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Henry Kressel
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Introduction – Competing for the future: How digital innovations are changing the world

DAVID Sarnoff, long the chairman of RCA and a pioneer in the electronics industry, summarized his career in these words: "I hitched my wagon to the electron rather than the proverbial star."[1]

The world has followed suit. The past sixty years have witnessed the most rapid transformation of human activity in history, with digital electronic technology as the driving force.

Nothing has been left untouched. The way people communicate, live, work, travel, and consume products and services have all changed forever. The digital revolution has spurred the rapid expansion of economic activity across the face of the planet.

In this book I will explore the unprecedented outburst of electronic innovation that created the digital revolution. Based on this example, I will examine how innovation works, what it has achieved, and what forms we can expect it to assume in the near future.

Since innovation does not happen in a vacuum, I will also explore the political and economic factors that can accelerate or impede changes in the industrial landscape. One of these is globalization, which creates neither a level playing field nor a truly "flat world." Governments everywhere are focused on industrializing as quickly as possible in the face of growing competition. As a result, attempts to gain national competitive advantage by building artificial walls are not going away.

Defining innovation

Before outlining the issues to be covered, we must clarify what constitutes an "innovation" in the first place. The blue laser diode that

[1] The *New York Times*, April 4, 1958.

enables the next generation of optical storage is obviously an innovation. But many would say an improved connector for circuit boards qualifies too. To avoid confusion, we need a definition that focuses the term on the kind of transformational technology that we're exploring. Here is a good starting point.

> Innovation is an historic and irreversible change in the way of doing things . . . This covers not only techniques, but also the introduction of new commodities, new forms of organization, and the opening of new markets.[2]

In this book, then, innovation refers to a technical development or invention that contributes toward creating new industries, new products and processes, and new approaches to solving complex industrial problems. Innovation includes commercializing the technology to move it into the market and disseminate it throughout the world.

Needless to say, some technical developments or inventions are more fundamental and far-reaching than others. The most potent force for change is a revolutionary innovation. This is a basic invention that ultimately replaces a technology once central to industry.

A revolutionary innovation is the tsunami of the industrial world. Its power spreads out from a central technology base, overcoming all resistance in its path through successive industrial innovations, until its effects are felt in the farthest reaches of the world economy.

Revolutionary innovations are followed and supported by innovations that are valuable in and of themselves, but are more evolutionary in nature. Evolutionary innovations help implement the fundamental discoveries and extend their reach.

Building the digital world

To understand how digital electronics conform to this pattern, we must first look at how the technology was developed. Then we will examine how it has affected industrial development around the world.

It promises to be a fascinating journey. The following overview can serve as a map of the terrain, to guide us through the issues we will encounter. To get started, let's orient ourselves by looking at where electronic technology came from in the first place.

[2] J. A. Schumpeter, *Readings in business cycle theory* (Philadelphia: The Blackiston Company, 1944), p. 7.

Modern electronics began with the invention of the vacuum tube (called a "valve" in the UK) in the early twentieth century. This device initiated the "analog" electronic age, from radio through telephony, television, radar, and the very beginnings of computing.

Today vacuum tubes have all but disappeared. They were replaced by two of the most revolutionary device innovations in history, the transistor and the semiconductor laser diode. These landmark inventions proved to be the key components in the digital technologies that have transformed the world. Chapter 1 talks about them in more depth.

Significantly, both the transistor and the laser diode were largely conceived and commercialized in the United States. Following World War II, the US had become the epicenter for technological breakthroughs, the result of enormous R&D investments by major corporations over a span of many years. These companies also carried out the commercial implementation of their discoveries.

US technical leadership persisted through the end of the twentieth century. As we shall see, however, in the later years this was due more to financial and social structures than industrial and governmental support. In fact, it was the availability of private venture capital in the United States during the 1980s and 1990s that drove many revolutionary innovations to their present dominance.

Venture funding made possible the formation of hundreds of highly innovative companies that created new digital electronic products to pioneer new markets. They produced innovations in communications and computing, particularly microprocessors and software, that generated whole new spheres of activity.

Now, at the start of the twenty-first century, the world order has changed. Innovation and the capital to finance new technology businesses are more globally distributed. This has profound consequences for regional economic development.

Innovation on a global scale

Today the talk is all about globalization, as if it were a new phenomenon. But globalization has been going on for thousands of years, with people migrating across lands and seas, carrying ideas and products with them. The real difference in the modern world is how much faster the process has become.

