The Progress of Computing

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Abstract

The present study analyzes computer performance over the last century and a half. Three results stand out. First, there has been a phenomenal increase in computer power over the twentieth century. Performance in constant dollars or in terms of labor units has improved since 1900 by a factor in the order of 1 trillion to 5 trillion, which represent compound growth rates of between 30 and 35 percent per year for a century. Second, there were relatively small improvements in efficiency (perhaps a factor of ten) in the century before World War II. Around World War II, however, there was a substantial acceleration in productivity, and the growth in computer power from 1940 to 2002 has averaged close to 50 percent per year. Third, this study develops estimates of the growth in computer power relying on performance rather than on input-based measures typically used by official statistical agencies. The price declines using performance-based measures are markedly higher than those reported in the official statistics.

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What has been the progress in computing? While this topic has been the subject of intensive research over the last five decades, little attention has been paid to linking modern computers to pre-World-War-II technologies or even pencil-and-pad calculations. The present study investigates the progress of computing over the last century and a half, including estimates of the progress relative to manual calculations.

The usual way to examine technological progress in computing is either through estimating the rate of total or partial factor productivity or through examining trends in prices. For such measures, it is critical to use constant-quality prices so that improvements in the capabilities of computers are adequately captured. The earliest studies examined the price declines of mainframe computers and used computers that date from around 1953. Recent work has been undertaken by the U.S. statistical agencies and covers a wide range of computer technologies. Early studies found annual price declines of 15 to 30 percent per year, while more recent estimates in the national income and product accounts find annual price declines of 25 to 45 percent.[2]

While many analysts are today examining the impact of the "new economy" and particularly the impact of computers on real output, inflation, and productivity, we might naturally wonder how new the new economy really is. Mainframe computers were crunching numbers long before the new economy hit the radar screen, and mechanical calculators produced improvements in computational abilities even before that. How does the progress of computing in recent years compare with that of earlier epochs of the computer and calculator age? This is the question addressed in the current study.

I. A Short History of Computing

Computers are such a pervasive feature of modern life that we can easily forget how much of human history was lived without even the most rudimentary aids to calculation, data storage, printing and copying, rapid communications, or computer graphics. It is roughly accurate to say that most calculations were done by hand until the beginning of the 20th century. Before that time, mechanical devices such as the abacus (which originated in China about the 13th century), the Napierian logarithm (from 1614), and a host of

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[2] See J. Steven Landefeld and Bruce T. Grimm, "A Note on the Impact of Hedonics and Computers on Real GDP," *Survey of Current Business,* December 2000, pp. 17-22 for a discussion and a compilation of studies.

ingenious devices designed by Leonardo da Vinci, Blaise Pascal, and Thomas de Colmar were invented but generally did not find widespread use among clerks and accountants.[3]

It is difficult to imagine the tedium of office work in the late 19th century. According to John Coleman, president of Burroughs, "Bookkeeping, before the advent of the adding machine, was not an occupation for the flagging spirit or the wandering mind…. It required in extraordinary degree capacity for sustained concentration, attention to detail, and a passion for accuracy."[4] Further, "lightning calculators," people who could add up columns of numbers rapidly, were at a premium.

In the late 1880s, a workable set of mechanical calculators was designed that gradually took over most laborious computational functions. Two ingenious designs were circular Odhner machines (invented 1875), and machines designed as a matrix array of keys (invented 1886) produced by Felt Comptometer, American Arithmometer, and later Burroughs. We have a 1909 report from Burroughs which compared the speed of trained clerks adding up long columns of numbers by hand and with a Burroughs calculator, as shown in Plate 1. These showed that the calculator had an advantage of about a factor of six:

> Ex-President Eliot of Harvard hit the nail squarely on the head when he said, "A man ought not to be employed at a task which a machine can perform."
>
> Put an eight dollar a week clerk at listing and adding figures, and the left hand column [see Plate 1 below] is a fair example of what he would produce in nine minutes if he was earning his money.
>
> The column on the right shows what the same clerk could do in one-sixth the time, or one and a half minutes.[5]

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[3] A comprehensive economic history of calculation before the electronic age is presented in James W. Cortada, *Before the Computer*, Princeton University Press, Princeton, N.J., 1993.

[4] Quoted in Cortada, *Before the Computer*, p. 26.

[5] Burroughs Adding Machine Company, *A Better Day's Work at a Less Cost of Time, Work and Worry to the Man at the Desk: in Three Parts Illustrated*, Third Edition, Detroit, Michigan, 1909, pp. 153-154.

The next revolutionary development in computation was the introduction of punched-card technology. We describe this system in detail to give the flavor of the early development of computers. The punched card system developed by Herman Hollerith (whose company later evolved into IBM) has been thoroughly described in the historical literature and its performance characteristics are clear.

The Electrical Tabulating System, designed by Hollerith in the late 1880s, saw limited use in hospitals and the War Department, but the first serious deployment was for the 1890 census. Using a specially designed machine known as a pantograph, clerks entered census data onto punch cards, which the tabulator read one at a time. The tabulator's operator pressed a grid of telescoping metal pins down onto each card, and the pins penetrated through punched holes in the card to complete electrical circuits. Certain circuits incremented mechanical counters, and the values read off these counters were used to produce the census summary tables. To speed further tabulations, a sorter was attached to the tabulator. When the tabulator read a card, a signal would travel to the sorter, and an appropriate box on the sorter would open. The operator could then place the card in the box, and move on to the next card. Each census card was a 12 by 24 grid, allowing for 288 punch locations. Since the tabulator handled one card at a time, word size was 288 bits. There were inaccuracies in the tabulations because of the now-famous chads, which often were incompletely detached and improperly read.

The Hollerith tabulator was the opposite of the general-purpose modern electronic computer. It was essentially a "one-note Hermie" that could perform only one function. It was unable to subtract, multiply, or divide, and its addition was limited to simple incrementation. Its only function was to count the number of individuals in specified categories, but for this sole function it was far speedier than all other available methods. During a government test in 1889, the tabulator processed 10,491 cards in 5½ hours, averaging 0.53 cards per second. In a sense, the Hollerith tabulator was the computer progenitor of IBM's "Deep Blue" chess-playing program, which is the reigning world champion but couldn't beat a 10-year-old in a game of tic-tat-toe.

Over the next half-century, several approaches were taken to improving the speed and accuracy of computation and are familiar to most people. The major technologies underlying the computers examined here are shown in Table 1. The major technological milestones were the development of the principles of computer architecture and software by John von Neumann (1945), the first electronic automatic computer, the ENIAC (1946), the development of the first microprocessor (1971), personal computers (dated variously from the Simon in 1950 to the Apple II in 1977 or the IBM PC in 1981), and the introduction of the world wide web (1989).

Overall, we have identified 187 computing devices in this study for which minimal price and performance characteristics could be identified. The full set of machines and their major parameters are listed in the Appendix.

II. Measuring Computer Performance

Background on measuring performance

We can distinguish two fundamentally different approaches to measuring computer power or prices: (1) ones that attempt to measure performance on a selected set of tasks and (2) measures that derive from the prices of inputs or components of computers. In general, computer scientists, users, and trade journals tend to emphasize performance while economic approaches, including "hedonic" price indexes, have relied upon the second approach. To the maximum possible extent, this study relies on indexes of performance rather than on inputs.

Measuring computer power has bedeviled analysts because computer characteristics are multidimensional and evolve rapidly over time. From an economic point of view, a good index of performance would include both measures of performance attributes on a number of tasks and a set of weights that indicate the relative importance of the different tasks. For the earliest calculators, the tasks involved primarily addition (say for accounting ledgers). To these early tasks were soon added scientific and military applications (such as calculating ballistic trajectories or weather forecasts). In the modern era, applications of computers range from number crunching in scientific applications to consumer applications such as surfing the web, word processing, downloading MP3 files, and virus protection.

Unfortunately, there is virtually no information on either the mix or relative importance of applications over time or of the market or implicit prices of different applications. The absence of reliable data on performance has forced economic studies of the hedonic prices of computers to draw instead on the market or implicit prices of the input components of computers. The hedonic approach is not taken in this study but will be discussed in a later section.

The present study measures the "power of computers" as the price of performing a set of computational tasks. The tasks examined here evolve over time as the capabilities of computers grow -- much as the standardized tests given to students change from those given to 3-year olds to those given to prospective graduate students. Table 2 gives an overview of the different measures of performance that are applied to the different computers.

The earliest calculators were often limited to one instruction (addition), but could sometimes parlay this into other arithmetic functions (multiplication as repeated addition). The earliest metric of computer performance therefore is simply addition time – definitely a most valuable attribute a century ago. This is converted into a measure of performance that can be compared with later computers using an information-theoretic measure devised by Morevec. For computers from around World War II until around 1975, we use a measure of performance developed by Knight that incorporates additional attributes. Modern computers have much more complex instruction sets and perform the instructions much more rapidly and accurately. Hence, for the modern period we use computer benchmarks that have been devised by computer scientists to measure performance on today's demanding tasks.

The Measure of Performance: Units of Computer Power (UCP)

The present study uses a measure of computer power that links together indexes of performance for different generations of computers. This measure is called *units of computer power* (or *UCP)*. A summary description is that a unit of computer power is the ability in an early computer to add twenty 32-bit (or 9-digit) numbers in one second. Computer power in a modern computer is more complex, and consequently we measure power in personal computers by the speed (and ability) to play chess, operate a large word-processing software program, simulate a crash, or recognize a face. Humans or early mechanical calculators could perform fractional UCPs, while modern high-end personal computers are estimated to operate at more than a billion UCPs.

Addition Time

The earliest machines, as well as manual calculations by humans, dealt primarily with addition. Plate 1 shows the results of a typical task as described in 1909. In fact, until World War II, virtually all commercial machines specialized in addition and treated multiplication simply as repeated addition. We can compare the addition time of different machines quite easily as long as we are careful to ensure that the length of the word is kept constant for different machines. For the comparisons used here, I take addition of 32-bit (or approximately 9-digit) numbers as the standard of comparison.

