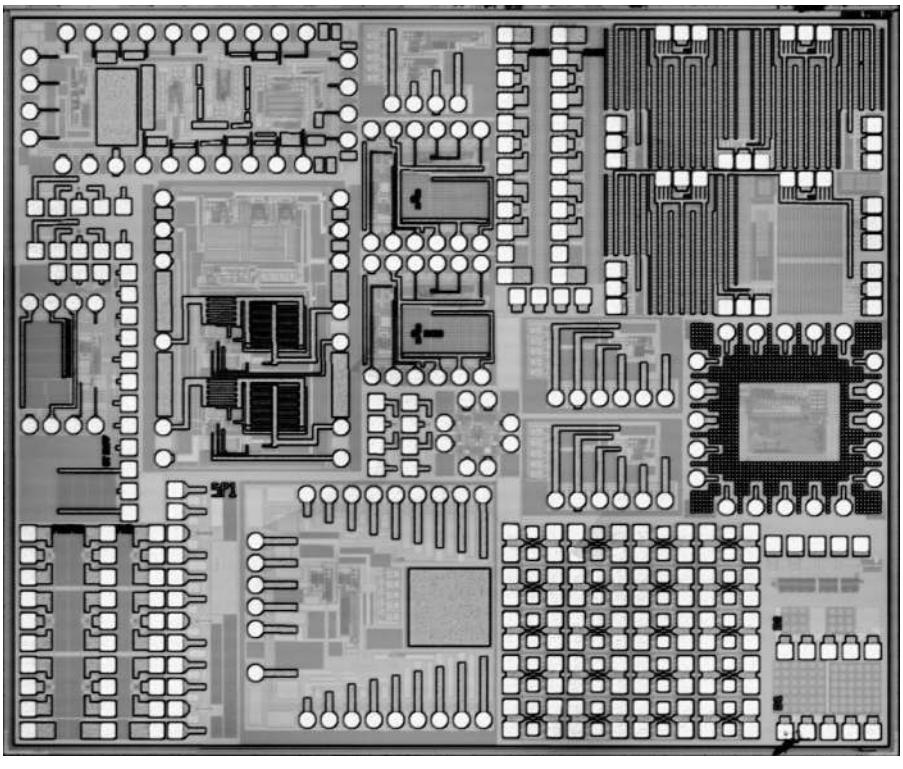
1 The Communications Revolution



An integrated circuit designed at Georgia Tech and fabricated at IBM. (See color plate 1.)

We Predict the Future . . .
By Inventing It.
Motto of Xerox PARC

1.1 The big picture

As I intimated in the Preface, we earthlings are smack in the middle of history's most sweeping technological revolution. Period. Amazingly, this global revolution is the play-out of a single pivotal discovery, a discovery unearthed by a trio of

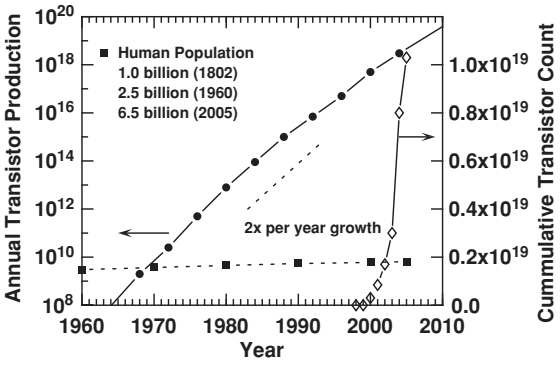


Figure 1.1 Evolution of annual global production of transistors and cumulative transistor count (after G. Moore). Also shown is the human population growth over the same period.

clever scientists. A discovery so profound in its consequences for everyday life that it merits attention by even grade-schoolers and grandmas. That discovery? The "transistor." Skeptical of my bold claim on the importance of this revolution? Clueless as to what a transistor actually is? Well, buck up and read on.