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The invention of printing in the fifteenth century led to an enormous increase in the spread of ideas, but it took about 100 years to make meaningful changes to Western society. The introduction of the steam engine in the eighteenth century triggered its own chain of industrial transformations, but it wasn't until the middle of the nineteenth century that its full impact began to register on societies around the world.

By contrast, digital electronics have profoundly altered societies around the globe in little more than twenty years. This has happened despite the fact that the electronics revolution has involved countries that were not full participants in the earlier industrial upheavals.

Part of the reason is political. After the two world wars of the twentieth century, Europe and Asia underwent nearly twenty years of reconstruction. Meanwhile, US businesses were becoming the undisputed leaders in technological industries. As we will see, the largest corporations established central research laboratories in the expectation that fostering industrial innovations would help assure their futures.

By the 1970s, however, we see the beginning of a new wave of very rapid globalization. The industrialized countries most devastated by the war in Western Europe had recovered, as had Japan, and they began to build their industries using technologies that had been largely innovated in the United States. They represented new, well-capitalized international competitors in the world market.

That was a rude awakening for the United States. Suddenly, industry leaders found themselves faced by formidable challengers. Complacency quickly gave way to panic. Most noticeable was the challenge mounted by Japanese companies, which were competing not only on price but also on quality. Forecasts of the inevitable takeover of US industry by large Japanese companies produced widespread public fear.

The feared collapse of the US economy under the onslaught of European and Japanese competition did not happen. What did occur was the rise of a whole new class of formidable Asian competitors to further threaten the dominance of incumbents. Starting in the late 1970s, South Korea, Taiwan, Malaysia, and the Philippines became centers of low-cost manufacturing outsourced from the US.

No one dreamed at the time that China would emerge as an industrial colossus any time soon. Its economy was too restrictive and too badly managed. But emerge it did, starting in the 1980s, when its government decided to open the country to market forces, entrepreneurial capitalism, and, increasingly, foreign investment.

Nor did anyone predict that India would become a major source for the international production of software. But today Bangalore is booming with software firms.

The acceleration of industrial development in the leading Asian economies has been astonishing. They have accomplished in just a few years what once took many decades. How were they able to manage it?

I will propose that this shock wave of rapid development resulted from a crucial combination of factors not present in previous phases of industrialization. First and most important was the readily transferable nature of the technology being commercialized. Although the revolutionary innovations in digital electronics originated primarily in the US between the 1940s and 1980s, they allowed an extraordinary degree of global industrial mobility.

Other factors included new government policies in the industrializing nations, and the availability of risk capital to fund new business ventures. We will consider the effectiveness of both approaches in fostering industrial development.

The new world order

Earlier waves of globalization saw industries move to new parts of the world. New centers of innovation arose. The movement of risk capital seeking the highest return financed industrial development in those new regions. We have witnessed the same train of events in our own time, but in a highly compressed time frame.

We have also seen the inevitable consequences of this process. Excessive investment overbuilds capacity, and a return to reality is accompanied by a destructive collapse. The boom and bust in telecommunications in the late 1990s, where trillions of dollars of value were wiped out in a few short years, is a classic example.

As the aftereffects of the tidal wave of digital electronics ripple in new directions, it is time to take stock of what has happened, why, and how. I trust that this book will provide a useful analysis.

More than that, I hope it will stimulate discussions not just about the future of technology, innovation, and industrialization, but about their global impact. One thing is certain: the future will be quite different from the linear extrapolations of the present.

In talking about the future, I am mindful of the spotty history of technological and market predictions. One of my favorite examples involves conflicting views on television. In 1939 David Sarnoff, the chairman of RCA, presided over the televised opening of the RCA Pavilion at the World's Fair. He said: "Now we add sight to sound. It is with a feeling of humbleness that I come to this moment of announcing the birth, in this country, of a new art so important in its implications that it is bound to affect all society. It is an art which shines like a torch in a troubled world."

Contrast his prophetic statement with the opinion expressed in a *New York Times* editorial at about the same time: "The problem with television is that people must sit and keep their eyes glued to the screen; the average American family hasn't time for it. Therefore the showmen are convinced that, for this reason, if no other, television will never be a serious competitor of [radio] broadcasting." Who would have guessed that the average household now spends over six hours a day watching television?[3]

[3] Quoted in the *New York Times*, August 28, 2005, Opinion, 12.

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PART I

The technology – how electronic devices work – digital systems and software

1 Genesis: Inventing electronics for the digital world

This book is about the creation and consequences of digital electronics.

Over the last half-century no other area of technical innovation has so drastically altered the way we live, work, and interact. Digital electronics give us instant access to a whole universe of information, and powerful tools to process it. They also equip us with an unprecedented ability to communicate instantly with people anywhere in the world.

