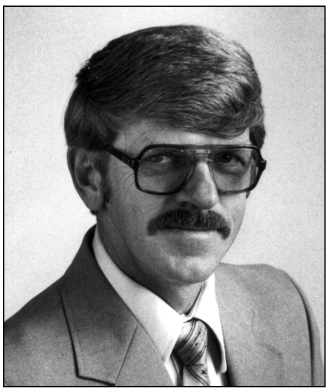
The Symbiotic Relationship of Science and Technology in the 21st Century



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Considering the range of human experience, both science and technology are relatively new fields of study. Certainly, primitive societies had some elementary understanding of nature, at least those elements that were most observable and obvious in their everyday experiences. Thousands of years before Christ, natural processes were used to produce cheese and beer, but without sophisticated instruments, there was little or no understanding of the science behind these processes. Evidence also shows that simple machines and tools were used long before Newton's laws were formulated and the principle of mechanical advantage elucidated.

Science before the scientific revolution was typically an intellectual pursuit, and the idea of using scientific knowledge to improve the quality of life through technological manipulation and product design was rarely pursued. What little innovation and invention occurred was typically done by artisans and craftsmen who knew little of scientific theory. Some of the most elaborate mechanisms were created to entertain the aristocracy and had little practical value.

Besides being hampered by crude research instruments, scientific discovery and understanding were also restricted by social institutions that valued conformity and status quo over discovery and exploration. This conservative philosophy led to the trial of Galileo as a heretic in 1633 for defending Copernican theory. Copernicus had challenged the concept that the earth is the center of the universe, a concept that was at the core of established religion. Just 34 years earlier, Giordano Bruno had been burned at the stake for questioning orthodox opinion in mathematics, theology, and philosophy. But science gained acceptance as exploratory tools improved, more observations were made, and ideas were promulgated via the printing press. And the church had to modify its perception of the universe.

The obvious connection between scientific principles and practical applications (technology) developed during the scientific revolution and was expanded in the industrial revolution. In recent times, many leaders and the public have developed an unflagging faith in the science-technology enterprise. Pytlik, Lauda, and Johnson (1978) asserted that this faith led the public to believe that "every flaw affecting the human was definable and could be solved through science and technology. To many, science seemed infallible, making people tolerant of its byproducs but unable to assimilate its true meaning" (p. 4).

Rustum Roy (1990), a leader in the National Association for Science, Technology, and Society, argued that historically, technology led to science more often than science led to technology. Surprisingly, recent studies have indicated that most technological knowledge is still built, not on science, but on previous technological knowledge. One study (Project Hindsight), conducted by the U.S. Defense Department, examined 710 events that were essential in the development of 20 major weapon systems during the 20 years following World War II. The investigators found that only two events (a minuscule .3% of the total) were the result of basic scientific research (Volti, 1992).

Another study analyzing British firms reported similar findings. However, a more recent analysis found a median delay of nine years between a scientific finding and its conversion to technology, a finding that would have modified the results of Project Hindsight somewhat if the researchers would have extended their study over a longer period (Volti, 1992). While it is true that applied science is generally technology (i.e., it is designed to extend human capability or modify an environment), it is also true that much technology that exists and is practiced is not applied science in the strictest sense of the term.

The purpose of this paper is to demonstrate that, increasingly, the paths of science and technology are not separate or unidirectional as indicated in the Project Hindsight study but illustrate a relationship of mutual dependency, that is, symbiotic. Today we can give many examples where science and technology complement each other, where one does not consistently lead or follow the other. It is the contention of the author that few fields of endeavor illustrate the symbiotic relationship between science and technology more clearly than biotechnology and, more specifically, genetic engineering.

Biotechnology and Genetic Engineering

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Even in name, biotechnology is a marriage of science and technology. By definition, biotechnology is a multidisciplinary applied science that draws on knowledge from biology, chemistry, physics, and engineering to use living organisms to make or modify products, to improve plants or animals, or to develop micro-organisms for specific uses (Office of Technology Assessment, 1984). Biotechnology has applications in a number of fields: medicine, agriculture, botany, waste treatment, marine and aquatic fields, and food and beverages (Seenath, 1988).