The mighty transistor: A microbial-sized, speed-of-light fast, dirt cheap, on–off switch . . . with a twist. Pervasive. Whether you appreciate it or not, the world is literally awash in transistors. The transistor was discovered–invented by John Bardeen, Walter Brattain, and William Shockley at Bell Laboratories on December 23, 1947, at about 5:00 P.M. EST! A fresh white snow was falling in New Jersey. In 1947, one transistor. Today, there are about 10,000,000,000,000,000,000 (10-billion billion) transistors on Earth, and this number is roughly doubling every 18 months (Fig. 1.1). More on growth trends in a few moments. Given our global population of over 6.5 billion souls [2], this means 1,538,461,538 (1.5 billion) transistors for every man, woman, and child. Imagine – from zero to 10,000,000,000,000,000,000 transistors in only a little over 60 years! For modern humans, growth from zero to 6.5 billion took nearly 30,000 years. But let me not oversimplify the fascinating field of paleoanthropology. Roughly 100,000 years ago, the planet was occupied by a morphologically diverse group of hominids. In Africa and the Near East there were *homo sapiens*; in Asia, *homo erectus*; and in Europe *homo neanderthalensis*. By 30,000 years ago, however, this taxonomic diversity had vanished, and humans everywhere had evolved into a single anatomically and behaviorally modern form near and dear to all of us. Sixty years for 10-billion billion transistors; 30,000 years for 6.5 billion people – quite a contrast in the historical record. Amazingly, those 1,538,461,538 transistors per person would fit comfortably into the palm of your hand. Something most unusual is definitely afoot.

In 1947 the freshly minted transistor was a thumbnail-sized object (Fig. 1.2). By 1997, only 50 years later, we could put 9,300,000 transistors onto a single piece of silicon crystal, 1 cm on a side, to build a microprocessor integrated circuit (in common parlance, a "microchip") for a computer capable of executing

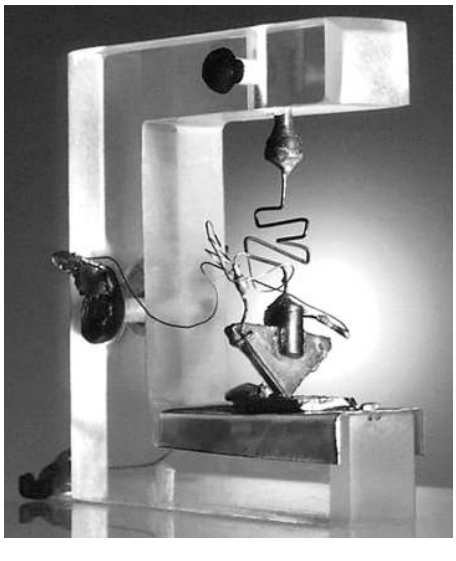


Figure 1.2 A replica of the first transistor, a germanium point-contact device, demonstrated on December 23, 1947. The transistor is roughly the size of your thumbnail (courtesy of Science and Society Picture Library). (See color plate 2.)

1,000,000,000 (1 billion!) numerical computations per second (Fig. 1.3). Talk about progress!

What are we doing with all of these 10,000,000,000,000,000,000 transistors? Gulp . . . Starting a Communications Revolution – capital C, capital R. This may come as a surprise. Revolution? Why a revolution? Well, you first need

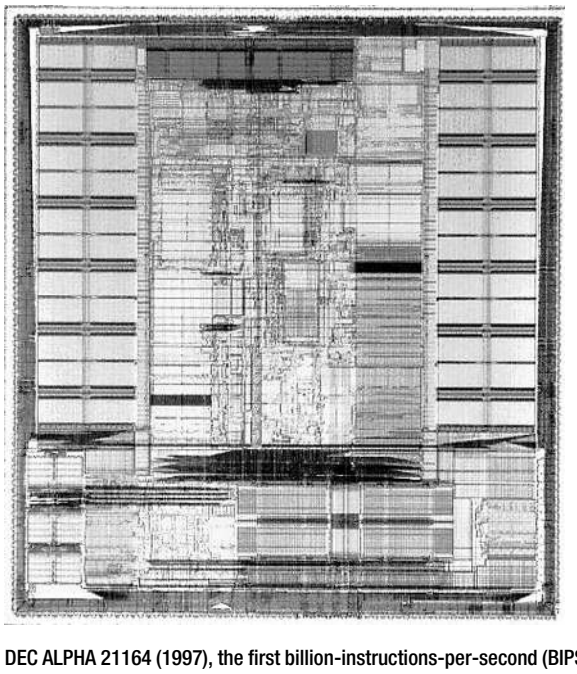


Figure 1.3 DEC ALPHA 21164 (1997), the first billion-instructions-per-second (BIPS) microprocessor. This microprocessor contains over 9,300,000 transistors and is roughly 1.0 cm on a side in size (courtesy of Digital Equipment Corporation).

