What Fraction of the U.S. GNP Makes Use of Devices Invented as a Result of the Success of the Quantum Theory of the Atom?

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Preamble

In the years 1900 to 1930, data from observations of the atom were studied in order to understand the structure of the atom. The motivation was classical: a curiosity-driven quest stimulated by the lure of a new level of understanding. The questions: What are the constituents of the atom, and what are the laws of nature (forces) to which the atomic constituents are beholden? Data consisted of the periodic table of the elements, the spectral radiations emitted from "hot" atoms, and the chemical behavior of atoms in combinations. Theorists entered the atomic domain armed with fairly sophisticated and quantitative mechanics, based upon Newton's theory and a powerful, mathematically elegant set of equations describing electrical and magnetic phenomena.

It turned out that this pre-existing knowledge was inadequate to explain the data which eventually included the existence of electrons (1900), nuclei (1910) with electrons capable of emitting photons of particles of light energy (1923). Success was only achieved with a revolutionary new concept of nature. It was called the Quantum Theory. By the 1930s it was clear that this theory was indeed able to explain all the data on atoms. The theory was quickly applied to chemistry and the behavior of solids - metals, insulators, semiconductors. It applied to molecules, the radiation from atoms and the interactions of light and matter. In the 1940s, this theory was applied successfully to nuclear structure, nuclear radiations and reactions. Out of these understandings came a vast technology which includes transistors, lasers, genetic engineering, modern chemistry, nuclear medicine, power, and weapons.

Warning! *Use only for occasional discussions. For more serious matters you should consult your personal economist.*

If all solid-state quantum devices were to cease functioning the instantaneous GNP would fall to zero. All communication would cease. TV and radio sets would go off. All newer cars with fuel injection would stop. Airplanes wouldn't fly, computers would be off, hospitals with their medical instruments and x-ray machines would reduce operations greatly, and production lines could not be controlled. In short, almost nothing would work. Clearly one could restore many of these functions which do not require solid-state devices, but the GNP is defined by economic activity and even non-essential activity contributes. Nevertheless, we do not believe that the quantum theory is responsible for 100% of the GNP. What is the fraction?

In what follows, the plan is to try to estimate the fraction of the economic activity that makes use of quantum mechanical devices. Our questionable methodology estimates the fraction of a given economic activity which uses post-atomic technology, for example, 100% of electronics and 0.1% of lumber production. Clearly the 100% is very close to being correct, but the 0.1% can be in serious error. In any case, our scheme arrives at 23% over a given set of direct activities. We argue that this fraction also works on the infrastructure. Whether the number is 20% or 30% makes very little difference to the bottom line: Scientists in a curiosity-driven quest for an understanding of what, in 1900, was a dimly conceived exotic concept, stimulated, by their discoveries, economic activity amounting to about $1000 billion (1987 dollars) of our annual GNP, which is about $4 trillion. One quarter of this part of the GNP, or $280 billion, is paid back to the federal government in taxes annually. This number can be very wrong, but still be an impressive return from science, compared to the $10 billions of federal funding which OMB defines as basic research.

What are the Technologies?

1) *Transistors*. The discovery and development of transistors is completely dependent on the theory of quantum mechanics. Some communications might have been possible without electron beams and transistors - after all, the telephone and telegraph predate these developments. What wouldn't have been possible is the rich fabric of modern communications.

2) *Computers*. Modern computers rely on three developments that spring from quantum mechanics and the experimental techniques that evolved with nu-

clear physics: the transistor, magnetic memories, and the flip-flop circuit that lets computers count.

3) *Lasers.* Lasers are a practical deployment of quantum mechanics. It is hard to imagine the laser principal being discovered without that theory. Society is approaching the point of a laser in every house (the compact disc [CD] player) and five in every supermarket (the bar code reader).

4) *Television.* The modern television tube is almost an exact embodiment of one of the first particle physics experiments, the measure of the charge and mass of the electron. All the elements of modern physics experiments appear in a TV tube - an accelerator, beam steering, and a detector. By now there have been a billion replications of this turn-of-the-century experiment with profound implications on our lives.

