analyzer and, in an outstanding master's thesis, proved that binary logic elements, as implemented in the IC, could solve all problems expressed through Boolean algebra. Claude was also well-known for building mechanical games, including the electromechanical, maze-solving mouse (Figure 2), an early artificial intelligence device. It was always motivating to bring students to his home to play with his many creative toys.

Claude is best known for work done at Bell Labs during World War II on channel capacity and information coding. He began research on cryptography and then moved to quantifying how much information could accurately be sent over a noisy channel. This fundamental work was published in 1948 in the *Bell System Technical Journal* as "A Mathematical Theory of Communication." He proved that there is a

FIGURE 2. Claude Shannon and his electromechanical, maze-solving mouse. Reused with permission of Nokia Corporation.

maximum, the channel capacity, to the number of information bits that can be accurately sent over a noisy channel and derived the formula for one class of channels based on its signal-to-noise ratio and bandwidth. He also demonstrated that, with the proper design of signals and coding, one could come arbitrarily close to achieving channel capacity (Shannon 1948; Soni and Goodman 2017).

After completing a doctoral thesis on the reliability of networks with noisy components, I joined the Department of Electrical Engineering faculty at MIT in 1959 and had the opportunity, with another faculty member, Jack Wozencraft, to teach a senior-level communications course. Rather than treating information theory as applied mathematics, we chose to show that, based on information theory, digital communications would be an increasingly effective choice in the future. We published the textbook *Principles of Communication Engineering* in 1965. It is interesting that one of the more advanced homework problems that I included in the book involves a signal constellation

that is today being used in the latest generation of cell phones for Internet access.

In 1964–65, on leave from MIT for a nine-month research fellowship at NASA's Jet Propulsion Laboratory, my wife Joan and I found we greatly enjoyed California. After returning to MIT, I received an invitation to teach at the then-new University of California, San Diego (UCSD). After some hesitation, Joan and I made the difficult decision to move the family to San Diego. On arrival and due to the recent publication of the book, I received many requests for consulting, more than I could handle on a one-day-a-week basis. I mentioned this to some friends from the University of California, Los Angeles (UCLA) faculty and they suggested we start a company and share the consulting. That was the start of my first company, Linkabit. Everybody laughed when they heard that name, but it began to grow rapidly. We quickly moved from consulting to developing products, and I decided I needed to take a year's leave to get things better organized. I did that. And I found developing products was so much fun that, at the end of the year, I chose to become a university dropout. I did rationalize the decision by noting that I had defended teaching theory for many years by claiming that it would be applicable to the real world. Now I had a chance to prove it.

We developed a number of interesting products at Linkabit, and several were pertinent to CDMA and cell phones. One, the Atlantic Packet Satellite Network, was an early contract won from the Advanced Research Projects Agency (ARPA), now the Defense Advanced Research Projects Agency (DARPA), to extend the Advanced Research Projects Agency Network (ARPANET) to Europe by using satellite. ARPA also was supporting a packet radio program in the United States, a predecessor to the present use of cell phones to transmit data. In 1977, DARPA suggested that the three networks be joined to test a new algorithm, the Internet Protocol (IP). We did send packets successfully around these three dissimilar networks using that protocol. Although we didn't think of the demonstration as special at the time, the Computer History Museum brought us together in 2007 for a 30th anniversary celebration of the first use of the Internet Protocol.

Linkabit also won a contract from the US Air Force to build a satellite terminal, the Dual Modem (Figure 3), initially for aircraft but later used by all the armed services. Until that time, terminals had been built using specialized hardware for each function, increasing size, power requirements, and cost. We thought perhaps we could do everything in software. One problem was that a central processing unit (CPU) on a single IC did not exist at the time. We assembled our own CPU from