to open your eyes wide and examine the technology that impacts your day-to-day existence, and then, as with most things, put those observations squarely in the context of history. And then reconsider carefully your world. Here I am using the word "communications" in an intentionally general way: Communications embody the totality of generating, manipulating, storing, transmitting, receiving, and hopefully constructively utilizing information. But what exactly is information? Well, knowledge in its broadest possible sense. Communications also connote movement of information – information flow – that might be as simple as calling your friend on a cell phone, or reading the newspaper, or listening to a Bach concerto – but it also might be as complex as a banking transaction of $5B beamed over a satellite link to other side of the world in 1.7 s (talk about moving money around!), or computing the path of an approaching hurricane in the Gulf of Mexico and then disseminating that warning to 100 million people via television and the Internet – in real time. Whatever the venue, at present, communications, inevitably, at some level – sometimes obvious, often not – trigger the use of Mr. Transistor. Our world, as we know and experience it, literally stands on the broad shoulders of our countless billions of microbial-sized transistors. Pivotal invention indeed. Skeptical? Prepare to be convinced!

Okay, kick back in your chair and prop your feet up so that you are comfortable, and consider: 10,000,000,000,000,000,000 transistors are out there on the streets, and they are ready, willing, and able to forever change the way you talk to your friends, study, socialize, shop, and play games. In short, transistors are radically altering human civilization – read: a BIG deal. This should be a sobering thought. If not, stop texting on your cell phone, go back and reread the last two pages, and then reconsider. Got it? Excellent!

This transistor-changes-the-world fact is something all of us, not just technically literate geeks, should be aware of; MUST be aware of. Hence this book. In this first chapter I set the stage. I first probe the nature of electronic communications using transistors ("digital" information – you know, "1s" and "0s"); attempt to scare you with some doomsday scenarios, in which I imagine life without transistors; introduce Moore's law; explore the magic of the semiconductor silicon, bricks-and-mortar for building Mr. Transistor; and finish by showing you visually just what he looks like. Relax, it's going to be fun. By the way, please turn your cell phone off!

1.2 The evolution of human communications

Okay, first things first. How exactly did we get to electronic communications by using transistors? Well, Fig. 1.4 depicts the (semipersonal, yes, but highly defendable!) milestones in the history of human communications, intentionally spaced in five-century intervals, 1/2 a millenium per tic! From 30,000 B.C.E. to 2000 B.C.E. (28,000 years!), human communication had no written basis. Modern alphabets began to emerge in the Near East circa 2000 B.C.E., marking