The focus of this paper, however, is primarily on one segment of biotechnology, that of genetic engineering. Genetic engineering draws its theory from the scientific field of genetics, which consists of three main branches: (a) Mendelian, classical, or transmission genetics, which is a study of the transmission of traits from one generation to the next; (b) molecular genetics, which is the study of the "chemical structure of genes and how they operate at the molecular level" and (c) population genetics, which addresses the "variation of genes between and within populations" (Weaver & Hedrick, 1992, p. 4). Genetic engineering relies primarily on the techniques and knowledge identified in the first two branches.

Gregor Mendel is usually given credit for starting the field of classical genetics in 1865 when he reported the findings of the scientific experiments he had done regarding the flower color and seed shape of the common garden pea. But part of the history of biotechnology and genetic engineering must include the instrument makers such as Janssen, Huygens, Leeuvenhoek, and Hooke who, in the 16th and 17th centuries, developed the early models of the light microscope and other laboratory equipment so necessary for examination and discovery. These technologies were crucial for the microbiologists, biochemists, and other scientists who have developed the area of study as we now know it. Figure 1 provides a timeline of selected scientific discoveries and technological developments in biotechnology and genetic engineering.

The history of genetics thus far recounted and illustrated in the first part of Table 1 has been a story of scientific discovery with technology supporting the effort by constantly improving the instruments for research. One of the first commercial applications (applied science = technology) of Mendel's findings, however, was the hybridizing of corn that began in the 1920s. This can be considered genetic engineering in crude form (i.e., providing for the transmission of traits).

The selective breeding of farm animals followed suit. Through careful records of milk output, dairy managers could identify the best breeding stock. Since the availability of the preferred breeding stock was limited, or rather distance made selective breeding impractical, artificial insemination became the process of choice that raised the milk output and quality of dairy herds, the weight gain efficiency of beef cattle, and "redesigned" hogs for a more health-conscious public.

The relationship between science and technology in these formative years is illustrated by Hurd's (1994) statement: "Science is a tool for generating new technologies and technology is a means for extending the frontiers of science" (p. 130). The use of more sophisticated technology, such as the Hubble space telescope, often leads to "unexpected observations that will require new theories or the modification of older theories to provide a valid interpretation" (p. 130).

Despite the importance of Mendel's work, it was not until the first decade of this century that the study of genetics resumed with considerable vigor. With better optics and research equipment, Thomas H. Morgan and associates (1910-1916) determined that genes are arranged in a linear order on the chromosomes and that genes could suddenly undergo a permanent change or mutation. Gene mutation was identified as the primary mechanism that drives evolution.

Genetic Engineering

Genetic engineering, sometimes called genetic manipulation, is defined as

> the artificial recombination of nucleic acid molecules in the test tube, their insertion into a virus, bacterial plasmid, or other vector system, and the subsequent incorporation of the chimeric molecules into a host organism in which they are capable of continued propagation. (*Genetic Engineering*, 1997, p. 762)

When Berg succeeded in his recombinant DNA experiments in 1972, and Boyer and Cohen successfully cloned DNA with a plasmid, the process had been identified that would become a multimillion-dollar industry in manufactured proteins. The secret to the procedure was the discovery by molecular biologists of enzymes called restriction endonucleases. These enzymes have the ability to "cut" DNA into reproducible fragments. Many restriction enzymes have been cataloged according to where they cut DNA molecules and which genes are isolated. Figure 1 illustrates gene splicing or recombinant DNA (rDNA), the process by which undesirable genes are replaced by preferred genes.

Table 1. **Timeline of the Science and Technology Events Leading to Genetic Engineering**