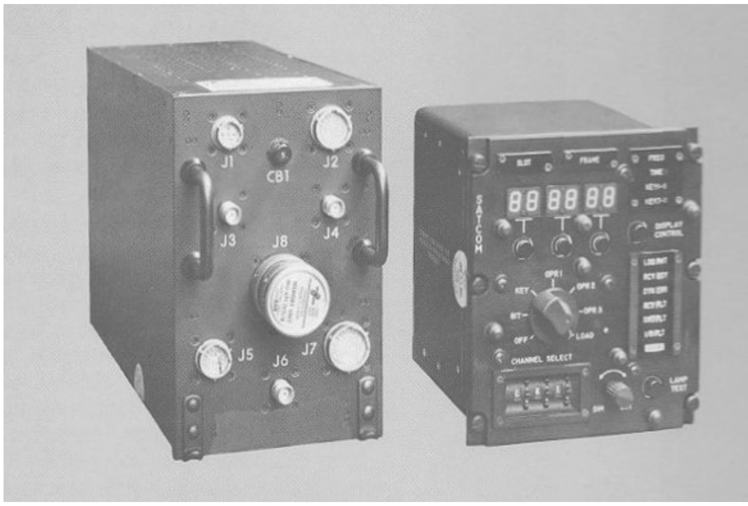

FIGURE 3. Image of the Dual Modem satellite terminal. Photo courtesy of the author.

various functions then available separately on chips. To reduce the cost of components and memory, we designed the computer using just 32 simple instructions. Interestingly, CPUs using a small number of simple instructions were introduced at the University of California, Berkeley and Stanford University in the 1980s, and named RISC for Reduced Instruction Set Computer. RISC is now the only technology used for CPUs in cell phones and is part of the magic. The Dual Modem project was also our introduction to spread spectrum, later the basis of CDMA in cell phones, since one of the required satellite modes involved frequency hopping. The military used frequency hopping to distinguish users, avoid jamming, and to make position location very difficult.

Another pertinent Linkabit project was VideoCipher, a scrambling system for transmitting television from satellite to home, initially developed for HBO. Here, we encountered our first political problem. Initially the link to be scrambled was from satellite to a cable head and could be a professional-size unit, maintained by trained technicians. But a home satellite user group appealed to Congress, arguing that a descrambler had to be available for home use so their dishes would remain useful. To satisfy this requirement, we needed to build an inexpensive, reliable, and relatively small unit. The only way to do so was to convert what had been many digital logic components to three ICs, including an encryption engine. Until that time, commercial ICs were being designed by hand with each IC mask cut out of Rubylith film, a very slow process. But Carver Mead at the California Institute of

Technology, and others at MIT and elsewhere, had been working on computer-based IC design and testing. A little earlier, I had one of our engineers, Klein Gilhousen, go up and spend a term with Carver to understand the process. We then obtained IC software from three universities and were working on stitching it together with our own software to try a design "homework" problem or two when suddenly we had to make three commercial IC chips for the home VideoCipher. Amazingly, all three chips worked the first time, resulting in a very successful product, manufactured at a plant we set up in Puerto Rico. And so that was our first exposure to the tremendous power of using the computer to design and test integrated circuits.

We sold Linkabit in 1980, and I retired in 1985. After three months, my wife and I decided that retirement wasn't such a good idea and, with six others who had worked with me at Linkabit, started a new company called Qualcomm. We did so with no business plan or product ideas, but did believe that wireless and digital would be interesting and hoped that we would come up with some good ideas. I told Joan that we couldn't possibly duplicate the success we had at Linkabit and might build up to 100 employees. Shortly after starting, while returning from Los Angeles where we were consulting on a mobile communications satellite program for Hughes Aircraft, I suddenly realized that perhaps CDMA might be a better solution for mobile communications. I won't get into too many of the details, but traditionally time division multiple access (TDMA) or frequency division multiple access (FDMA) is used to provide multiple users noninterfering access to a block of radio spectrum. We then did enough work to confirm that CDMA might have capacity to support many more users in a given spectrum. Unfortunately, as a fairly new company, we didn't have the resources at that time to pursue CDMA.