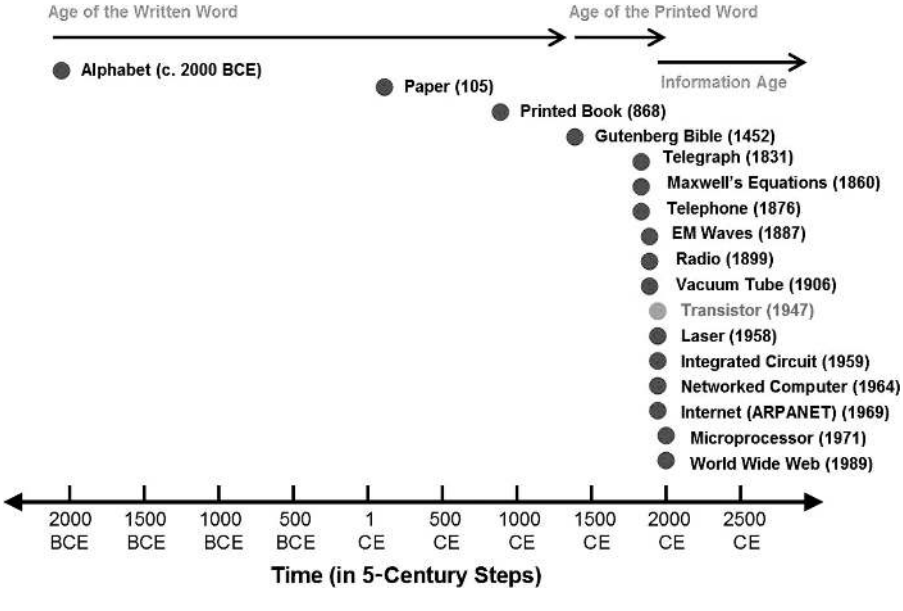


Figure 1.4 Some milestones in the history of human communications.

the beginning of what we will call here the "Age of the Written Word." Early clay tablet documents were hand-lettered, requiring enormous effort to produce, and clearly were reserved for the privileged few. AND, they tended to break when you dropped them on the floor! Enter paper. Although paper was actually invented by the Chinese in the second century C.E., our "Age of the Printed Word" did not begin in force until the development of movable type and the resultant efficient printing press, in the mid-15th century (see sidebar discussion).

Geek Trivia: Exactly How Old Are Books?

The earliest printed book with a date inscription is the "Diamond Sutra," printed in China in 868 C.E. It is believed, however, that book printing may have occurred well before this date. In 1041 C.E., movable clay type was first invented in China. Goldsmith Johannes Gutenberg invented (independently, obviously) his printing press with movable metal type in 1436. His "new" printing process was fine-tuned by 1440, and ready for application to the mass printing of primarily religious texts, the most famous of which was the Gutenberg Bible, first available on September 30, 1452 (Fig. 1.5).

Movable type led to a rapid proliferation of book production, beginning, of course, with the justifiably famous Gutenberg Bible in 1452 (only one tic to the left of present day). Mass-produced books, and soon after all manner of newspapers and pamphlets, were suddenly readily produced, enabling the rapid dissemination of ideas and knowledge. Think universities. Why should you care? Well, this book-based knowledge explosion ultimately spawned the Enlightenment, and with it modern science, together with its practical-minded cohort – engineering – in

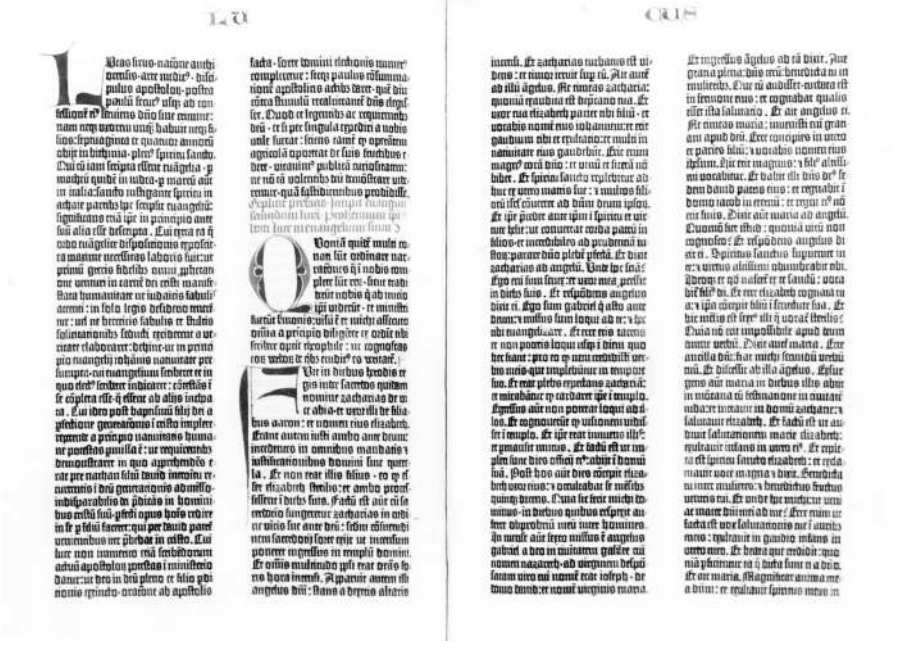


Figure 1.5 Two pages of an original Gutenberg Bible (courtesy of the U.S. Library of Congress).

tow, which so marvelously exploits scientific discoveries in such interesting ways, many of which will be revealed within the covers of the book you hold.