5) *Nuclear Energy.* Experiments to understand atomic structure naturally led to unlocking the tremendous energy inside the atomic nucleus. We do not yet know how man will be served by unlocking this genie. The problems may be with man, not the fruits of nature.

6) *DNA.* DNA is the stuff of biology, you say. True, but the techniques for understanding the structure relied heavily on quantum chemistry and x-ray crystallography. These, in turn, depend on the insights of quantum mechanics.

What are the Specific Revenues from These Technologies?

1) *Transistors.* Direct sales for 1984 were $9.6 billion. But note that there is an effective multiplier of a factor of nearly 15 here. The amount of electronic equipment containing transistors that was sold was $144.0 billion. (Note that this item partially double-counts items 2 and 4.)

2) *Lasers.* The magazine *Laser Focus* (January 1986 p. 84) reports that world-wide direct sales of laser components for commercial purposes amounted to $0.46 billion in 1985. Military systems sales exceeded $1.5 billion. This number does not include the associated equipment to operate the lasers. The markets are growing about 20% a year with one area, optical memories such as CD systems, expected to see very large growth.

3) *Computers.* The 1983 computer shipments had a value of $56.4 billion. *Datamation* (June 1, 1985) estimates 1984 U.S. revenues of the 100 largest companies active in the computer field as $106 billion.

4) *TV.* $50 billion (1984 dollars). This includes direct sales of television equipment and television-station revenue.

5) *Nuclear Energy.* In 1984, U.S. nuclear power plants produced 341 billion kwh of power. At $.07/kwh this corresponds to $24 billion.

6) *DNA.* Figures for the emerging biotechnology field are difficult to obtain. The Department of Commerce has projected that the domestic sales of biotechnology-based pharmaceutical and agricultural products was $0.2 billion in 1985. Investments in the field over the last five years has averaged $0.5 billion/year (*Science Magazine*, January 3, 1986).

What Fraction of the Gross National Product is Impacted by These Developments Now?

Making a concrete estimate here is fraught with pitfalls. What follows can easily be criticized. To get an estimate, the 1982 standard statistical categories for agriculture, mining, contract construction, manufacturing, transportation, communications, and utility revenues have been analyzed. An effort has been made to weight product categories appropriately. For many of these, R&D costs are know and have been added in as shown. The detail is contained in Attachment A.

In brief we attribute 23% of the 1983 gross national product to activities that are heavily influenced by developments stemming from the investigation of the atom at the turn of the century. While this number may seem high we also find reasons to believe that it is low. Consider the material that follows.

What Fraction Will They Be at the End of the Decade?

The figure on page 177 is taken from the book *The Microelectronics Revolution*, T. Forester, ed., (MIT Press, 1981). It shows the changing composition of the U.S. work force from 1860 projected to 1990. By then nearly 50% of the work force will be involved in information activities. A very large fraction of these activities rely strongly on the developments in basic physics in the early part of the century.

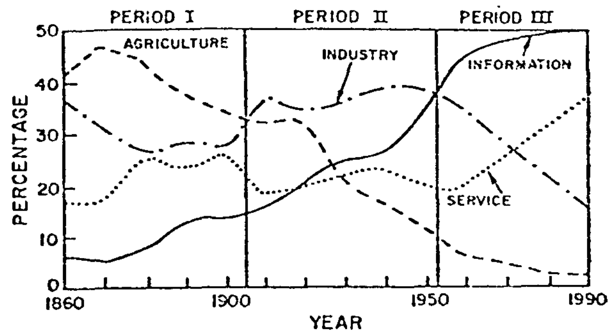

Fig. 1. Changing composition of the U.S. work force, 1860 to (projected) 1990.