Moravec's Information-Theoretic Measure of Performance

The only study that I have uncovered that attempts to calculate the long-term performance of computational devices is by Hans Moravec, a computer scientist at Carnegie-Mellon. To compare different machines, Moravec used a very abstract definition, one based on the production of information. Under the information-theoretic approach, computing power is defined as the amount of information delivered per second by the machine – that is, the quantity of information produced as the machine moves from one internal state to another.[6] Information is defined in the sense of Shannon as the "surprise" about the outcome. Quantitatively, if there is a probability p that the machine will move into one of two binary states, then the information delivered if it does go into that state is $-\log_2(p)$ bits of information.

This can then be put on a standardized basis by considering words with a standard length of 32 bits (equivalent to a 9-digit integer), and instructions with a length of one word. In other words, the benchmark programs analyzed are assumed to contain about 32 bits of information per operation. Hence, adding two 9-digit numbers will produce an answer that has about 32 bits of information in the sense used here. It is assumed for Moravec's measure that the only operations considered are addition and multiplication, and that these are weighted seven to one in the operation mix. Using this definition, the information-theoretic definition of performance is:

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[6] See Moravec, *Mind Children: The Future of Robot and Human Intelligence*, Harvard University Press, Cambridge, MA, 1988, especially Appendix A2 and p. 63f.

Computer power (Moravec)
$= 0.05 \{[6 + \log_2 (\text{memory}) + \text{word length}]/[(7 \times \text{add time} + \text{mult time})/8]\}$

The factor of 0.05 is used to convert to modern benchmark estimates. Applying this formula to a machine that can perform 20 million additions per second, with 32 bit words, a multiplication time five time slower than the addition time, and 640 bits of memory yields a computer power of 1 MUCP (one million units of computer power). This formula provides a natural link to addition as a measure of performance.

The attractiveness of this approach is that each of these parameters is available for virtually all computers back to 1940, and for some calculators before that period. The disadvantages are that it omits many of the important operations of modern computers, it considers only machine-level operations, and it cannot incorporate the advantages of modern software, higher-level languages, and operating systems. For these, we turn to Knight's measure and benchmark measures.

Knight's measure

One of the earliest studies of computer performance was by Kenneth Knight of RAND in 1966.[7] He gathered performance data on five kinds of operations (fixed-point addition, floating-point addition, multiplication, division, and logic instructions). He then collected information on the mix of these operations for both 100 scientific problems for an IBM 704 and an IBM 7090 and nine commercial programs (accounting, inventory control, etc.) on an IBM 705. Unfortunately, there appears to be no trace of his data, so we cannot easily compare the underlying data with those in other studies. Knight's formula was relatively complex, but can be summarized as follows:

Knight's Index of Computer Power
$\approx 10^6 \{ [(\text{word length} - 7)(\text{memory})]/[\text{calculation time} + \text{input-output time}]\}^{1/2}$

Knight's formula is quite similar to Moravec's except that he includes a larger number of performance characteristics and that he uses the actual mix of instructions on sample problems rather than an assumed mix.

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[7] Kenneth Knight, "Changes in Computer Performance," *Datamation*, vol. 12, no. 9, Sept. 1966, pp. 40-54 and "Evolving Computer Performance 1963-1967," *Datamation*, vol. 14, no. 1, Jan. 1968, pp. 31-35.

Modern Benchmark Tests

Measures like additions per second or more complex indexes like those of Knight or Moravec are generally thought inferior to modern benchmarks of computer performance. Computers today do much more than bookkeeping, and a performance benchmark must reflect today's mix of activities rather than that of a century ago. For this purpose, we turn to modern benchmark tests.

A benchmark is a test that measures the performance of a system or subsystem on a well-defined set of tasks. There is an entire industry devoted to devising benchmarks. This is not surprising given the diversity in types and uses of computers; after all, computers are used for word processing, cryptography, games, econometric estimation, air-traffic control, computer-assisted design, web surfing, payrolls, and operating anti-missile systems. For example, a common benchmark test for PCs in 2002 (Worldbench 4) would test the performance on Adobe Photoshop 5.0, Corel Photo-Paint 8,Intuit Quicken Deluxe 99, Lotus 1-2-3 r9, Lotus Word Pro 9, Microsoft Access 2000, Microsoft Excel 2000, Microsoft PowerPoint 0, Microsoft Word 2000, Netscape Communicator 4.73, and Visio 5.0 Standard Edition. Supercomputers often use the LINPACK benchmark, which solves a dense set of linear equations.

For purposes of historical comparison, an important benchmark is "Dhrystone MIPS." (We discuss the concept of MIPS, or millions of instructions per second, in the next section.) This benchmark relies on the Dhrystone benchmark, which is a short synthetic benchmark program developed in 1984 to test system (integer) programming. The use of the term "MIPS" is misleading and in fact represents the performance relative to a benchmark machine. Over the last two decades, "MIPS" ratings have been set by comparing the Dhrystone rating of a machine with the Dhrystone rating of a benchmark machine. The standard is that a Digital Equipment Corporation VAX 11-780 is assumed to be exactly a 1 MIPS system. To make comparisons from this study comparable with that of other studies, we calibrate our units to "Dhrystone MIPS." This means that 1 MUCP will be equal to 1 Dhrystone MIPS. Similarly, the Moravec power formula is calibrated so that it equals 1 MIPS for the VAX 11-780. Until the mid-1990s, benchmark ratings were generally calculated by dividing the Dhrystone rating of the machine in question by the VAX 11-780's Dhrystone rating of between 1657 (version 2.1) or 1758 (version 1.1).

The original Dhrystone test system is obsolete in terms of current machine architecture. The most widely used benchmarks for personal computers today are those designed by SPEC, or the Standard Performance Evaluation Corporation. The current version used for personal computers is SPEC CPU2000.[8] SPEC CPU2000 is made up of two components that focus on different types of compute intensive performance: SPECint2000 for measuring and comparing computer-intensive integer performance, and SPECfp2000 for measuring computer-intensive floating-point computation.

Table 3 shows the suite of activities that SPEC2000 tests. These are obviously not the routine chores that people require of their personal computers, and to some extent, therefore, the benchmarks are not weighted by the economic importance of different applications. We discuss briefly below whether using performance standards for frontier computing tasks is an appropriate metric.

MIPS as a misleading benchmark

One of the most common measures of computer performance is MIPS, or millions of instructions per second. In simple terms, IPS measures the number of machine instructions that a computer can execute in one second. MIPS has been used as a benchmark for many years and is the lingua franca of the computer-benchmark society.

MIPS measures performance in terms of “instructions per second.” To understand the logic of this measure, we begin with some elementary definitions. Computers that use the von Neumann architecture contain an internal clock that regulates the rate at which instructions are executed and synchronizes all the various computer components. The speed at which the microprocessor executes instructions is its “clock speed.” For most personal computers up to now, operations have been performed sequentially, although

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[8] See http://www.spec.org/osg/cpu2000/ .

with the development of parallel processing, computation may become more rapid as instructions are performed simultaneously.[9]

The other major definition is an instruction. An instruction is an order given to a computer processor by a computer program. At the lowest level, each instruction in a digital computer is a sequence of 0s and 1s that describes a physical operation the computer is to perform; for example, an instruction might be to add two numbers or to move a "word" from one location to another. Computers with complex instruction sets might have between 200 and 400 machine-language instructions, while computers with reduced instruction sets would have only 30 to 50 unique instructions.

Instructions differ in terms of the size of the "word" that is addressed. The size of a word varies from one computer to another, depending on the CPU. In the earliest computers (such as the Whirlwind I), words were as short as 16 binary digits or 5 decimal digits. Most personal computers today use 32-bit words (4 bytes). On large mainframes, a word can be as long as 64 bits (8 bytes). The most common instructions in early computers used one word, although the length might be one-half or two words. In modern machines, word size is at or migrating toward 64 bits.

Using these definitions, we can then define the number of instructions per second (usually measured as millions of instructions per second, or MIPS) by

$$\text{MIPS} = \text{clock rate}/(\text{cycles per instruction} \times 10^6)$$

Hence, a computer, which executes 10 million instructions in 2 seconds, has a rating of 5 MIPS.

Given the discussion above, it is easy to see why MIPS is defective in a number of respects. First, it does not specify the size of the word or the nature of the instruction. Long words have more computational value than short words. Some instructions (such as division) require much more computer power than simple instructions (such as addition). The definition does not consider the mix or the number of instructions. Most important, it does not

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[9] Many of the major topics in computer architecture can be found in books on computer science. For example, see G. Michael Schneider and Judith L. Gersting, *An Invitation to Computer Science,* Brooks/Cole, Pacific Grove, California, 2000.

actually measure performance. It is akin to measure the performance of an engine as its RPM rather than in terms of speed, fuel economy, and safety. In short, it violates the central rule of index numbers by failing to consider an invariant bundle of characteristics.

III. Data

The approach used in this study was inspired by a study of artificial intelligence and robotics by Hans Moravec.[10] That source contains data on add time, multiplication time, device cost, MIPS equivalent, memory, and word length. There was little documentation of the Moravec data, and some of it was inaccurate, so we set about verifying all data from original sources.

Data for early computers (from 1945 to 1961) were largely drawn from technical manuals of the Army Research Laboratory, which contain an exhaustive and careful study of the performance characteristics of systems from ENIAC through IBM-702.[11] Additionally, studies of Kenneth Knight provided estimates of computer power for the period 1945 through 1966. Data on the most recent computers have been carefully compiled by John C. McCallum and are available on the web.[12] Many of these were independently verified. The data on prices and wage rates were prepared by the author and are from standard sources, particularly the U.S. Bureau of Labor Statistics and the U.S. Bureau of Economic Analysis.

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[10] Hans P. Moravec, *Robot : Mere Machine to Transcendent Mind*, Oxford University Press, 1998 and "When will computer hardware match the human brain?", *Journal of Transhumanism*, vol. 1, March 1998. Morevec's data are available at www.transhumanist.com/volume1/moravec.htm.

[11] See particularly Martin H. Weik, A Survey of Domestic Electronic Digital Computing Systems, Ballistic Research Laboratories, Report No. 971, December 1955, Department of the Army Project No. 5b0306002, Ordnance Research And. Development Project No. Tb3-0007, Aberdeen Proving Ground, Maryland available at http://ed-thelen.org/comp-hist/BRL.html. This was updated in Martin H. Weik, *A Third Survey of Domestic Electronic Digital Computing Systems,* Report No. 1115, March 1961, Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland, available at http://ed-thelen.org/comp-hist/BRL61.html#table-of-contents.