It is no coincidence that the milestones in human communications (refer to Fig. 1.4) are very densely packed within the past 100 years. Science (and engineering) had to evolve some sophistication first, of course, before the technological explosion took place. In many ways, the telegraph (you know, dots and dashes – Morse code), which at its central core proved that (rapid) communications at a distance were possible using electrons, set into motion events that set the stage for the invention of the transistor. More on this fascinating story in Chap. 3.

Alas, ubiquitous Mr. Transistor. December 23, 1947, marks the birth of what many term the "Information Age," to my mind, the third principal age in the evolution of human communications.[1] By the way, for the trivia-minded (count me in!), the term "Information Age" was coined by Wilson Dizard in his 1982 book *The Coming Information Age: An Overview of Technology, Economics, and Politics*. After that bright lightbulb of human ingenuity in 1947, the rest seemed to almost naturally unfold, with a lot of hard work and cleverness by the pioneers of course – the integrated circuit, the microprocessor, memory chips, computers, networks, cell phones, the Internet; you name it. All of these downstream technological marvels inevitably trace their roots to the humble transistor, and none could work without it today. Zero, zilch! Transistors, whether you appreciate them or not (don't worry, you soon will!), exist by the millions in

[1] For an interesting discussion of the parallels of Gutenberg's invention and the transistor as enablers of their respective communications revolutions, see J. T. Last's discussion in [1].

every piece of technology you own: your car, your cell phone, your i-Pod, your dishwasher, your TV, your camera, probably even your credit card!

Imagine – a new age of human civilization beginning only 60-ish years ago. We live in exciting times. The Information Age was born, and the Communications Revolution that is currently playing out in this new millennium represents the means by which this new age of human civilization will unfold. Shouldn't you know something about this? Shouldn't everybody? Read on.

Geek Trivia: Stump Your Friends!

Care for some relevant trivia to stump your friends? Sure! Question: How many personal computers were there on Earth? Answer: 593,085,000 (all of these answers are 2005 numbers). Question: How many Internet users were there worldwide? Answer: 1,018,057,389. Question: How many cells phones were in use globally? Answer: 2,168,433,600! Question: What country had the highest per capita number of Internet users? Answer: Iceland, with 6,747 per 10,000 inhabitants (surfing the Web, a great way to spend those long, dark winters!). Geek challenge: Update these numbers to present day!

1.3 Doomsday scenarios

Okay, fine . . . I get it. You're wondering . . . "Are transistors really THAT big a deal? Perhaps this guy has overplayed his hand." Hey, a little skepticism is healthy! If you're game, let's engage in a slightly diabolical thought experiment to test my claim regarding the importance of transistors in the grand scheme of things. It will also help you appreciate just how deeply embedded transistors are in everyday life. Here goes. Imagine for a moment that I could suddenly, with the snap of my fingers, erase transistors from the face of the Earth; blot them from the historical record. How? I don't know, maybe a meteor containing "Transistorite" lands in the Gobi Desert (you know, Superman's Kryptonite, but for transistors). Simple question. One second later, only one, how would your life change? For the sake of argument, let's assume you are living, like me, in Atlanta, Georgia, in the United States. Let's now consider the implications of erasing transistors from human civilization, in each of the following life arenas: communications, transportation, health care, and economics. Hold on tight – it gets pretty scary.

Communications: This one is simple. It's back to drums and smoke signals! Your cell phone goes instantly dead mid text message. Hint: There is no such thing as a telephone that does not have a transistor lurking under the covers somewhere. Even a call made from that antique transistorless rotary phone in the attic has to be routed electronically on a landline, so the electronic "clicks" your rotary pulse dialer outputs vaporize into thin air. Ditto for radio – there is nothing to transmit or receive that WREK 91.1 FM broadcast (Georgia Tech's student radio station). Your radio now sits dumb, an ornament on the shelf. Global radio