	Science	Technology
>5,000 BC		Making of beer in Babylon
1590		First compound microscope - Z. Janssen
1684		Two-lens eyepiece - C. Huygens
1838-39	Living tissue composed of cells - Schleiden, Schwann	
1853		Dark-field microscope condenser - H. Wenham
1859	*On the Origin of Species* - C. Darwin	
1865	Postulated laws of genetics - G. Mendel	
1869	Discovered DNA in trout sperm - F. Miescher	
1865-90		More microscope improvements - Spencer, Tolles
1882	Chromosomes described - Flemming	Improvements in specimen preservation, staining
1902	First genetic disease noted - A. Garrod	Modern binocular eyepiece - F. E. Ives
	Proposed chromosome theory - W. Sutton, T. Boveri	Undated: lab tools improved: centrifuge, vortex mixer, culture incubators, etc.
1910-16	Demonstrated that genes are on chromosomes - T. Morgan, C. Bridges	
1920		Beginning of corn hybridization - G. H. Shull, E. M. East, D. F. Jones
1924-26	Wave length of electrons postulated - Broglie, Schrodinger Magnetic & electric fields act as lenses for charged particles - Hans Busch	
1927	Induced mutation by X-rays - H. J. Muller	Ultracentrifuge developed
1931	Evidence for recombination - H. Creighton, B. McClintock	
1932		Electron microscope system; images produced - Bruche & Johannson, Knoll & Ruska
1935		Phase contrast on microscope - F. Zernike E-microscope resolution exceeded light microscope
1939-45		Improvements, production of E-microscopes
1940		Rapid increase in artificial insemination of cattle
1944	Evidence that DNA is genetic material carrier - Avery, McLeod, McCarty	More lab instruments necessary for genetic engineering were developed and improved over time:
1953*	Structure of DNA discovered: the double helix - J. Watson, F. Crick, R. Franklin, M. Wilkins	
1957	DNA polymerase I discovered - Kornberg	Spectrophotometer, UV and visible light
1958	Mode of DNA replication demonstrated	UV transilluminator
1960	mRNA and role in encoding information for amino acids discovered	Pipettes, micropipettes Electrophoresis apparatus
1962*	Existence of restriction endonucleases in bacteria demonstrated - Arber, Smith, Nathans	Biological tools such as plasmids, other
1966*	Genetic code completely elucidated - M. Nirenberg, H. G. Khorana, and Holley	cloning vectors; restriction endo-nucleases, ligases, and polymerases;
1970	First restriction endonuclease isolated	hosts for cloned genetic information; etc.
1972*	First recombinant DNA molecules produced in vitro - P. Berg	
1973	DNA inserted into plasmid vector and transferred to host *E. coli* - H. Boyer and S. Cohen	
1974	World moratorium on some types of recombinant DNA experiments	
1975	Southern blotting method developed for detecting specific DNA sequences	
1976	NIH prepares first guidelines for physical and biological containment	
1977*	Determined base sequences of DNA - W. Gilbert, F. Sanger	First biotech firm established - Genentech
1977*	Introns discovered - Sharp and Roberts	
1978		Human insulin cloned in lab - Genentech, licensed to Eli Lilly
1979		Human growth hormone cloned - Genentech
1981		nterferon, natural tumor fighting protein, cloned - Genentech Transgenic mice and *Drosophila* flies produced
1982		Eli Lilly produces insulin - first rDNA drug

continued

Table 1. **continued**

1984		EPA approved trials of bacteria designed to protect strawberry plants from frost damage Social activists block "ice-minus" tests until 1987
1985*	Polymerase chain reaction developed for in vitro amplification of DNA - Mullins, Smith DNA finger printing developed - A. Jeffreys (British)	Growth hormone commercialized - Genentech
1988	Located Huntington disease gene on C-4 - N. Wexler, M. Conneally, J. Gusella	First genetically engineered animal patented - *Oncomouse*, with cancer gene
1990	Discovered cystic fibrosis gene - L. Tsui, F. Collins, J. Riordan Human Genome Project begun - J. Watson and others	First gene therapy trials begin in U.S.
1992		Automated DNA sequencing technologies Field testing of corn hybrid genetically altered to resist European corn borers - Ciba Seeds
1993		Field testing of glyphosphate-tolerant soybeans by adding gene that increases production of EPSP enzyme - Ciba Seeds
1992-94		Genome tools - Lawrence Liverpool Nat'l Lab: High-speed, high-purity chromosome sorter; High-speed flow cytometer; Liquid ion-exchange chromatography
1994		First FDA approved gen. altered food: Flavr-Savr
1995	First complete DNA sequencing of a free-living organism *Haemophilus influenzae*	
1995-97	Nine more complete DNA sequences completed including yeast, the first eukaryotic organism	
1997		Nuclear transplanation experiment using nucleus from differentiated cell produces a lamb Dolly Genetic chip to hold personal data being developed

Sources: Barnum, 1998; Mariella & Copeland, 1995; Markert, 1989; Studt, 1998; Watson, 1980; Weaver & Hedrick ,1992; Winchester & Wejksnora, 1996. *Nobel prizes awarded.