[12] See http://www.jcmit.com/cpu-performance.htm .

Reliable data for the earliest calculators and computers (for the period 1857 through 1945) were not available published studies. With the help of Eric Weese of Yale University, data from historical sources on the performance of 20 machines from before World War II were obtained. The data on manual calculations were taken from a Burroughs monograph and were verified by hand calculations that suggest that the estimates are tolerably close. (For reference purposes, if with 99 percent accuracy you can add two five-digit numbers in 10 seconds and multiply two five-digit numbers in two minutes, you have the computational capability of the "manual" computer in our calculations.)

We have estimated the capabilities of early machines based on then-current procedures. For example, most of the early machines were unable to multiply. We therefore assume that multiplication was achieved by repeated addition. Additionally, the meaning of memory size in early machines is not obvious. For machines that operate by incrementation, we assume that the memory is one word. There are major discrepancies between different estimates of the performance of early machines, with estimates varying by as much as a factor of three. Given the difficulties of collecting data on the earliest machines, along with the problems of making the measures compatible, we regard the estimates for the 1890-1945 period as subject to large errors.

The data underlying the figures and tables are shown in the Appendix Table. We also show the difference among different measures in the next section. The construction of the performance series denoted MUCP was described above. The only other non-trivial calculation is the cost per operation. These calculations include primarily the cost of capital. We have also included estimates of operating costs as these appear to have been a substantial fraction of costs for many of the computers and may be important for recent computers. For the capital cost, we estimate a user cost of capital with a constant real interest rate of 10 percent per year, an exponential depreciation rate of 20 percent per year, and a utilization factor of 2000 hours per year. These assumptions are likely to be oversimplified for some technologies, but given the pace of improvement in performance, even errors of 10 or 20 percent for particular technologies will have little effect on the overall results. To paraphrase Bob Gordon's remark, in this area economics is a one-digit science.

IV. Results

Overall trends

I now discuss the major results of the study. It will be useful to start with the overall picture in Figure 1, which shows the trend in the cost of computing over the last century and a half. Begin by examining the vertical axis, which measures the price of a MUCP of computing power in 1996 prices, running on a scale from $\$10^{-8}$ per MUCP to $\$10^{6}$ per MUCP, that is by 14 orders of magnitude. The basic picture is simple and striking. There was relatively little progress in computing from the mid 1800s until around 1940. Since 1940, the progress has been virtually continuous and extraordinarily rapid.

Figure 2 shows the cost of computing for different fundamental technologies. There was very modest progress during the mechanical age, although electromechanical machines appear to increase speed and performance by a factor of about ten. Once the switch was made to electronic computing and modern computer architecture, the progress was rapid and virtually unbroken even as the transitions were made from one major technology to another. The decline in the cost of computation from the earliest period until today ranged from around \$10,000 ($\$10^{-5}$) per MUCP in the late 19th century to around \$0.0000001 ($\$10^{-7}$) per MUCP today, for an improvement of approximately a trillion, or 10^{12}.

An alternative measure is the cost of computer power relative to the cost of labor (the units are therefore MUCP per hour of work).[13] This is essentially the inverse of total labor productivity in computation. Relative to the price of labor, computation has become cheaper by a factor of 5×10^{-12}, or by a factor of approximately 5 trillion. A century ago, the cost for 20 standardized operations at 1998 wages using manual calculation was around \$1. That had fallen to $\$10^{-12}$ for computers available in early 2001.

Figure 3 shows the results in terms of pure performance, that is the equivalent speed of different machines. Before World War II, computation

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[13] The advantages of using wage as a deflator are twofold. First, it provides a measure of the relative price of two important inputs (that is, the relative costs of labor and computation). Additionally, the convention of using a price index as a deflator is defective because the numerator is also partially contained in the denominator.

speeds were in the order of between 0.01 and 1 units of power (i.e., between 10^{-6} and 10^{-8} of a MUCP). Manual calculations were clocked to have a speed of 0.08×10^{-6} MUCP. The increase in computational power relative to manual calculations or the mechanical calculators of around 1900 has been phenomenal. The increase in computer power has been 75,000,000,000 relative to manual calculations and 15,000,000,000 relative to the average mechanical calculator of the 1900 era.

We noted in the last section that the measures of performance differ because of inconsistencies in the data as well as the use of different benchmarks. Figure 4 shows the range of estimates of computer power for the different computer. It is clear that there are large error margins for many computers.

Trends for different periods

We next examine the progress of computing for different subperiods. On the whole, the picture is clear that progress was slim before 1940 and rapid afterwards. Given the heterogeneous nature of the different machines examined here, however, it is difficult to create a constant-quality price index that accurately tracks performance and price over short periods of time. We have therefore taken two slightly different approaches to examining subperiod performance – examining representative computers and regression analysis.

Tables 4 and 5 show the data on representative computers for nine different epochs (including manual calculations as the first period). Looking at Table 5, this approach shows modest growth in performance from manual computation to 1940. The average increase in computer productivity shown in the last column of the second row of Table 5 – approximately 1½ percent per year – was probably close to the average for the economy as a whole during this period.

A more robust estimate of the decadal improvements is constructed using a log-linear spline analysis. Table 6 shows a regression of the logarithm of the constant-dollar price of computer power with decadal trend variables, while

Table 7 and Figure 5 show the annual rates of improvement (measured as the inverse of the rate of declines in prices).[14]

Most histories of the computer suggest that there was a major break in the trend around World War II with the development of the basics of modern computer architecture, including the von Neumann design for stored programs along with the use of relays and vacuum tubes and as the first electronic computers were built (the ENIAC, the EDSAC, and the UNIVAC). The plots and the regression analysis confirm that there was indeed a tectonic shift around 1940, which marked the beginning of the explosion in computer power, performance, and productivity growth. A regression of the logarithm of the cost of computer power on time and a shift variable in 1940 estimates an acceleration in productivity growth of 0.40 (represented an annual average of 49 percent per year) with a t-statistic of 27.7 – which is off the chart in terms of statistical significance.[15] Over the last two decades, performance was also extremely rapid with the introduction of high-level languages and the development and continuous improvement of microprocessors.

One important question is whether there has been an acceleration in the pace of improvement or in the fall in prices in the last few years. Using decadal trend-break variables, we find statistically significant breaks in 1940, 1960, and 1980. The first and third breaks are accelerations in productivity and the second is a deceleration. The plots and regression analysis indicate that there was a relative “stagnation” in the 1960-80 period, with a decline in the real cost of computation of “only” 30 percent per year, and an acceleration to around 80 percent per year since 1990.

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[14] A warning on calculating rates of growth for computers and other high-tech industries. The coefficient of a logarithmic regression is the instantaneous growth rate not the annual growth rate. These two numbers will be close for small numbers (2 or 3 percent per year) but will diverge significantly when the growth rate is high. For example, a coefficient of 0.572 in a regression of log price on time represents an instantaneous growth rate of 57.2 percent per year but an annual growth rate of 77.2 percent per year.

[15] A warning on comparing the estimates using the rate of decline of prices with the rate of improvement in computer power: Decline rates are essentially the inverse of the growth rates. That is, the decline rate d is related to the growth g rate by $(1 + d)$
$= 1/(1 + g)$. Therefore, when growth rates are large, decline rates may look significantly smaller. For example, a growth in computer power per dollar of 80 percent per year is only a decline rate of 44 percent per year. This will be an important factor in comparing different studies.

The rapid improvement in computation power is often linked with "Moore's Law." This derives from Gordon Moore, co-founder of Intel, who observed in 1965 that the number of transistors per square inch on integrated circuits had doubled every year since the integrated circuit was invented. Moore predicted that this trend would continue for the foreseeable future. When he revisited this question a decade later, he thought that the growth rate had slowed somewhat and forecast that doubling every 18 months was a likely rate for the future. Computational power actually grows more rapidly than Moore's Law would predict, however, for computer performance is not the same thing as transistor density. From 1982 to 2001, the rate of performance as measured by computer power grew 12 percent per year faster than the transistor density of the chip. Note additionally that computer power grew at a phenomenal rate long before the widespread introduction of the integrated circuit.

Another interesting feature is the capital cost of the computer devices, shown in Figure 6. Capital costs per device shot up sharply in the 1940s as the first behemoth computers were built. However, particularly since the personal computers were introduced, the capital cost of the devices has declined sharply. Similarly, Figure 7 shows the progress in cycle speed over the last six decades, indicating that the progress has been quite steady.

One of the concerns with the approach taken in this study is that our measures might be poor indexes of performance. We have compared UCP with addition time in Figure 8 (similar results are found for clock speed). Both simple proxies show a very high correlation with our synthetic measure of UCP over the entire period. However, computer power grows 1.4 percent per year more rapidly than add time and 7 percent per year more rapidly than cycle speed.

A final point to note is that the variance of prices across different devices has declined markedly over the last century. Performance differed greatly among devices a century ago, while there is little difference in the performance per unit cost among the different devices in the last decade.

A useful summary of the overall improvement in computing relative to manual calculations is shown in the following table:

Improvement from Manual to 2002	Improvement (ratio)
Cost of device (1998 prices)[16]	0.19
Computer speed (MUCP)	75,000,000,000.
Calculation per $(MUCP per 1996$)	600,000,000,000.
Labor cost of computation (MUCP per hour)	4,700,000,000,000.

In short, relative to hand calculations like those performed by the young J.D. Rockefeller, the cost of the devices has declined sharply. The number of calculations per second increased by a factor of 75 billion. Compared to a skilled clerk of around the turn of the century, the cost of calculations has fallen by a factor of 600,000,000,000 relative to other consumer prices and by a factor of 4,700,000,000,000 relative to the cost of labor.

What is Computer Performance?

This study has emphasized the importance of "performance" in measuring the output and prices of computer power. For the earliest devices, performance was relatively easy to define and measure, involving primarily speed of addition and reliability. As computers took on more tasks, defining their performance became increasingly difficult. Reliability is no longer an issue for routine applications because the error rate is so low, but compatibility and connectivity are now major issues.