stations go silent. Same story for television. TV screens go blank, worldwide, now a *Poltergeist* snow land. CNN no longer connects you in real time to events unfolding around the world. Oprah is cut off midsentence. How about the Internet? No transistors, no computers; no computers, no networks; no networks, no Internet. No cable modem, DSL line, or T1 fiber line works anyway. So forget all those on-line communications you depend on. Your computer screen goes blank; that IM note (all lowercase, grrrr!) you just typed remains forever unanswered. There are no satellite uplinks or downlinks or optical-fiber backbones, or functional transoceanic cables for moving information around the globe. All instantly silenced. Country-to-country links are dead. There are inevitable political implications. Without communications systems, president-to-president "hot lines" are down, all diplomatic ties severed. The world is profoundly and instantly opaque, akin to days of old when it took 2 months to say "hi" across the Atlantic by boat. Generals with itchy trigger fingers get understandably nervous, hopefully not panicky – not to worry, the nukes can't be launched even if they push the dreaded "red button." All in one second. No transistors, no global communications infrastructure.

Transportation: I'm afraid this one is pretty simple too. It's back to hoofing it! If you are lucky enough to live on a farm, a horse, or maybe a horse and buggy, will reemerge as your preferred means of transport. Bikes are fine for around town – unless you live on Telegraph Hill in San Francisco! I wouldn't really want to bike from Atlanta to New York for a business meeting though. Here's the scoop. Unless your car predates 1980 (if it does you need a new one anyway!), your engine immediately dies, and you coast to a dead stop. Electronic fuel injection (yep, uses transistors) exists in virtually all automobiles today (more trivia to stump your friends – the last passenger car to have a carburetor was the 1990 Subaru Justy). You quip – "but cars were around before transistors!" Correct, but you will not find one today without transistors, lots of electronics, and probably several dozen on-board computers (fuel injectors, engine controls, sensors; the list is long). Unless you are a highly skilled mechanic with a junkyard conveniently located next door, you are unlikely ever to convert your now dead-as-a-doornail Beamer into a functioning car. It would take the car industry years to convert plants to make such a beast, even if they remembered how. Because I'm not a sadist, let's assume you are not on a jet crossing the country. It shouldn't surprise you that a modern passenger jet has a ton of control electronics and literally hundreds of on-board computers, not to mention the satellite-based GPS that flies the plane for 95% of the way. Ever wonder why the flight attendants are so insistent that you turn off all your electronic gadgets during takeoff and landing? They are afraid that spurious transmissions from your gadget (electronic leakage) may inadvertently interfere with their much more expensive gadget! In short, all planes are grounded. Permanently. Ditto my comments on planes before transistors; unless you are an employee of the Smithsonian's Air and Space Museum, and you can fly a Messerschmidt 109, you're out of luck. All in one second. No transistors, no global transportation infrastructure.

Health care: Here things are slightly better, but only if you are healthy and intend to stay that way for a good while. Alas, life is rarely so convenient. Last year, Americans suffered about 1.5 million heart attacks; about 18 million currently have diabetes; about 173,000 were diagnosed with lung cancer. The miracle that is modern medicine is something we all too often take for granted. Yes, it is frighteningly expensive; yes, health care costs are skyrocketing out of control; yes, not enough people have adequate (or any) health insurance – still, when you are very ill, stop to consider what it would be like to go to the hospital for treatment, not today, but say 200 years ago, or even 100 years ago (read: preantibiotics); not at Saint Joseph's Hospital in Atlanta, but to the village barber who would promptly bleed you (using a rusty knife) to improve your health. I think you will readily concede that we are indeed blessed in our access to modern medicine. It may seem less obvious that transistors play a major role in health care, but . . . sigh . . . it's true. Your medical records are stored electronically in a massive computer database. Poof, they are now gone. The drugs that are at the doctor's disposal require development, testing, and manufacturing on a scale unthinkable without computers. Subtract those once the pharmacy runs out. Even medical school training would be awfully tough to contemplate without computers. Diagnostic tests inevitably include computer-based analysis: blood series, urine analysis, EKG, EEG, CT scan, you name it. Your doctor will now have to treat you blind. (A reminder that the quaint notion of the ambling old country doctor who draws only on intuition and experience for treatment is just that – quaint and old. Country doctors will now be forced back into vogue, however.) Any hospital surgical team is effectively shut down now. Bypass, brain tumor, C-section, appendix? Nope. The autoclave that sterilizes surgical instruments is, surprise, computer controlled; not to mention the anesthesia dispensers, and the myriad of real-time health monitors that comfortingly sound their "beep-beep" that all is well. Your insurance processing and records are likely all electronic also. Gone. Importantly, all of the miraculous treatment options available today come to a grinding halt. No CT scan. No PET scan. No Gamma Knife. No chemotherapy. All those remarkable new discoveries in genetics associated with mapping the human genome, and the vast potential for health care they are likely to embody, are no more – EXTREMELY computer-intensive research. The list could go on. When the lights go out on transistors, so to speak, you may perhaps have a little bit more time to coast if you have no health problems, but not likely for very long. We all age, after all. All in one second. No transistors, no global health care infrastructure.