I was privileged to contribute to these developments, first as a scientist engaged in creating new electronic devices and systems, and then as a venture capitalist involved in creating successful new businesses.

From these vantage points, I watched digital electronics grow from a technical specialization into a revolutionary force that generates new industries and transforms developing economies into global competitors, and does both seemingly overnight.

To sense the full extent of its impact, first visualize a contemporary scenario. A programming group in India is working on a project from the US. They are using computers built in China, with LCD displays made in Korea, driven by software from Silicon Valley and Germany. They communicate with colleagues in the US and other countries over the Internet, by e-mail and voice. It all seems quite normal today.

Now try to picture the same situation twenty-five years ago. You can't. There was little global sourcing of technical expertise then. High-tech manufacturing in developing Asian economies was just getting started. The major sources of equipment were Japan, the US, and Europe. Collaboration over the Internet was a science-fiction fantasy. Digital electronics had yet to transform our lives.

That's how fast and how thoroughly things have changed. If we're to track these developments and their implications, there is obviously a lot of ground to cover.

Where should we begin our journey? My choice is to start where I began my career, with solid-state devices, which were the genesis of the whole field of digital electronics.

Why start with these early innovations? Because so much of the progress in digital systems grew out of the advances in structures and materials embodied in these basic devices. An understanding of how they work gives you a better grasp of the evolution of digital technology. By knowing their physical characteristics you can also better appreciate the limitations that will sooner or later put the brakes on further progress.

The crucial factor of device miniaturization is a prime example. When I was working on electronic devices, miniaturization was a dream endeavor for materials scientists. But its significance extends far beyond the solution of a technical challenge.

The drive to miniaturize led to the concept of reducing the size and cost of digital systems. Miniaturization has been driving performance increases in semiconductor devices and magnetic disk storage for the past forty years. Marvelous advances in software, after all, need an ever-increasing number of transistors running at ever higher speeds to process their commands.

By constantly reducing device sizes, scientists have kept systems small and inexpensive while their power and complexity have increased. The fact that people can carry and afford to own sophisticated cell phones that fit in their pockets is a direct outcome of the effort to miniaturize devices.

Today, unfortunately, even technologists ignore the roots of digital technology. I have interviewed job applicants with backgrounds in computer science and digital systems for many years. More often than not, I ask them to explain to me how a transistor works.

What I usually get in response is a sage discourse on Moore's Law and how this inexorable law of nature will continue to drive up the value of digital systems for the foreseeable future. When I remark that Moore's Law is neither a law of nature nor inexorable, and press them again as to just how a transistor *really* works, I'm often answered by an embarrassed silence.

The fact is that everyone, engineers included, takes the basic devices for granted. They're looked at as immutable, like the rising and setting of the sun. Yet when it comes to continuing the progress of digital electronics, this is where the real energy lies. It's the power dissipation of devices that sets serious limits on future performance gains in digital systems. I take pains in this chapter and the next to explain why and how these limitations will be circumvented.

So we open our study with some material to help you understand the physical basis of digital electronics. At the end of the first two chapters you can take some satisfaction in knowing that you're better versed on the subject than some engineers I've met, and it's only taken you an hour to get there.

In this first chapter I have also included an introduction to the next wave of device technology, based not on semiconductors but on polymers, which are organic materials. No one dreamed that this would happen forty years ago when technologists worked only on crystalline semiconductors.

An insider's perspective

I confess to some bias toward technical information. I started my career at RCA as a physicist fascinated by solid-state devices. This passion remained with me throughout the many projects I worked on, including these developments:

- the company's first production silicon transistor (1960);
- integrated circuits (1961);
- microwave devices for the Apollo mission radios (1961);
- practical semiconductor lasers (1967);
- solar cell energy converters (1974);
- fiber optic systems for military applications (1975);
- high-efficiency light sensors for fiber optic systems (1979).

It was my good fortune to be in the right place to make these contributions. I was at RCA at a time when that company prided itself on fostering electronic innovations and was willing to invest the money necessary to take them to market.

At RCA Laboratories, I was surrounded by remarkable researchers. In the 1960s and 1970s, my friends down the hall there developed the modern MOSFET (metal oxide semiconductor field-effect transistor), CMOS (complementary metal oxide semiconductor) integrated circuits, the solid-state imager, and the first liquid crystal displays. These inventions are at the heart of the digital devices and systems we use every day.

We knew that those were remarkable times. But none of us could have predicted where our work and that of others in our nascent fields would lead. Our industry conferences focused on technical developments, not