We instead decided to complete work on another product, OmniTRACS, designed to provide two-way satellite communications and vehicle location for the trucking industry. Since the system operated through existing satellite transponders normally used for satellite TV and for business communications via VSAT (very small aperture terminal; first developed at Linkabit), we required powerful spread spectrum to avoid interference with those primary licensed services. This technology did help us prepare for cellular CDMA. We later learned that the first patent on the frequency hopping version of spread spectrum had been awarded to Hedy Lamarr, an actress many of you may remember. She was famous for her beauty and perhaps for the first nude scene in a movie. However, during the buildup to World War II, while working with a friend who was a pianist, she thought about jumping among the different keys on the piano and came up with the

idea of frequency hopping. If an enemy listener didn't know which key you were going to jump to ahead of time, you would have an advantage of spreading their intercept over a large frequency band. Unfortunately for her, the military immediately classified the patent and she never received any compensation for the invention.

Qualcomm completed development of this equipment and signed its first contract with the then-largest long haul truck operator, Schneider National, in October 1988. Company efforts were immediately redirected to possible use of CDMA for cellular. There were a few problems. The first generation (1G) of cellular used FM radio, which was analog, and there were doubts about growth because the original phones were huge and required a car trunk or a strong arm to carry them around. Both phones and airtime were expensive. AT&T, whose research arm Bell Labs had invented the cell phone, chose not to enter the business at that time following a projection by McKinsey that there would only be nine hundred thousand subscribers by the year 2000. The actual number was 109 million. By the mid-1980s, the industry realized that indeed there would be a rapidly growing number of subscribers, and to accommodate them a second generation (2G) of cellular, based on digital, was required. Digital promised higher quality and higher capacity—that is, more subscribers per antenna in a given amount of radio spectrum. The industry considered time division (TDMA), frequency division (FDMA), and code division (CDMA) multiple access, but dropped consideration of CDMA early because it was thought to be too complicated with many difficult problems. There was also belief that CDMA did not have a capacity advantage. After a bitter fight between supporters of TDMA and FDMA, a vote in the United States in January 1989 selected TDMA. Following selection of a different variant of TDMA for GSM (global system for mobile) in Europe, companies worldwide mobilized to standardize, develop, and launch TDMA cellular networks.

Following Qualcomm's October 1988 redirection to CDMA, by March 1989 we had enough confidence in having solved known CDMA problems that we knew we ought to inform the industry that, even after the TDMA vote, another possibility was promising and offered higher capacity. During a June 1989 presentation to the industry, I thought somebody might raise their hand and say, "Here is a problem you missed." No one did so. But, based only on viewing slides, nobody was fully convinced either. We had no choice but to work very rapidly over the next few months to develop demonstration hardware to convince the industry that CDMA was viable and would provide significant capacity gains. The first base station and "mobile" phone are shown on the left in Figure 4, but the phone required a van to drive

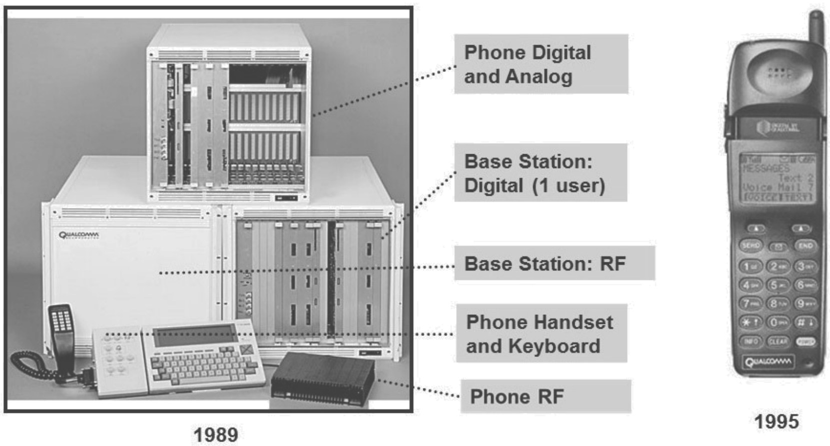

FIGURE 4. Images of the 1989 demo system "mobile" phone with two base stations and the 1995 first commercial phone with dual 1G and 2G modes. RF = radio frequency. Photos courtesy of Qualcomm.

it around. The industry came to San Diego in November to view the demonstration, and, after an undisclosed hiccup that almost sunk the company at the very beginning due to a problem with a Global Positioning System (GPS) satellite receiver, we had a very successful demonstration. The demonstration was then moved to Midtown Manhattan and repeated.