In this regard, it is natural to ask whether the changing character of computers is likely to bias the measures of computer power. In constructing a measure of performance, we would ideally want to have a list of tasks and appropriate expenditure weights on those tasks. The major defect with the recent-period benchmarks used here (SPEC and Dhrystone) is that they make no attempt to weight the scores on different applications by their relative performance. Moreover, they focus on testing high-end workstations and number-crunching, whereas the bulk of computers are desktops used for low-end consumer and business applications. A preliminary comparison of benchmark tests used for major low-end applications for PCs (such as

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[16] For the device cost, we use mechanical calculators rather than paper and pencil.

spreadsheets, word-processing, and data-base management) suggests that the improvements in consumer applications over the 1992-2002 period were significantly slower than those reported for scientific applications under the SPEC benchmark tests. Doing more careful comparisons of different benchmarks is an important area to pursue.

On the other hand, in linking together the benchmarks, we are overestimating the performance of earlier computers because many tasks that today's computers can perform (such as running Windows 2000, downloading web pages, producing computer graphics, or playing MP3 music files) were infeasible a decade ago. A measure of the increase in the versatility is the number of APIs (application programming interfaces) that are contained in Windows. According to Judge Jackson's *Findings of Fact* in the Microsoft antitrust case, Windows 98 supports over 70,000 applications.[17] This growing number and variety of software applications is one of the features of performance that is not captured in any current measure of computer performance.

One way of thinking about the potential bias is to determine whether the constructed price index would differ depending upon whether the output mix contained early or late applications. (This is equivalent to using Laspeyres and Paasche price indexes to determine index-number bias.) If we take an early output mix – addition only – then there is virtually no change in the price index over the period from manual computations to 1990 (see Figure 8). On the other hand, today's output bundle was infeasible a century ago, so a price index using today's bundle of output would have fallen even faster than the index reported here. Using the Laspeyres-Paasche bounds test, therefore, suggests that the bias is likely to be upward rather than downward, indicating that, if anything, the price of computation has fallen even faster than the figures reported here, at least through 1990. The divergent results of different benchmarks since 1990 cast doubt on whether the same result would apply in the last decade.

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[17] *Findings of Fact,* paragraph 40.

V. Comparison with Hedonic Indexes of Computer Prices

Hedonic approaches

Economists today tend to favor the use of hedonic or constant-quality price indexes to measure improvements. The hedonic approach attempts to measure the change in "quantity" of goods by examining the change in characteristics along with measures of the importance of the different characteristics. Under the direct approach, a hedonic function is estimated for each period and the shift of the function is estimated either using time dummy variables or by examining the shift in the function.[18]

For example, Paul Chwelos investigated the characteristics of computers that were important for users and information scientists in 1999 and found the top six characteristics were (1) performance, (2) compatibility, (3) RAM, (4) network connectivity, (5) industrial standard components, and (6) operating system.[19] He then estimated the change in the cost of providing the bundle.

Clearly, such an approach is not feasible over the long run. In the present study, we examined only the price of a single characteristic, performance. This decision reflects the fact that only two of the six performance characteristics discussed in the last paragraph [number 1 (performance) and number 3 (RAM)] can be tracked back for more than a few decades. Network connectivity is a brand-new feature, while operating systems have evolved from tangles of wires to Windows-type operating systems with tens of millions of lines of high-level (secret) code that probably is beyond the ken of more than a single individual. This discussion indicates that computers have experienced not only rapid improvements in speed but also a rapid increase in applications.

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[18] There are many excellent surveys of hedonic methods. A recent National Academy of Sciences report has a clear explanation of different approaches. See Charles Schultze and Christopher Mackie, *At What Price? Conceptualizing and Measuring Cost-of-Living and Price Indexes,* National Research Council, Washington, D.C., 2002.

[19] See Paul Chwelos, *Hedonic Approaches to Measuring Price and Quality Change in Personal Computer Systems*, Ph. D. Thesis, the University of Victoria, 1999,p. 43. Performance was defined as a "characteristic of the a number of components: CPU (generation, Level 1 cache, and clock speed), motherboard architecture (PCI versus ISA) and bus speed, quantity and type of Level 2 cache and RAM, type of drive interface (EIDE versus SCSI)."

One of the persistent difficulties with hedonic price estimates in general, and for computers in particular, is that they have tended to focus on input or component characteristics rather than on performance variables.[20] In an earlier study, I examined the case of lighting by estimating prices constructed from linked input prices (candles, kerosene, electricity, etc.) and those as the price of the output (lumen-hours). From this, I concluded that there was a major discrepancy between the input-based approach and the output- or performance-based approach.[21]

Similar questions arise in the case of computers. Generally, hedonic studies rely on measures of the prices of components, brand names, as well as some component performance indexes. Some studies combine rudimentary performance measures, such as MIPS, with component characteristics and other dummy variables. There are virtually no estimates of computer prices that rely upon the actual performance of computers in benchmark tests.[22]

One symptom of the inapplicability of input-based hedonic approaches is coefficient instability. This can be illustrated in the careful study by Berndt,

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[20] This point has been sometimes noted among analysts in this area. For a recent discussion, see Paul Chwelos, "Approaches to Performance Measurement in Hedonic Analysis: Price Indexes for Laptop Computers in the 1990's", Graduate School of Management, University of California, Irvine, California, August 18, 2000. The point was discussed as early as 1989 by Jack Triplett, who stated, "None of these synthetic benchmarks has yet been used in hedonic functions for computer processors. Since finding a satisfactory speed measure is the biggest challenge to measuring price and technological change in computer processors, future work will no doubt explore the usefulness of synthetic benchmarks." (See "Price and Technological Change in a Capital Good: A Survey of Research on Computers," in Jorgenson D. W. and R. Landau, eds., *Technology and Capital Formation,* Cambridge, MA, MIT Press, 1989, 127-213.)

[21] See William Nordhaus, "Do Real Output and Real Wage Measures Capture Reality? The History of Light Suggests Not," Robert J. Gordon and Timothy F. Bresnahan, *The Economics of New Goods*, University of Chicago Press for National Bureau of Economic Research, 1997, pp. 29-66.

[22] The major exception See Paul Chwelos, *Hedonic Approaches to Measuring Price and Quality Change in Personal Computer Systems*, 1999.

Griliches, and Rappaport.[23] Their year-by-year regressions show that the coefficients on random access memory, size of hard disk, weight, and size have inconsistent (changing) signs, while the coefficient on speed changes by a factor of more than 10 from year to year (see their Table 4). The problems can also be seen in the resulting price indexes for desktop computers, where estimates of the average annual rate of change of the quality-adjusted price indexes range from -9.7 to -36.6 percent per year for the 1989-92 period depending upon the specification. A second problem that seems to characterize the personal computer market is that imperfect competition may lead vendors to overprice high-performance models relative to older models, which leads to a downward bias of matched-model price indexes relative to performance-based price indexes.[24]

How do the performance-based indexes used here compare with conventional price indexes for computers? The summary table of different price indexes for recent periods is provided in Table 8. For the official price we use the deflator for computers (more precisely, computers and peripheral equipment) prepared by the Bureau of Economic Analysis (BEA) for the National Income and Product Accounts (NIPA).[25] The BEA data are generally derived from price estimates prepared by the Bureau of Labor Statistics (BLS).[26]

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[23] See Ernst R. Berndt, Zvi Griliches, and Neal J. Rappaport," Econometric estimates of price indexes for personal computers in the 1990s," *Journal of Econometrics*, vol. 68, 1995, pp. 243-268.

[24] See Michael Holdway, "Quality-Adjusting Computer Prices in the Producer Price Index: An Overview," available at http://stats.bls.gov/ppicomqa.htm , undated but apparently from 1999.

[25] The data are available at http://www.bea.doc.gov/.

[26] A descriptions of current BLS procedures is contained in Michael Holdway, "Quality-Adjusting Computer Prices in the Producer Price Index: An Overview," available at http://stats.bls.gov/ppicomqa.htm , undated but apparently from 1999. Earlier procedures are described in James Sinclair and Brian Catron, "An experimental price index for the computer industry," *Monthly Labor Review*, October 1990, pp. 16-24. A recent paper describes the use of performance tests in computer prices, see Michael Holdway, "An Alternative Methodology: Valuing Quality Change for Microprocessors in the PPI," available at http://www.bea.doc.gov/bea/about/advisory.htm .

Figure 9 shows a comparison of our performance-based price with the NIPA price (both in nominal prices) over the period 1970 to 2001.[27] They are indexed to equal 1 in 1970. The two series diverge significantly. Over the 1970-2002 period, our performance-based nominal price declined by 35 percent per year while the NIPA price declined by 12 percent per year. Thus, the performance-based price has fallen more than three times as rapidly as the official price. (All figures are geometric averages.)

For the shorter period from 1987 to 1998, we have detailed price indexes from several sources. For this period, according to the BEA, the nominal price of electronic computers (SIC 3571) fell by 15 percent per year. The BLS producer price index (PPI) looks not dissimilar: the PPI for electronic computers and computer equipment fell by 13 percent over the period from December 1990 to December 2000. By contrast, according to our estimates the nominal cost per operation fell by 41 percent per year.[28] Clearly, the official indexes look substantially different from the performance-based measures developed here.

How might we reconcile the significant discrepancy between the performance-based price series and official price indexes? To begin with, note that these two series shown in Figure 9 are not exactly comparable because the computer price is the deflator of computers and peripheral equipment whereas the performance-based measure is for computers only. In addition to computers, the NIPA series contains items like storage devices, terminals, and printers, whose prices have declined less rapidly than computers. Over the period 1987-98, the price index for the broader category fell about 3 percent per year more slowly that the index for electronic computers. The estimated PPI for computers just discussed also shows a relatively small decline over the last decade. So while some of the difference in prices is composition, there still remains a major gap.

Second, recent research raises questions about whether the BEA price index for computers is representative of hedonic pricing for computers as a

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[27] For this estimate, we assume that the NIPA price decline for 2002 will be 15 percent.

[28] Data on prices by four digit industry are from the BEA web site cited in the last footnote but one. (From worksheet hedonic industries 111900.xls.) The number of 41 percent is calculated from a spline regression but is consistent with other calculations for the period.

whole. A survey by Berndt and Rappaport indicates that the mean decline of alternative indexes for personal computers has declined by 36 percent per year over their sample period, which is significantly faster than the BEA index.[29]

Finally, the government price indexes for computers are hedonic indexes of the prices of the components of computers, or inputs into computation, while the measures presented here are indexes of the performance of computers. The hedonic measures will only be accurate to the extent that the prices of components accurately reflect the marginal contribution of different components to users' valuation of computer power. It is worth noting that current government hedonic indexes of computers contain *no* performance measure.[30]

A recent study by Paul Chwelos has found results very similar to those reported here. Chwelos investigated the use of performance-based measures in estimating prices of desktop and laptop computers. Based on his results, he concludes, "Using the results from the interactions approaches, it appears that in the 1990s, laptop PCs have declined in quality-adjusted terms at about 39% per year, while desktop PCs have declined at approximately 35% per year."[31] His results show somewhat smaller declines that the findings in this study: Over the same period (1990-98), our estimates are that the nominal price of computations declined at 41 percent per year.