The Symbiotic Relationship

The symbiotic relationship was not initially apparent. But as the 20th century progressed, the technology and science of biotechnology became so intertwined that it became increasingly difficult to distinguish between the two. The American Association for the Advancement of Science (1989) saw this relationship in a broader context as characteristic of current science, technology, and mathematics. In its recommendations for elementary and secondary education, *Science for All Americans*, the following statement summarizes this perspective:

> It is the union of science, mathematics, and technology that forms the scientific endeavor and that makes it so successful. Although each of these human enterprises has a character and history of its own, each is dependent on and reinforces the others. (p. 25)

One of the shifts in the old science-technology paradigm that strengthened the symbiotic relationship was the identification of new "tools" for performing the work of both science and technology. These tools—retroviruses, adenoviruses, and bacteria plasmids—are not mechanical but biological in nature, too small to be seen by the naked eye. Hence, the methods of technology and science have become so similar in genetic engineering that the primary means of distinguishing them is by the *purpose* of a given enterprise, that is, whether the process was being done strictly to gain new scientific information or to make a marketable product. But even this distinction is artificial since research scientists, employed by biotechnology industries, continue to add to the body of scientific knowledge while developing new bio-related products and techniques. If a commercial company identifies a new retrovirus for opening a human cell, or develops the process for manufacturing an important therapeutic human protein in a vat of bacteria, or identifies a plasmid vector that is capable of crossing the brain barrier, the company has extended our understanding of the biology and chemistry of the human body and provided another tool for conducting research.

Genentech, founded in 1976, was one of the new companies that was formed exclusively to exploit the commercial potential of genetic engineering. Genentech established an early success pattern by producing insulin

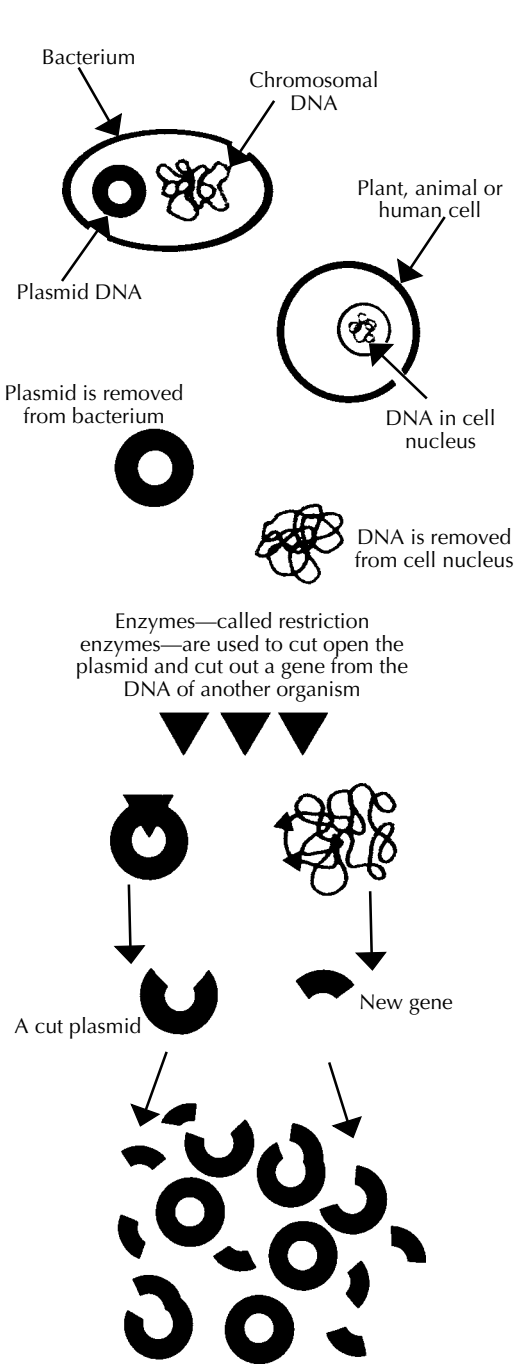
outside the human body in 1978 (licensed to Eli Lilly); the human growth hormone to counter dwarfism in 1979; interferon, a tumor-reducing protein, in 1981; and more. Figure 2 illustrates the process by which these proteins are produced. Well over 100 firms now exist in the genetic engineering business, and the Patent and Trademark Office is inundated with patent applications for genetically manipulated plants, animals, and substances. By May 1995, 11,815 patents for genetically engineered substances had been approved (Woodward, 1995).