At that point, a number of cellular carriers became very interested, since the capacity increase from first generation to second generation was at best a factor of 3 using TDMA, whereas for CDMA the factor was 10–20 and perhaps even higher (now about 50). With such a potential economic advantage, several carriers offered to support us in raising the additional resources required to shrink the demonstration phone to commercial size and cost. The carriers helped convince a number of manufacturers to work with us. We developed a then-novel business case in which the manufacturer would take a license that included an up-front fee to support the development effort and a small per phone royalty, should CDMA ever be successful. This funding supported the development of three ICs for the phone and three for the base station, aided of course by commercial computer IC design and test software developed in the years since VideoCipher. Two years later, in November 1991, we invited the industry back to try commercial-size CDMA phones. The industry was sufficiently excited and recommended that a CDMA standard be developed in addition to the TDMA standard.

Although standards normally take several years, we completed the process in 16 months, based on the substantial testing already carried out to convince industry skeptics. The approved standard allowed us to market CDMA equipment internationally.

The first CDMA cellular network was launched in Hong Kong in November 1995, just seven years after Qualcomm resumed its focus on CDMA. You might rightfully ask, "Why Hong Kong?" Well, at that time, most business people in Hong Kong didn't have offices but carried out business in the streets with their cell phones. Spectrum was very congested, and CDMA provided the needed higher capacity. The next two systems to open were in South Korea. You might again ask, "Why South Korea?" South Korea had for several years been trying to build up their industrial base to compete with Japan in consumer products. But they were always a couple years behind Japan and therefore had to compete on cost. So the selling point was: Japan is going with TDMA, and if you go with CDMA, there is an opportunity to leapfrog the Japanese manufacturers.

At that time, neither Samsung nor LG had any significant cellular business. And so, it was an interesting argument. They did go ahead, and we opened the next two networks in South Korea. I should note that until that point we had been unable to convince anybody to manufacture CDMA phones because they were unsure there would ever be a sufficient market. Based on its prototype, Qualcomm developed its first commercial phone (shown on the right in Figure 4) and set up manufacturing in San Diego. And so the first phones used in Hong Kong were manufactured in San Diego. The next phones used in South Korea were also manufactured in San Diego, as were the early phones in the United States.

Well, the entry of CDMA started major competitive wars. Companies and many operators had made large investments in TDMA. In Europe, the governments had signed a memorandum of understanding to only use GSM, a form of TDMA, and were at that time not open to any other technology. Intense competition for second generation cellular spread around the world, and, with a time lead and government support, GSM built a significant lead.

And the battle did occasionally get a bit nasty. There was a front page story in the *Wall Street Journal* that asked whether my claims about the advantages of CDMA were "hope or hype" (Hardy 1996). A Stanford professor was quoted as saying that we had fundamental technical problems we didn't know how to solve. Elsewhere, another Stanford professor said that we "violated the laws of physics." Now whenever I give a talk at Stanford, I point out that CDMA works everywhere in the world, except within a five-mile radius of Stanford.