It is important to recognize that the convention of describing computer performance in terms of the rate of decline in the *nominal* price of computers is highly misleading. The estimated 41 percent per year decline in nominal computation prices shown in Table 8 corresponds to a real increase in performance of 73 percent per year. A decline of 32 percent per year in the

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[29] Ernst Berndt and Neal Rappaport, "Price and Quality of Desktop and Mobile Personal Computers: A Quarter Century of History," NBER manuscript, Cambridge, Mass., July 31, 2000.

[30] The variables in the current BLS hedonic regression for personal desktop computers (as of June 1999) contains one performance proxy (clock speed), two performance-related proxies (RAM and size of hard drive), an array of feature dummy variables (presence of Celeron CPU, ZIP drive, DVD, fax modem, speakers, and software), three company dummy variables, and a few other items. It contains no performance measures.

[31] Chwelos, op. cit., p. 79.

nominal computing price along with a 6 percent inflation rate generates a real growth in computing power of 56 percent per year. Most of the apparent discrepancy between the present study and other studies is that we look at productivity improvement while others look at price declines; I also suspect that some studies define growth rates using logarithmic declines.

The results from both the present study and the Chwelos study reinforce the questions raised about the accuracy of the input-based hedonic approach. (It is worth reiterating that for the later part of the period, in the 1990s, our performance-based price is based on sophisticated benchmark performance measures, such as the Dhrystone MIPS or SPEC2000 indexes described above.[32]) Using benchmarks would be the preferred way of estimating true prices if appropriate benchmarks were available. There appears to be a major discrepancy between the results of performance-based estimates of computer prices and those used in government statistics. The large discrepancy between the official hedonic prices and the performance-based measures is quite disturbing because it raises the possibility that the hedonic measures may be far wide of the mark as a measure of the performance of computers today.

VI. Supercomputers and Quasicomputers

While this study has emphasized conventional computers, it will be useful to devote a moment's attentions to the dinosaurs and microbes of the computer kingdom.

Supercomputing

Scientists and policy makers naturally tend to emphasize supercomputing as the "frontier" aspect of computation or the "grand challenges of computation." These are the romantic moon shots of the computer age which excite deans and senators. When proponents of supercomputers point to the grand challenges, what are the examples? Generally, supercomputers are necessary for the simulation or solution of extremely large non-linear dynamic systems. Among the important applications discussed by scientists are applied

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[32] There does not appear to be any work investigating the relationship of the hedonic prices to performance. An interesting study would be to take the hedonic values from the BLS and other methods and to compare those to the estimated value using different benchmark evaluations.

fluid dynamics, meso- to macro-scale environmental modeling, ecosystem simulations, biomedical imaging and biomechanics, molecular biology, molecular design and process optimization, cognition, and fundamental computational sciences.[33] To pick the second of these areas, environmental modeling, there are enormous demands for improvements in modeling of climate systems and interactions between oceans, the atmosphere, and the cryosphere; our understanding of many issues about the pace and impact of climate change will depend upon improving the models and the computers to solve the models.

The progress in supercomputing has to some extent paralleled that in smaller computers. As of fall 2001, for example, the largest supercomputers operated at a maximum speed of 7226 gigaflops (billions of floating point operations per second or Gflops). At a benchmark of 2.5 UCP per Flop, this machine is therefore approximately an 18,000,000 MUCP machine, and therefore about 10,000 times faster than our fastest personal computer. The performance improvement for supercomputers has been tracked by an on-line consortium called "TOP500." It shows that the top machine's performance grew from 59.7 Gflops in June 1993 to 7226 Gflops in June 2001.[34] Over this period, the peak performance grew at an annual rate of 82 percent per year – which is very close to the performance of the personal computers that form the core of our database for the 1990s.

The price of supercomputing is generally unfavorable relative to personal computers. IBM's stock model supercomputer, called "Blue Horizon," is clocked at 1700 Gflops and had a list price of $50 million, for about $30,000 per Gflops, which makes it approximately 10 times as expensive on a pure price-performance basis as IBM's personal computers. It is reported that as of 2000, do-it-yourself supercomputers were available for between $1000 and $10,000 per Gflops, the lower end of which is approximately the same as personal computers. In any case, we have excluded supercomputers from our recent calculations even though they are, along with Deep Blue, in a sense the modern analogs of the single-"minded" Hollerith Tabulator or Burroughs adding machines.

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[33] See the discussion in National Research Council, *High Performance Computing and Communications: Foundation for America's Information Future*, 1996.

[34] See www.top500.org .

Embedded microprocessors and microcontrollers

At the other end of the computational spectrum are the microbes of computational life -- embedded microprocessors and microcontrollers, which are computers with less than full capabilities and which are embedded in other equipment. These have been called the "digital brains that are pivotal to a wide variety of embedded electronic systems for dedicated applications such as laser printers, cellular phones, Internet appliances, routers, automotive engine controllers, set-top boxes, and more."[35]

These lesser electronics are not the romantic darlings of the press, just as *Ants IV* will never outsell *Jurassic Part IV*. Although you won't find microcontroller chips on the Discovery Channel or in *Scientific American,* they are ubiquitous in everyday life, found in appliances (microwave oven, refrigerators, television and VCRs, stereos), computers and computer equipment (laser printers, modems, disk drives), automobiles (engine control, diagnostics, climate control), environmental control (greenhouse, factory, home), instrumentation, aerospace, and thousands of other uses.[36]

Microcontrollers are basically slimmed-down microprocessors or very-low-end computers, and they are becoming increasingly powerful over time. These devices vary widely in performance depending upon whether they are used for controlling thermostats or routing Internet mail. For example, the Dallas Semiconductor DS89C420 Ultra High-Speed Microcontroller has peak processing speeds of 50 MIPS at a maximum clock speed of an 8-bit 50 MHz device with 16 KB of flash memory and is priced at $10 apiece in large lots. On a performance basis, 50 MIPS (or MUCP) PCs were reaching the market in 1992 and 1993, so the microcontrollers are slightly less than a decade behind the frontier microprocessors. The price per MUCP for a microcontroller today is about 40 percent of that for a high-end PC. There are no studies on the price and performance history of these computer microbes.

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[35] Gartner group, *Embedded Microcomponents Worldwide,* undated at http://gartner11.gartnerweb.com/public/static/home/ourservices/scopes/n01mcroww.html.

[36] The web page for Dallas Semiconductor gives a good idea of the range of applications for microcontrollers. See http://dbserv.maxim-ic.com/solutions_start.cfm .

According to various sources, there were 4.3 billion microcontrollers shipped in 2000 for with a value of $16 billion, or an average value of around $4 per device. The prices in 2001 ranged from $1.80 for a low-end 4-bit chip to $10 for a high-end 16-bit device. As computing technology becomes increasingly powerful and inexpensive, embedded microcontrollers are likely to grow in power and sophistication. I speculate in the next section on the shape of economic life when microcontrollers become as powerful as today's supercomputers.

VII. Conclusions

The progress of computing

The purpose of this study is twofold. The key purpose is to extend estimates of the price of computers and computation back in time to the earliest computers and calculators as well as to manual calculations. Along the way, we have developed performance-based measures of price and output that can be compared with input- or component-based measures.

Before reviewing the major conclusions, we must note some of the major reservations about the results. While we have provided performance-based measures of different devices, we note that the measures are generally extremely limited in their purview. They capture primarily computational capacity and generally omit other important aspects of modern computers such as connectivity, reliability, size and portability, as well as compatibility across different hardware and operating systems. In one sense, we are comparing the transportation skills of the computer analogs of mice and men without taking into account many of the "higher" functions that modern computers perform relative to mice like the IBM 1620 or nineteenth-century ants like the Hollerith tabulator.

In addition, we emphasize that some of the data used in the analysis, particularly those for the pre-World-War II period, are extremely crude. Additionally, the measures of performance or computer power used for early computers (either the information-based measure or millions of instructions per second) have been superceded by more sophisticated benchmarks; while conventional equivalence scales exist and are used when possible in this study, the calibrations are not above reproach. Subject to these reservations, the following conclusions seem warranted.

First, there has been a phenomenal increase in computer power over the twentieth century. Performance in constant dollars has improved since 1900 by a factor in the order of 10^{12} (that is, 1 trillion), which represents a compound growth rate of almost 40 percent per year for a century. In fact, most of the increase has taken place since 1940, during which the average rate of improvement has been at an annual average rate of 48 percent. These increases in productivity are far larger than anything else in the historical record.[37] Moreover, the increase began long before dot.coms appeared, and well before the "new economy" became fashionable or later fell from grace.

Second, the data show convincingly a sharp break in trend around 1940 – at the era where the technological transition occurred from mechanical calculators to what is recognizably the ancestor of modern computers. There was only modest progress – perhaps a factor of 10 – in general computational capabilities from the skilled clerk to the mechanical calculators of the 1920s and 1930s. Around the beginning of World War II, all the major components of the first part of the computer revolution were developed, including the concept of stored programs, the use of relays, vacuum tubes, and eventually the transistor, along with a host of other components. Dating from about 1940, computational speed increased and costs decreased rapidly over the course of the 20th century. The pace of improvement shows no sign of slackening, and indeed the price and performance improvement has been higher over the last two decades than in the prior four decades. This increase in productivity has recently been independently identified in the movement from a three-year to a two-year product cycle for microprocessor devices.

Third, these estimates of the growth in computer power, or the decline rate in calculation costs, are higher than standard hedonic price measures for computers that are used in the official government statistics. The reasons for the divergence are not clear, but one reason is likely to be that the measures

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[37] Scholars have sometimes compared productivity growth in computers with that in electricity. In fact, this is a snails-to-cheetah comparison. Over the half-century after the first introduction of electricity, its price fell about 5.5 percent per year on average relative to wages, whereas for the six decades after the beginning of World War II the price of computer power fell 36 percent per year relative to labor costs.

developed here are indexes of performance, while hedonic approaches used by governments today are based on the prices of components or inputs. To the extent that the price structure of components does not reflect the marginal contribution of different components to computer performance, the hedonic price estimates may provide misleading estimates of the "true" price of computers.