These Technologies are the Bow Wave of the Future

What determines the future is what we do today and what our forefathers did 75 years ago. An important question to ask is what are the critical technologies today. We know of one germane list, "The Military Critical Technologies List," October 1984 (DOD AD-A146 998). This list is no doubt biased. For example, it doesn't touch on the important areas of health and nutrition. Twenty arrays of know-how are listed. Fundamental understanding of the nature of the atom plays a very major role in 16 of these.

Does All This Matter? The Twenty-First Century is Only a Decade Away

There is an interesting anecdote from the last century that speaks directly to this point. Heinrich Hertz, an eminent physicist of his day and the discoverer of radio waves, tried to measure the properties of what we now know as the free electron in the mid-1880s. In the process he built the first prototype of what has become the modern TV tube, but he did not find any electrons. Partly because of his reputation the search slowed. It was more than a decade later before J. J. Thompson actually measured the properties of the electron. All of modern electronics flowed directly out of that discovery. One might argue that the weight of Hertz's negative result slowed the development of modern electronics by 15 years and thereby affected every aspect of the twentieth century. Just imagine the development of commercial TV before World War II. Would history have been affected?

Are we missing similar opportunities now?

Attachment A

Fraction of 1983 Gross National Product (National Income) Attributable to Modern Physics. Source data from *1986 Statistical Abstracts of the United States*, p. 437. R&D numbers are drawn from Science Indicators 1985, p. 254. Numbers are in billions of dollars. Totals may not add because of rounding and omissions for clarity.

CATEGORY	INCOME	R&D	ATTRIBUTE	COMMENT
Agriculture	60.9			
Mining	40.0			
gas	(26.4)		6.6	25% explor
Contract constr.	112.3			
Manufacturing	579.9			
Durable	329.5			
Lumber	15.5	0.17	0.1	50% R&D
Furniture, etc.	9.5	"	"	
Stone, etc.	16.6	0.49	0.2	40% R&D
Primary metals	28.6	1.10	0.6	50% R&D
Fab. metals	41.2	0.63	0.3	50% R&D
Machinery-ne	64.3	8.38	4.2	50% R&D
Elec., electron	57.5	13.65	43.1	75%
Trans. equip.	31.6	13.74	23.1	a.
Motor vehic.	34.4	5.49	"	a.
Instruments	21.7	4.39	21.7	All
Misc. indust.	8.6	0.61	0.3	50% R&D
Non-durable	250.4			
Food, etc.	46.9	0.88	0.2	20% R&D
Tobacco	5.3			
Textiles	15.4	0.14	0.1	50% R&D
Apparel	19.2	"	"	w. apparel
Paper	22.6	0.75	0.4	50% R&D
Print & Pub.	36.9			w.print
Chemicals	44.8	7.39	22.4	50%
Petroleum	36.6	2.23	18.3	50%
Rubber	18.5	0.82	4.6	25%
Leather	4.0			

a. For motor vehicles and transportation equipment have assumed 100% of the aircraft and missile R&D ($13.74B) and 50% of the other R&D ($5.49B) plus 10% of the manufactured product.

Transportation	87.7		inc. unlist
Railroad	15.9		
Local	4.6		
Trucking	36.7	3.7	10% f. electr.
Water trans.	5.8	0.6	10% f. electr.
Air trans.	16.4	8.2	50% (Mowery)
Communications	60.1	45.1	75%
Utilities	64.3	32.1	50%
TOTAL	1005.2	235.9	23%

INFRASTRUCTURE ACTIVITIES (see below)

Trade	386.4
Finance	394.0
Service	426.6
Government	391.7
Other	48.3
TOTAL	1646.0

Infrastructure activities are assumed to have the same factor as the other sector. As an example, T. Breshanaham of the Stanford University Center of Economic Policy estimates that the financial services industry has a direct return of at least a factor of three for investments in computer hardware. If the overall impact of the computer field is assumed to follow the same picture and financial services participate proportionally (16% of the GNP) there is a 12% impact of computers on financial services. We estimate that the other portion of electronic sales (e.g., in communications) impacts at the same level.