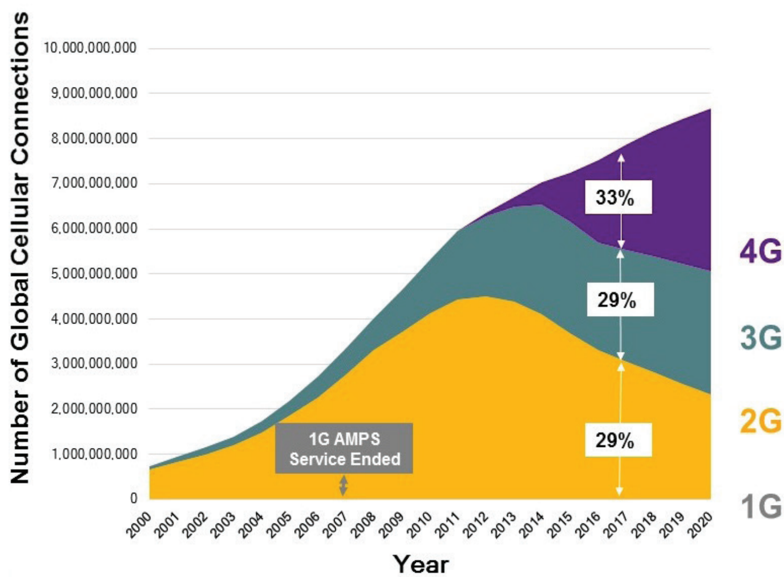

FIGURE 5. Number of global cellular connections per year across four generations (1G, 2G, 3G, and 4G), each generation supporting increased data bandwidth and more frequency bands. AMPS = advanced mobile phone system. Data from GSMA Intelligence.

While the second generation war continued through the 1990s, the global cellular industry was recognizing that, in addition to voice, an efficient mobile connection to the Internet was essential. Many studies were conducted worldwide, and a third generation (3G) standard was undertaken by the International Telecommunication Union (ITU). After considerable research activity and sparring among companies, a general agreement was reached that CDMA would be the basic technology for the third generation, albeit with three flavors, CDMA2000, WCDMA (wideband code division multiple access), and TD-SCDMA (time division synchronous code division multiple access). For CDMA, the war had come to an end and mobile access to the Internet became pervasive and increasingly dominant over fixed access in developing countries. A decade later, Long-Term Evolution (LTE) was introduced as a fourth generation (4G) to provide even higher peak data rates and efficiency. LTE is based on orthogonal frequency division multiple access (OFDMA) technology. Figure 5 shows the long transition times for each generation. The first generation lasted from the early 1980s to about 2007 when the last 1G networks were turned off. The 2G, 3G, and 4G networks all remain in use, each with a lifetime of about three decades, as older phones find homes in developing countries. Part of the magic in your phone is the ability to automatically select a frequency

band and technology and operate with multiple generations as you roam to different markets.

Around the same time as the first generation was being turned off in 2007, Steve Jobs introduced the iPhone. The iPhone provided an elegant solution for the user interface, allowing different applications to be selected intuitively on a large multi-touch screen. Prior to the iPhone, when describing broad new capabilities being added to the cell phone, I would often be interrupted by people saying they did not know how to use existing capabilities, even simple voice ones. I recall, around 2000, saying that we would be adding a camera to the phone and hearing the response, "Why would I ever want a camera on my phone?" Ever since Jobs came up with this very friendly user interface, we have been adding more and more capabilities to an increasingly smart phone.

What enables us to add all of these capabilities, including communications, computing, position location, camera, camcorder, games, and sensors, and do so in a compact form at a reasonable cost and running on a battery? This magic is achieved through exploiting Moore's Law. An interesting aside—as I was thumbing through the tables of books for sale outside the auditorium, I came across a book titled *Understanding Moore's Law: Four Decades of Innovation*, edited by David Brock. It reprinted Gordon Moore's original manuscript, and the last figure in the manuscript is Moore's prediction in 1965 of how the number of transistors that can be fabricated on a single IC would double every year from 1959 to 1975, reaching 64,000 (Moore was a co-founder of Intel). Moore was optimistic on the time required to double, in that, on average, doubling has required two years.

Truly amazingly, however, the doubling has continued every two years through 2017, reaching about 6 billion transistors per IC, and is predicted to have two more generations to run with existing technology. Exponential growth is pretty astounding, recalling the fable of the payoff the inventor of chess requested of the ruler of India, which involved doubling the number of grains of rice on each square of a chessboard requiring 2^63 or 8 billion billion grains. He was killed. However, the impact of the doubling of the number of transistors per IC has broad implications to economies and governments. When CDMA was finally accepted in China in 2001, I met with President Jiang Zemin. His first question to me was how many more generations did I think Moore's Law had to run. I suspect he was thinking about the future of the semiconductor business in China.