Genetic engineering is moving in several directions at once. The commercialization of genetically manipulated plants and animals began in the late 1970s. Transgenic mice and *Drosophila* fruit flies were produced in 1981. The first patent for a genetically engineered animal was granted in 1988 for *Oncomouse*, a mouse that carries a cancer-gene. The mice and fruit flies were obviously developed to aid disease research, but a number of genetically manipulated improvements have also been made in animals and crops for agricultural profitability.

A corn hybrid genetically altered to resist European corn borers was field tested by Ciba Seeds in 1992. Soybean seed is now available that has been genetically engineered to tolerate glyphosphate herbicides such as Roundup®, which kills virtually all vegetation (Monsanto, 1992). Monsanto has also developed cotton plants that are protected against the cotton bollworm and potatoes that are virus and insect resistant. Without question, the success of these experiments required a sound understanding of prior science, and the development of these animals and plants has contributed much to our scientific understanding.

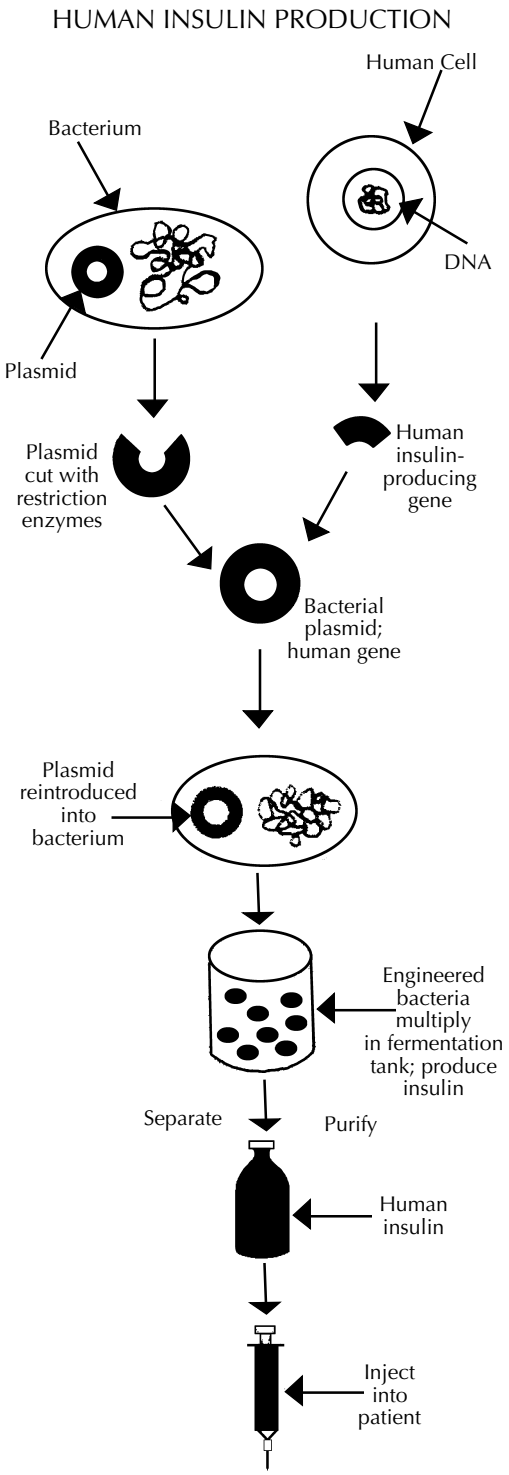
Courtesy of Monsanto

Instead of using bacteria or fungus as hosts to produce human proteins, researchers at Genzyme Corporation and Tufts University have managed to insert a human gene for TPA—a protein to reduce blood clotting in heart attack victims—into a goat's DNA so that the nannies are able to produce TPA in their milk. The process by which this is done requires that a segment of human DNA containing the TPA-producing gene is combined in the lab with the goat's mammary control DNA. This modified gene is microinjected into a fertilized goat's egg. A "foster mother" receives the manipulated egg. Enough offspring express the desired gene to make the concept of transgenic animals feasible and potentially highly profitable. Milk is not the only way to produce human-needed drugs in transgenic animals. The DNX company has produced



The cut ends of the plasmids and the cut ends of the new genes are chemically "sticky" so they will attach to each other—recombine—to form a new loop containing the inserted gene. This technique is called "gene splicing" or recombinant DNA technology.