Fourth, the phenomenal increase of computer power and decline in the cost of computation over the last four decades have taken place through improvements of a given underlying technology: stored programs using the von Neumann architecture of 1946 and hardware using increasingly efficient Intel microprocessors beginning with the 4004 in 1971. While this is only one example (albeit a most singular one) of productivity improvement, the fact that it took place in a relatively stable industry, in the world most stable country, relying on a largely unchanged core technology, is provocative for students of industrial organization to consider.

When Things Begin to Think

These results raise a further set of questions to which the answers are much more speculative but also much more important. When if ever will the astounding increase in the productivity growth, and in the growth of productivity growth, of computers end? When if ever will the decline in the decline rate of the cost of computerized operations saturate? If the astounding rate of productivity growth continues, when will computers evolve into machines with essentially human levels of intelligence?

These are crucial questions for economics and for human civilizations. To take the last question, computer scientists estimate that human computational and storage capabilities are approximately one million times larger than today's top personal computers.[38] That is, we humans are "petaflop" machines, or machines with computational capacities equal to one quadrillion (10^{15}) floating-point operations per second, or

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[38] See Hans P. Moravec, *Robot: Mere Machine to Transcendent Mind*, Oxford University Press, 1998 and Ray Kurzweil, *The Age of Spiritual Machines : When Computers Exceed Human Intelligence*, Viking Press, 1999. The title of this section was inspired by Kurzweil's book.

approximately one billion MUCP.[39] At the present rate of improvement in computational ability of about 80 percent per year, supercomputers will attain the storage and computational capacities of humans within 6 years. Indeed, IBM is constructing the first “petaflop machine” with a target date of 2003.[40]

While many computer scientists emphasize the importance of gigantically powerful machines solving the “grand challenges of computing,“ the real importance of increasingly powerful computers for human societies is probably the availability of devices that are fast, cheap, smart, small, and powerful. A major revolution will come when cheap “micropetacomputers” become available – these being tiny machines with memory, storage, and computing capacities that are roughly a million times greater than today’s personal computers and cost $1 or less. Such devices will be intelligent, virtually free, essentially weightless, and small enough to fit unnoticeably into your shoe or under your skin. A micropetacomputer with human computing capabilities will be on the scene before 2025 if computing capabilities continue to grow at the current rate of 80 percent per year. At current trends, the cost of such a machine will be around $2000 by 2025 and $1 by 2035.

How will life and the economy operate with humanlike computers costing $1 or less embedded in microprocessors, robots, shoes, and humans? There are likely to be billions and billions of such devices – recall that the U.S. produced more than 4 billion “embedded” microcontrollers produced in 2000. These devices will be everywhere – cooking, working, thinking, scheming, bargaining, learning, talking back, negotiating, as well as designing and producing other computers, devices, and robots. Cheap intelligent devices are likely to be able to monitor our health and driving and children, manage our portfolios, bargain with other computers, populate space, comfort us when we are low, search for aliens, and eventually propagate themselves and write software for yet other intelligent devices. The military uses will probably be frightening,

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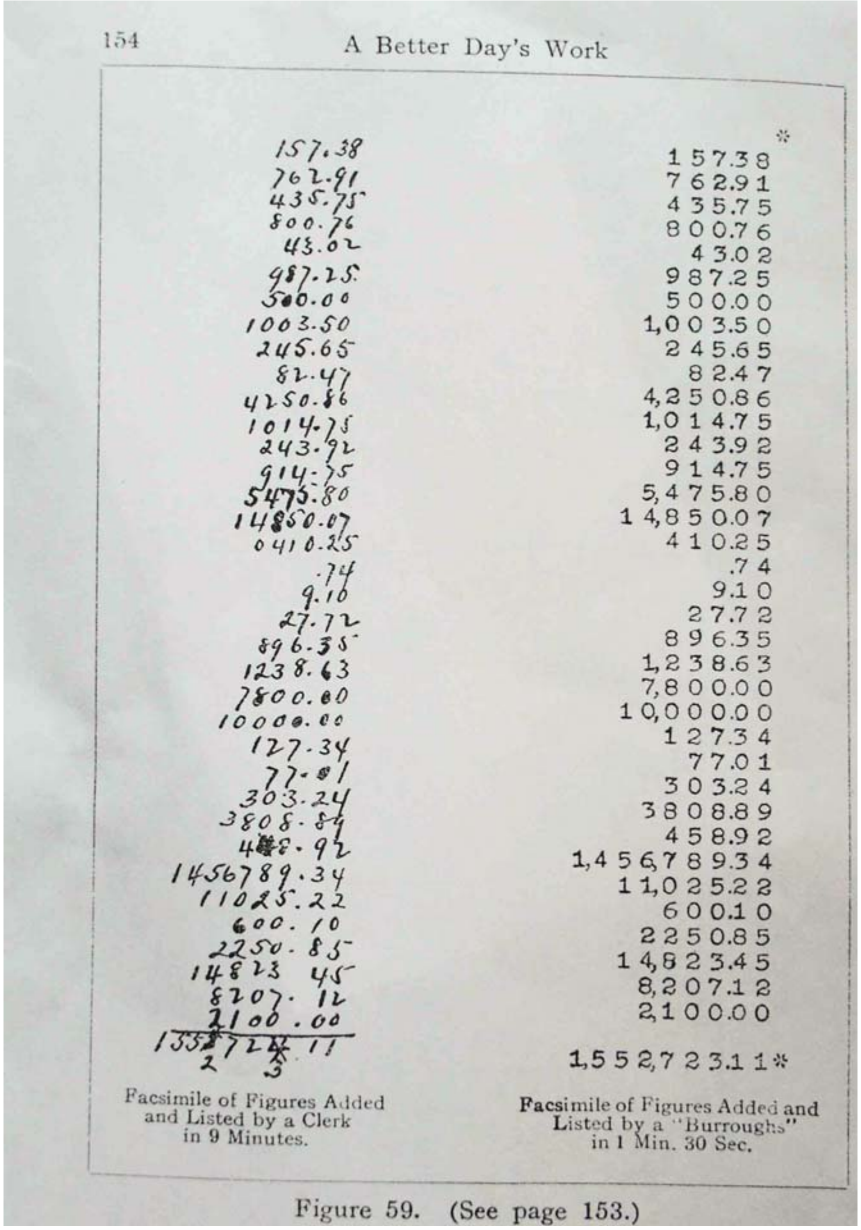
[39] A floating point operation per second, or “flop,” is yet another measure of computer performance, also usually calibrated to a particular benchmark. Most benchmarks find that 1 million flops correspond to between 2 and 3 MUCP.

[40] IBM is developing a supercomputer called “Blue Gene” with 256 towers, each with 4 boards, each with 36 processors, each with 32 cores, each with 1 gigaflop of processing power. This machine will have a petaflop of computational capacity, approximately 1 million times the capability of current personal computers, and the estimated cost is $100 million.

including such things as widespread use of robots, sensors, and remote weapon systems.

While computer scientists and science fiction writers have begun to speculate on the nature of life and work in such a world, these speculations have yet to penetrate mainstream commentary and economic analysis. Will these be a fourth factor of production in our textbooks? What will be the rules concerning planting intelligent devices near or in people? What will such devices do to the military balance of power? What will be the ethics of creating or destroying apparently conscious computer-entities? Who will be managing whom?

If nonhuman capital with human capabilities costing virtually nothing is indeed a serious possibility in the next half century, then the organization of economic and social activity in such a world should be high on the research agenda today.



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	*
157.38	157.38
762.91	762.91
435.75	435.75
800.76	800.76
43.02	43.02
987.25	987.25
500.00	500.00
1003.50	1,003.50
245.65	245.65
82.47	82.47
4250.86	4,250.86
1014.75	1,014.75
243.92	243.92
914.75	914.75
5475.80	5,475.80
14850.07	14,850.07
0410.25	410.25
.74	.74
9.10	9.10
27.72	27.72
896.35	896.35
1238.63	1,238.63
7800.00	7,800.00
10000.00	10,000.00
127.34	127.34
77.01	77.01
303.24	303.24
3808.84	3808.89
488.92	458.92
1456789.34	1,456,789.34
11025.22	11,025.22
600.10	600.10
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14823 45	14,823.45
8207. 12	8,207.12
2100.00	2,100.00
1352722.11 2 3	1,552,723.11 *
Facsimile of Figures Added and Listed by a Clerk in 9 Minutes.	Facsimile of Figures Added and Listed by a "Burroughs" in 1 Min. 30 Sec.

Figure 59. (See page 153.)

Plate 1. **Comparison of Manual Calculation with Manual Calculator**

This photograph shows a comparison of manual calculators and computations by a clerk in adding up a column of numbers such as might be found in a ledger. The calculator has an advantage of a factor of six. (Source: Burroughs Adding Machine Company, *A Better Day's Work at a Less Cost of Time, Work and Worry to the Man at the Desk: in Three Parts Illustrated*, Third Edition, Detroit, Michigan, 1909, pp. 153-154.)

1. Manual (see Plate 1) – up to roughly 1900
2. Mechanical – 1857 to 1933
3. Electromechanical – 1890 to 1945
4. Relays – 1939 - 1944
5. Vacuum – 1942 - 1961
6. Transistor – 1956 - 1979
7. Microprocessor – 1981 - present

Table 1. **The Seven Stages of Computation**

The dates in the table represent the dates for the technologies that are represented in this study.