Moore's Law has provided even more than repeated doublings. Each doubling has come with a free lunch in that not only does it provide more transistors, but also transistors with higher speed,

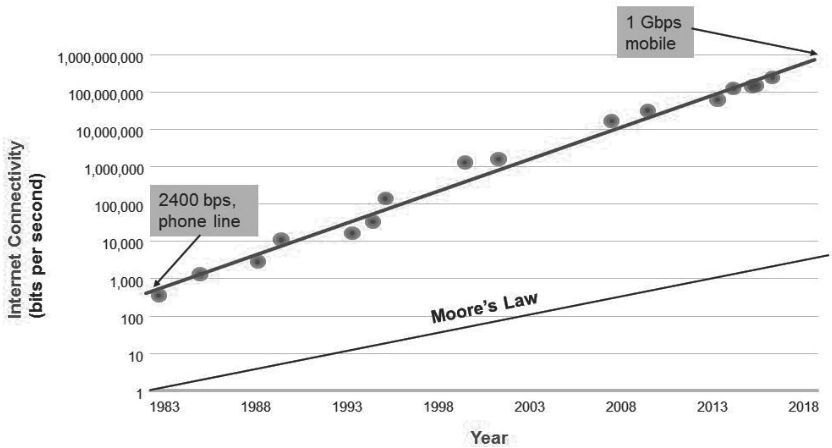

FIGURE 6. Highest data rate available for general Internet access. Data from Nielsen Norman Group.

requiring less power, and with lower cost—until recently. Among all the other capabilities we now include in smartphones, faster transistors and more complex circuitry enable higher and higher data rates for mobile access to the Internet. Prior to wireless access, when you traveled, you carried a set of tools to connect your modem to a phone line, supporting a data rate of 2,400 bps (bits per second), which slowly grew to 9,600 bps and 64 kbps (thousand bits per second). Today, new mobile phones are capable of 1 Gbps (billion bits per second), more than competitive with landlines (Figure 6). The mobile devices benefit from the use of multiple internal antennas and exploit Moore's Law to do the additional computing to be able to closely approach Claude Shannon's capacity limitation.

As an example, the latest Qualcomm IC is a system on a chip with over 3 billion transistors. The variety of functions implemented on the chip is shown in Figure 7. This generation of technology has line widths of 10 nanometers. In comparison, the diameter of a DNA molecule is about 2.5 nanometers, so we're getting down to biological dimensions, and this technology path is reaching an end. Design is underway on 7 nanometers and beginning at 5 nanometers, providing over 6 billion and over 12 billion transistors, respectively. Two more generations raise all types of possibilities. Research and development groups are actively improving digital photography and ultra-high-definition TV and camcorders, improving screen graphics, enhancing security, and speeding and sharpening position location by observing not just the US

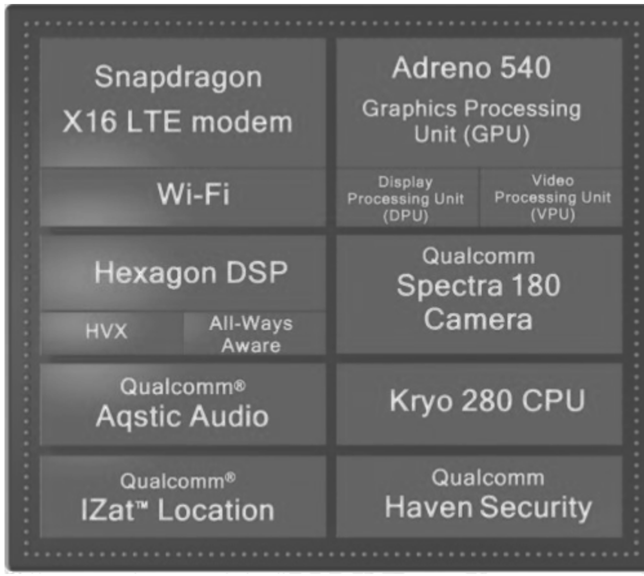

FIGURE 7. Functions implemented on Snapdragon 835 chip, the latest Qualcomm IC with over 3 billion transistors. Photo courtesy of Qualcomm.

GPS satellites, but also the Russian GLONASS, the Chinese BeiDou, and soon the European Galileo satellites.