Figure 1. **rDNA technology.** ***Courtesy of Monsanto.***



Pharmaceuticals produced with genetic engineering technology are administered to patients by traditional methods.

Figure 2. **Human insulin production.** ***Courtesy of Monsanto.***

transgenic pigs that carry the gene for human hemoglobin and produce the human cells in their blood (Glanz, 1992).

One phase of genetic engineering is called gene therapy, the goal of which is to insert DNA into human cells to either replace genes that are not functioning properly or to create proteins for such purposes, or stimulating cellular immunity. More than 3,200 genetic defects, potential targets for gene therapy, have been cataloged. Among the most common candidates for gene therapy are cystic fibrosis, AIDS, diabetes, cancer, hemophilia, emphysema, sickle-cell anemia, and Tay-Sachs disease (Begley, 1995). In 1990, the first government-sanctioned human gene therapy began with a child receiving modified cells for severe combined immune deficiency (SCID). Scientists and biotechnologists alike were very optimistic about the potential success of this new means of treating genetic diseases. By early 1998, the National Institutes of Health had approved 222 experimental procedures, 190 for testing therapeutic approaches (Henig, 1998). However, Friedman noted in 1997 that "no approach has definitively improved the health of a single one of the more than 2,000 patients who have enrolled in gene therapy trials worldwide" (p. 96).

Final Comments

The symbiotic relationship between science and technology is illustrated convincingly by the parallel and collaborative development of genetics and genetic engineering. This relationship has produced an increasingly powerful force in society with ethical, legal, and political ramifications. Combined, they will be a powerful lobbying group for government funds as well as for favorable legislation.

We are, at our foundation, a technological society, a technological culture. Technology—to manipulate, modify, and exploit—is so fundamental to our outlook and to our process of life in the United States that it is inseparable from our conceptions and understanding of life. Our use of and dependence on technology is pervasive, and yet our understanding of technology in society is often elementary (Wiens & Wiens, 1996). A discussion of genetic engineering would not be complete without reference to some of the concerns raised by those who believe we must advance with caution, for example, Rifkin (1998), Volti (1995), Wheeler (1993), and Zallen (1998).

Biotechnology and genetic engineering will not eliminate much of medicine as we know it, but will revolutionize the treatment of many diseases and offer the potential for changing

human beings in ways only contemplated previously in science fiction. There will be increasing pressure to allow genetic enhancement (the ability to "improve" the appearance or abilities of otherwise healthy individuals) for those who can afford it. With the emphasis on the Human Genome study and genetic engineering, it is tempting to fall into the "nature is everything" trap, failing to remember the contribution of nurture.

W. French Anderson, the director of the first attempt at direct gene therapy, noted that genetic enhancement is "going to happen, and nobody can stop it" (cited in Kiernan, 1997, p. A17). This deterministic attitude suggests that this technology is beyond our control.

Humans live in an ever-changing social environment, very different from that of nonhuman animals. Nurture and the social environment are critical factors in human development. Ian Wilmut, the Scot who brought us Dolly, the cloned sheep, stated, "Why would we want to clone ourselves? Even if we truly desire an exact duplicate of someone . . . the plain truth is that we won't get it . . . . We are more than our genes" (cited in Zabludoff, 1998, p. 6). This argument is expanded by Cohen and Stewart (1994) in an article titled "Our Genes Aren't Us." The authors contended that "contrary to popular belief, our DNA alone doesn't determine who—or even what—we are" (p. 78).

The potential for dramatic change in what it means to be human is present in certain areas of genetic manipulation. Without a doubt, new technology creates new ignorance. We do not fully comprehend the risks and changes that may be delayed, unintended, and unrelated to the central purpose of genetic engineering procedure. We must proceed with caution in those areas where our understanding is limited.

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