1. Addition time
2. Millions of instructions per second
3. Moravec's formula:
   f(add-time, mult-time, memory, word size)
4. Knight's formula:
   g(word size, memory, calc-time, IO time, …)
5. Synthetic benchmarks:
   Dhrystone
   SPEC (latest being SPEC2000)

Table 2. **Alternative measures of performance used in this study**

SPECint2000

- Compression
- FPGA circuit placement and routing
- C programming language compiler
- Combinatorial optimization
- Game playing: Chess
- Word processing
- Computer visualization
- Perl programming language
- Group theory, interpreter
- Object-oriented database
- Compression
- Place and route simulator

SPECfp2000

- Physics: Quantum chromodynamics
- Shallow water modeling
- Multigrid solver: 3D potential field
- Partial differential equations
- 3D graphics library
- Computational fluid dynamics
- Image recognition/neural networks
- Seismic wave propagation simulation
- Image processing: Face recognition
- Computational chemistry
- Number theory/primality testing
- Finite-element crash simulation
- Nuclear physics accelerator design
- Meteorology: Pollutant distribution

Table 3. **Suite of Programs Used for SPEC2000 Benchmark**

This table shows the benchmarks used to evaluate different computers. The first set use largely integer applications while the second are largely floating-point scientific applications.

Source: John L. Henning, "SPEC CPU2000: Measuring CPU Performance in the New Millennium," *Computer,* July 2000, p. 29.

Technology	Period	Computer Power (MMUCP)	Cycle Speed (Khz)	Bytes of rapid access memory	Capital cost per UCP (1996 dollars)	Total cost per MMUCP (1996 $)	Labor cost of computation (hours per UCP)
Manual	19th century	3.68E-08	na	na	1.00E+00	1.64E+04	9.81E+03
Early Mechanical	1900	1.79E-07	na	na	5.34E+03	4.10E+03	2.56E+03
Late Mechanical	1940	3.44E-07	1.20E+00	na	5.98E+03	5.04E+03	1.52E+03
Relay/Vacuum	1950	1.63E-03	4.87E+02	1.01E+03	2.02E+06	4.64E+01	7.11E+00
Transistor	1960	1.85E-02	1.80E+02	1.48E+04	1.29E+06	2.95E+00	3.32E-01
Transistor	1970	1.41E+00	4.00E+03	5.51E+04	7.88E+05	3.15E-02	2.82E-03
Early Microprocessor	1980	5.04E-01	2.92E+03	1.47E+05	4.09E+04	4.07E-03	3.48E-04
Microprocessor	1990	1.00E+01	2.55E+04	5.28E+06	5.83E+03	2.34E-05	2.03E-06
Microprocessor	2000	1.56E+03	9.28E+05	2.03E+08	2.11E+03	6.88E-08	5.38E-09

Table 4. **Basic Performance Characteristics by Epochs of Computing**

Source: Each year takes the average of representative computer systems around that date. The data for individual computers are given in Appendix. Estimates use geometric means of the values for different technologies.

Period	Technological transition	Computer Power (MMUCP)	Cycle Speed (Khz)	Bytes of rapid access memory	Capital cost per UCP (1996 dollars)	Improvement in Computer Power (Inverse of price decline per MMUCP,1996 $)	Labor cost of computation (hours per UCP)
Manual to 1900	Manual to mechanical	35.5%	na	na	419.9%	30.6%	-22.8%
1900 -1940	Improved mechanical	2.0%	na	na	0.3%	-0.6%	-1.5%
1940 - 1950	First electronic computers	50.8%	33.8%	na	32.7%	25.5%	-22.9%
1950 - 1960	Introduce transistor	26.9%	-9.3%	30.1%	-4.3%	31.0%	-26.0%
1960 - 1970	Mainframes	52.9%	35.5%	13.8%	-4.7%	56.1%	-37.3%
1970 - 1980	First PCs	-9.6%	-3.1%	10.2%	-25.2%	22.3%	-18.6%
1980 - 1990	Diffusion of PCs	35.6%	24.6%	43.9%	-18.0%	69.0%	-40.7%
1990- 2000	Modern era	65.6%	43.3%	44.1%	-9.7%	79.2%	-44.7%

Table 5. **Growth Rates of Different Performance Characteristics of Performance In Different Epochs of Computing (average annual geometric growth rates)**

Source: See note to Table 4.

Dependent Variable: ln(Cost)
Included observations: 187

Variable	Coefficient	Std. Error	t-Statistic
C	-18.8	21.6	-0.87
YEAR	0.015	0.011	1.30
DUM40	-0.526	0.064	-8.24
DUM50	0.0499	0.103	0.48
DUM60	0.197	0.104	1.89
DUM70	0.0113	0.099	0.11
DUM80	-0.279	0.087	-3.20
DUM90	-0.055	0.082	-0.67

R-squared	0.975329
Adjusted R-squared	0.974365
S.E. of regression	1.242425

where

Cost is the price per MUCP divided by the GDP price index, 1996 = 1
YEAR is calendar year
DUM[t] takes a value of 0 until year t and YEAR-t thereafter,

Table 6. **Regression Analysis for Trends in Computing Power**

Regression shows the trend in the logarithm of the deflated price of computer power as a function of year and time dummies.

Improvements in productivity of computers
[Average annual rate of change, 1996 prices]

1850-1940	-1.5
1940-50	66.8
1950-60	58.7
1960-70	30.3
1970-80	28.8
1980-90	70.3
1990-2001	80.0

Table 7. **Change in Price of Computation Over Different Epochs**

Source: Estimates are predictions from the regression in Table 6 using decadal dummy variables for each decade beginning in 1940. We have inverted these to convert them into rate of growth in computer power per constant dollar.

Note: The annual rates of change in Table 7 are derived from the coefficients of the logarithmic regressions in Table 6 with the sign changed. Those in Table 6 are the instantaneous growth rates, which will be significantly smaller than annual growth rates when numbers rise into the double-digit range. More specifically, the Table 4 numbers are calculated as g(Table 7) = exp[g(Table 6)]-1, where g(Table k) is the growth rate in Table k.

Study	Period	Method	Rate of nominal price decline (percent per year)	Source
Government price data				
Price index for computers and peripherals (NIPA)	1990-2000	Hedonic	-18	[b]
PPI: Electronic computers and computer equipment	1990-2000	Hedonic	-13	[c]
PPI: Semiconductors and related devices	1990-2000	Hedonic	-34	[c]
Academic studies				
Berndt and Rappaport, personal computers	1989-1999	Hedonic	-36	[a]
Chwelos, desktop computers	1990-1998	Performance	-35	[d]
This study				
Price of computer power ($ per MUPC)	1989-1999	Performance (MMUCP)	-44	[e]
Same	1990-1998	Performance (MMUCP)	-41	[e]
Same	1990-2002	Performance (MMUCP)	-42	[e]

Table 8. **Comparison of Price Indexes for Different Studies**

This table shows estimates of the decline in prices of computers from different studies and methodologies. Note that, as explained in the text, the nominal price declines are very misleading as a measure of the growth in performance. During the period 1990-98, the rate of decline in nominal computation prices for the present study was 44 percent per year while the corresponding rate of increase in the growth of performance was 83 percent per year.

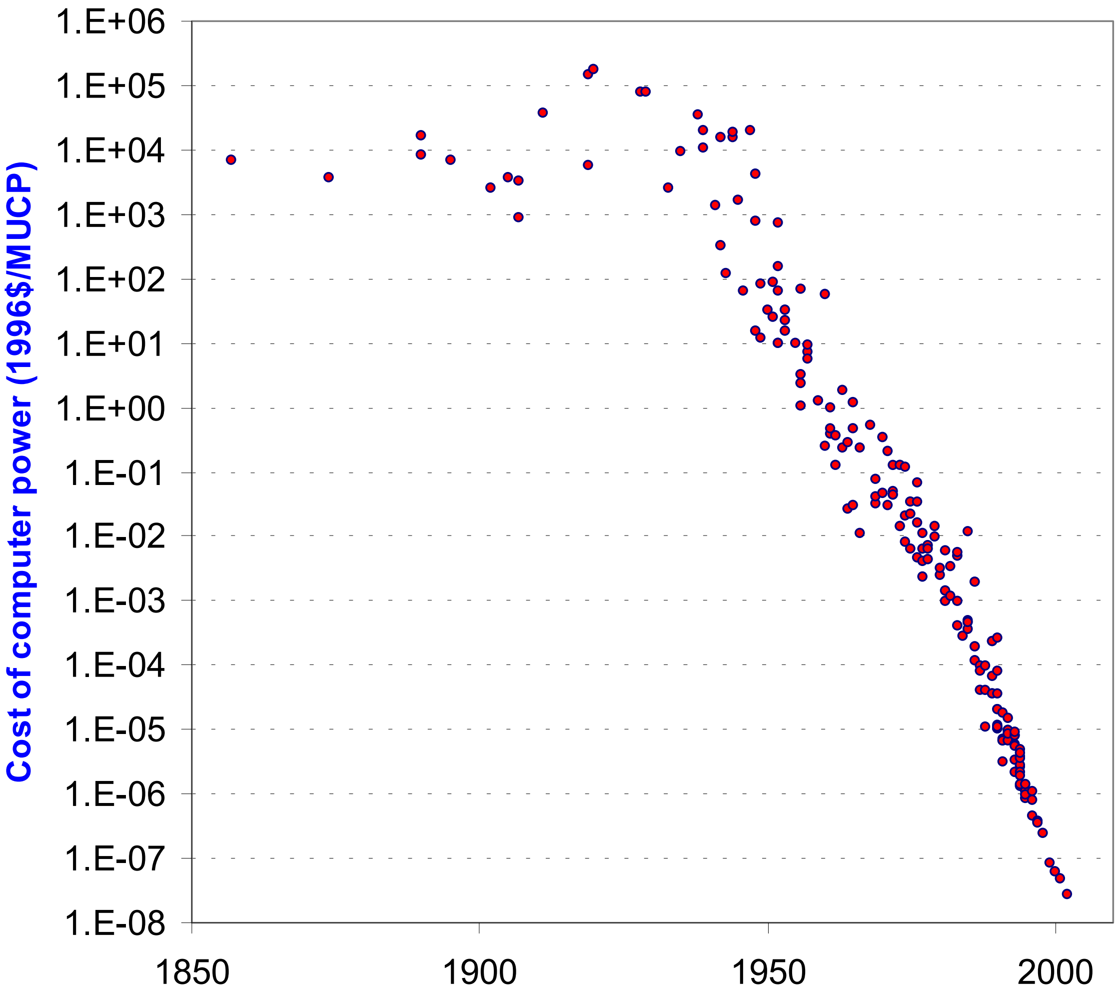

Figure 1. **The progress of computing measured in cost per million standardized operations per second (MUCP) deflated by the price index for GDP**

Source: See Appendix.