New applications that are being greatly improved with the increased IC capability include augmented reality (AR), familiar from its use with sports TV to show, for example, scrimmage and first down lines in football. Another AR application becoming popular allows you to hold up your phone in a foreign city to read a sign transliterated to a Latin alphabet. One that I am anticipating as my memory weakens applies AR to recognize a face as I walk into a room, augmenting what I am seeing with name information and reminding me of further details. Well, shortly you won't have to hold up the phone to do that but will wear a pair of glasses that supports augmented reality using an internal cellular IC and includes a speaker to whisper in your ear—I can't wait.

Another application now in its infancy is virtual reality (VR) that immerses you in a virtual world in which you can look around and soon move around. The *Washington Post* published an article describing a use of VR by the Hirshhorn Museum in Washington, DC, to help people with certain disabilities virtually enter each of the rooms in the "Infinity Mirrors" exhibit by the Japanese artist Yayoi Kusama (Overly 2017). This proved to be a more practical approach than rebuilding the entrances to the rooms to allow access.

Now we are looking ahead to the fifth cellular generation (5G) that supports a broad range of uses often referred to as the Internet of Things, or IoT. Early on we had mobile e-book readers in which the text was delivered to the reader from a data center over the mobile network without humans being involved other than placing an order. Now, household appliances, energy meters, light bulbs, thermostats, security systems, first responder alerts, pet collars that trigger a text message if the pet wanders out of an electronically fenced area, transmission systems, wind and solar farms, and much more are being connected to the Internet. Increasingly, vehicle-to-vehicle (V2V), vehicle-to-pedestrian (V2P), and vehicle-to-environment (V2E) communications, together referred to as V2X, require very rapid response times to support autonomous driving and increased safety. A key goal of 5G is significant reduction of latency for certain communication modes.

A few APS Meetings back, we had a drone fly into the room under full human control as part of an examination of legal issues involving drones. Drones require reliable communications, position determination in three dimensions, navigation, video and camera capabilities, and processing and fusion of a variety of sensors, and in the future will require computing power to build up a world view of the drone environment with recognition of objects in view. The cell phone system-on-chip (SoC) handles all these functions expeditiously, including internal artificial intelligence capability, and so provides a good component to support an autonomous drone.

Observing that cell phone access was becoming almost ubiquitous and the cost of mobile devices was rapidly decreasing, several years ago Qualcomm initiated a number of social and economic development efforts through its Wireless Reach program, partnering with companies, nongovernmental organizations, foundations, and governments. An early project involved microfinance and, later, mobile money. Starting in Indonesia, funds were loaned to entrepreneurs, usually women, to buy a "business in a box" containing a cell phone, agreement with an operator to share air time revenue, tall antenna, battery and charger, and marketing information. The program was successful for the first few years but then many customers began buying their own cell phones. The participants did not want to lose their extra income, so working with the Grameen Foundation and others, we developed a number of applications that they could market, including applications to advertise and fill jobs, order and pay for goods, and provide support to establish and grow small family businesses.

In India, Senegal, and later Brazil, programs were started to support farmers and fishermen. Initially, working with the Indian National Council of Applied Economic Research, a Fisher Friend mobile

application was created to provide information via text or voice messages concerning weather and sea conditions, which fish were biting where, and, perhaps most importantly, which port and market within the port would pay the most for the fish caught, eliminating the middleman. For farmers, applications were developed to provide disease information and guidance on pesticides as well as pricing information.

Medical projects also continue to have high priority. In Peru and elsewhere, clinics were provided with equipment to support telemedicine. Equipment sophistication has grown, and, in Morocco, a portable ultrasound device connected by mobile communications with a diagnostician is used to provide care for pregnant women, allowing a response to be obtained quickly and at a low cost. An unexpected outcome was that a high percentage of women who had the ultrasound examinations decided, rather than giving birth at home, to give birth at a clinic—another significant health payoff.

For a project in Egypt, an on-site dermatologist uses a cell phone camera to send information and photographs to a specialist for diagnosis. For a recent project in Brazil, a Snapdragon-equipped drone utilizes onboard artificial intelligence to fly preprogrammed courses over fields, observing the crops at several regions of the radio spectrum, including ultraviolet and infrared, to analyze drought conditions, insect infestations, and other problems. The farmers are then able to focus on the parts of the fields that need attention and not apply a brute force approach of treating all of their fields.