Economics: Remember those bartering-based medieval economies? You'll need to – the industrialized world is going to quickly look very agrarian. It should not surprise you that computers have completely restructured the global economy. In the richest countries, only 5% or so of financial transactions occur with paper money (i.e., "hard" currency). The other 95%, at least at some level, are processed electronically – yep, using transistors. For consumers, for instance, electronic banking [also known as electronic fund transfer (EFT)] gives

near-instantaneous 24-hour access, world wide, to our cash through automated teller machines (ATMs), and direct deposit of paychecks into our checking accounts gives us the cash to draw on. No more. No ATMs work. They will soon be smashed open for the remaining cash inside, reluctantly (and mutely) surrendering a rather large, one-time payout. Because you have direct deposit, you now effectively work for free. Your company has no way – without computers – to generate a paycheck for your toils! Not that you could cash it anyway; the bank can't open its electronically controlled vault. Your life savings instantly vanish. Banks are closed, permanently. Forget Jimmy Stewart's *Wonderful Life* triumph over money panic – Potter wins this one. No more 401k. Global bank-to-bank monetary transfer instantly halts. The notion of currency exchange is meaningless; there is no way to move it around. The world's Stock Exchange boards are now blank, the mouths of the suddenly silent commodities traders at the New York Stock Exchange circular and aghast. Stock? How? It can't be bought or sold. Without any form of payment, the movement of goods rapidly grinds to a halt. Fuel production instantly ceases (hopefully not via a "kaboom"). Without goods moving around, the very notion of "stores" and consumerism is suddenly irrelevant. Within a week there will be nothing to buy on the shelves, and no cash to buy it with anyway. If you live on a farm and can grow some food, and perhaps barter for the rest of your needs, you should be in at least decent shape; for a while. Newsflash – not many of the 300+ million Americans live on farms! The rest of us are going to go hungry. Grocery stores will not receive any resupply, and yep, there are computer controls on all the refrigeration systems. Everything is now starting to melt. Cash registers, with their laser-based bar-code scanners, don't work either – there is no such thing as a computerless crank-handle "cha-ching" cash register except in the Smithsonian, and I doubt you can use an abacus. You get the idea. All in one second. No transistors, no global economic infrastructure.

An identical thought process could be applied to virtually any venue of human activity. Consider these activities: (1) *entertainment*: (How will you play a DVD without a DVD player? Forget your i-POD and your i-Phone! How will you watch your favorite TV program? How will you IM or text your friends?); (2) *publishing*: (How will you typeset a magazine or a book without a computer? How do you plan to print it without a printer? How will you get it to the stores?); (3) *sports*: (Will anyone watch the game or listen to it without radio, TV or the Internet? How will players or fans get to the field without a car or a plane? How will you buy your tickets without an ATM machine for cash or on-line ticketing? Will the athletes really play for free if they can't access their multimillion dollar bank accounts? Back to playing just for the love of the game – nice thought!) (4) *education*: (How will you type up that paper without your computer? How will you do on-line searching for your research paper? How will you look up a book at the library? Photocopy it? How will you give a powerpoint presentation?)

This list could stretch on for miles. We're talking utter chaos. Globally. Dark Ages as we have never known them, even in medieval Europe. Anarchy. Mass suffering and loss of life. As I think you must agree by now, my bold claims have in fact not been overstated: Life as we know it would simply cease to exist if we