An earlier project had its roots back in 2000 when I accompanied President Clinton on a "digital divide" tour to North Carolina. Using a prototype wireless broadband data system to access the Internet, Qualcomm demonstrated significant advantages for a small, rural manufacturer of on-premise, reliable, and rapid two-way communications with customers, suppliers, and industry consultants. Governor Hunt was present and noted that it was one thing to come and show the usefulness of an experiment, but that we needed to come back later to do something more permanent. And so, in 2007, with the high-speed service available commercially, we returned and provided smartphones—of course less capable than today's smartphones—to students in four different North Carolina high schools.

At the end of the first school year, I returned to review the results, recognizing that anytime you carry out an education experiment, students will always show some improvement if just from the attention. The results, however, were quite surprising. One participating teacher taught one class with phones and one class without phones. For the class with phones, 100% of the kids passed their Algebra I state

exam. For the class without phones, only two-thirds of the students passed. What was happening? In talking with students, two things were identified as having major impact. Most important was the capability to access the Internet 24-7. Students with phones noted that in the past, when they could not solve a homework problem and their parents could not help, they would wait until the next day. Now, they could go online, get help from other students, and continue with their homework. Another major impact resulted from students who came up with a clever solution or insight, made a video, and shared it around the net. The peer-to-peer aspect proved beneficial to both those teaching and those being taught.

Another aspect of the magic inside your phone is the large number of sensors. Included in many phones are temperature, altitude, humidity, and proximity sensors, a gyroscope, and fingerprint recognition allowing you to conveniently prove you are who you say you are. Several may be active even when the phone appears to be off, allowing certain stimuli, such as a voice instruction, to make the phone active, all while conserving battery energy. Phones also have external sensors that communicate with the phone by a low-power radio link. For example, for neuroscience activities, a small sensor can be placed on a subject's forehead to communicate electroencephalogram (EEG) measurements to the phone for analysis. Using its display, the phone is programmed to present a range of stimuli to the subject and to analyze his or her EEG response. An interesting application is early prediction of migraine headaches based on analyzing the response to a sequence of pictures flashed on the screen. Early results indicate a significant probability of predicting the onset of a migraine on the previous day.

Finally, I'll mention one example of continuing efforts to greatly expand the efficacy of the cell phone in supporting healthy living. In 2012, Qualcomm announced a $10 million XPRIZE competition to develop a compact set of sensors and diagnostics able to track five vital signs and diagnose 16 medical conditions, relaying the information to the cloud. The effort was inspired by the tricorder of *Star Trek* fame. About 300 teams entered the competition. The first and second prizes were recently awarded. The first-prize team included two brothers, one an emergency room doctor and one an engineer, who applied artificial intelligence to provide their diagnosis, training the AI with data from a large number of patients. Many of the teams, including the winners, continue their efforts to enhance sensors, develop diagnostics, and improve algorithms within the ever more powerful cell phone to better approach the "tricorder." The magic within the cell phone will continue to drive powerful telemedicine.

Thank you very much.

References

Hardy, Quentin. 1996. "Jacobs's Patter: An Inventor's Promise Has Companies Taking Big Cellular Gamble." *Wall Street Journal*, September 6, A1, A6.

Overly, Steven. 2017. "People in Wheelchairs Couldn't See Yayoi Kusama's 'Infinity Mirrors.' The Museum Found an Innovative Fix." *Washington Post*, March 9. https://www.washingtonpost.com/news/innovations/wp/2017/03/09/people-in-wheelchairs-could-not-see-one-of-the-u-s-s-most-exciting-art-exhibits-so-the-museum-found-an-innovative-solution/?utm_term=.5a2ae6bf398d.

Shannon, C. E. 1948. "A Mathematical Theory of Communication." *Bell System Technical Journal* 27 (3): 379–423.

Soni, Jimmy, and Rob Goodman. 2017. *A Mind at Play: How Claude Shannon Invented the Information Age*. New York: Simon & Schuster.