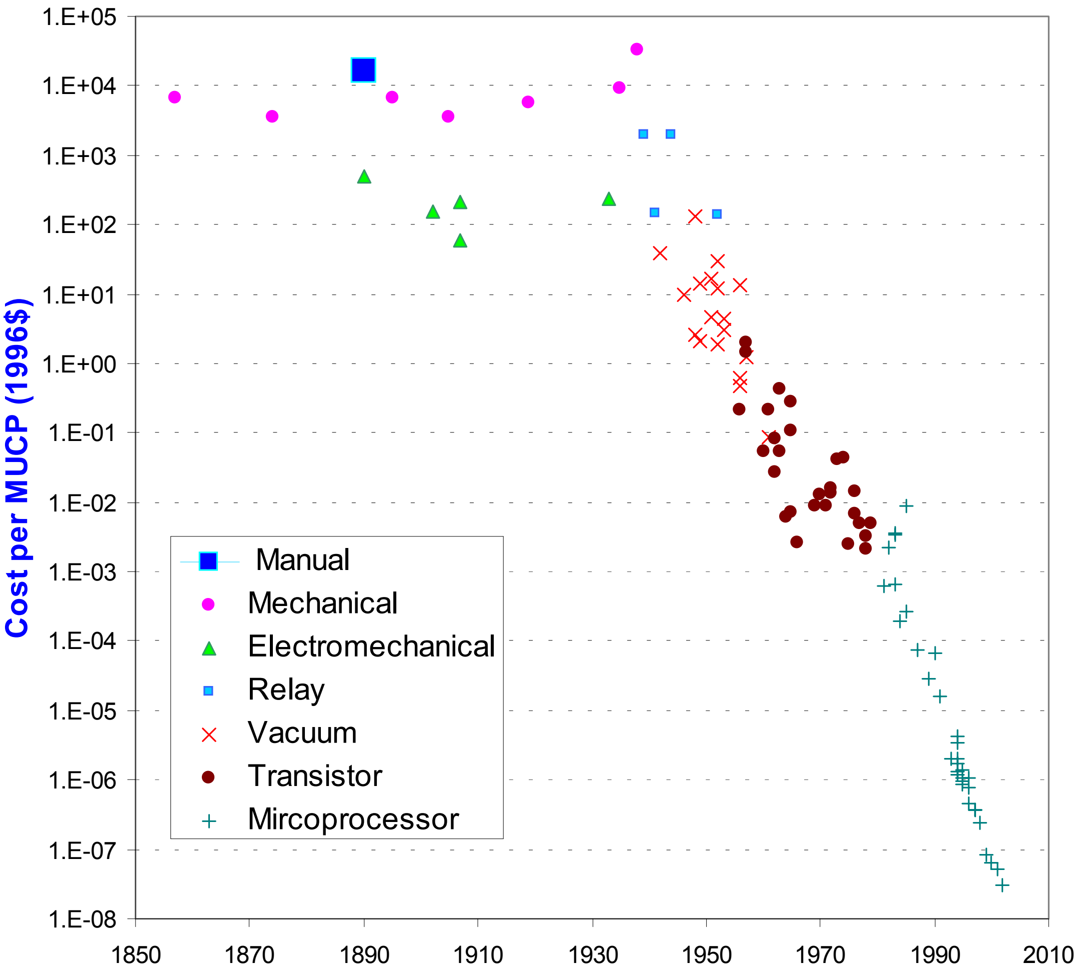

Figure 2. **The cost of computer power for different technologies**

Source: See Appendix.

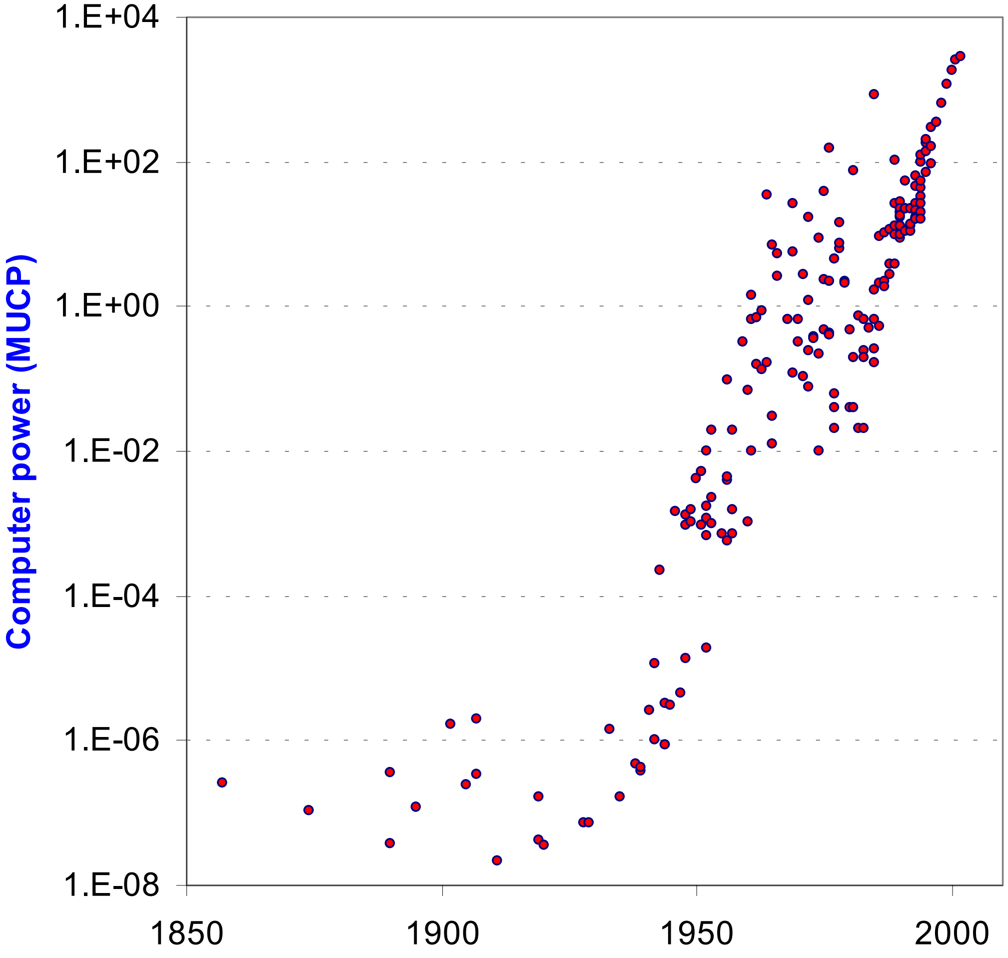

Figure 3. **The progress of computing power measured in millions of operations per second (MUCP)**

The measure shown here is the index of computing power. For a discussion of the meaning of MUCP, see text.

Source: See Appendix.

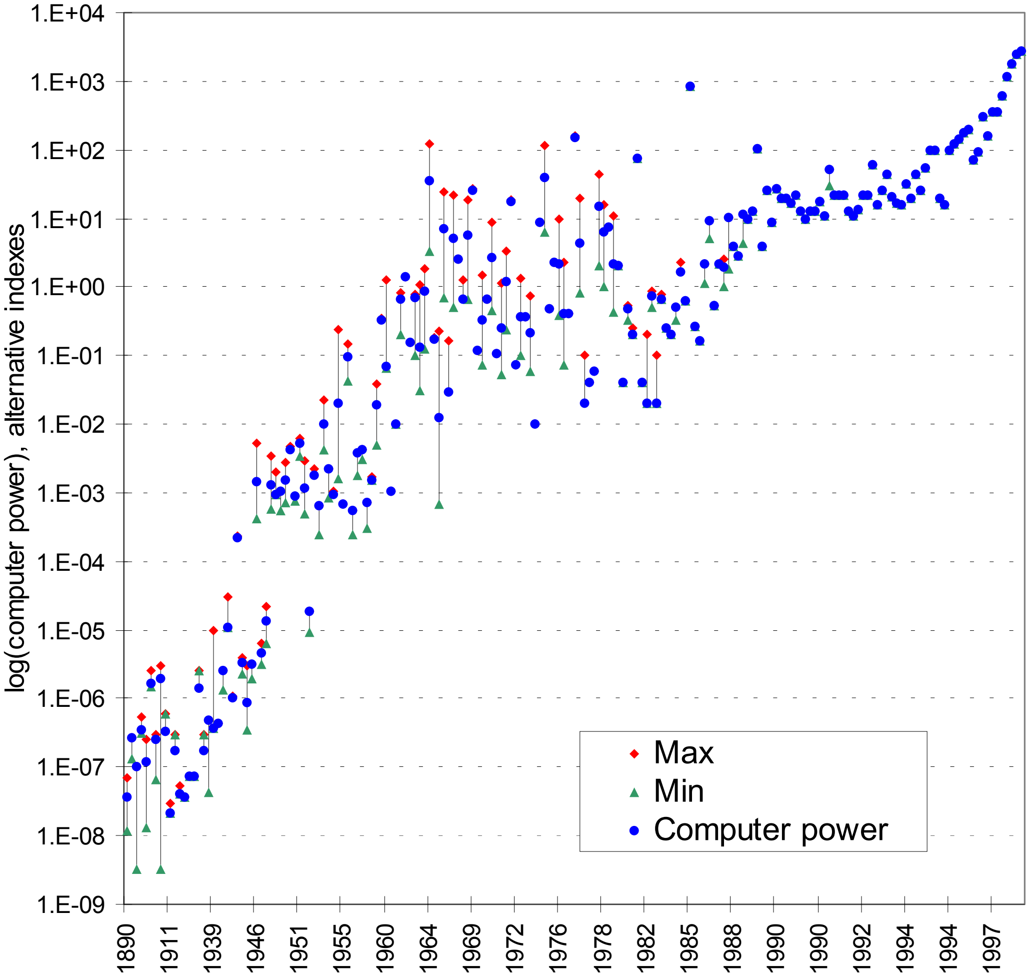

Figure 4. **Range of Estimates of Computer Power Using Different Indexes**

Different approaches to measuring computer power provide alternative measures. This graph shows the highest estimate (diamond) and the lowest estimate (triangle) along with the value used in this study (circle). Particularly in early years, alternative estimates as well as inconsistent data give highly divergent measures of power. In recent years, differences are much smaller as benchmark measures tend to provide similar estimates of power.

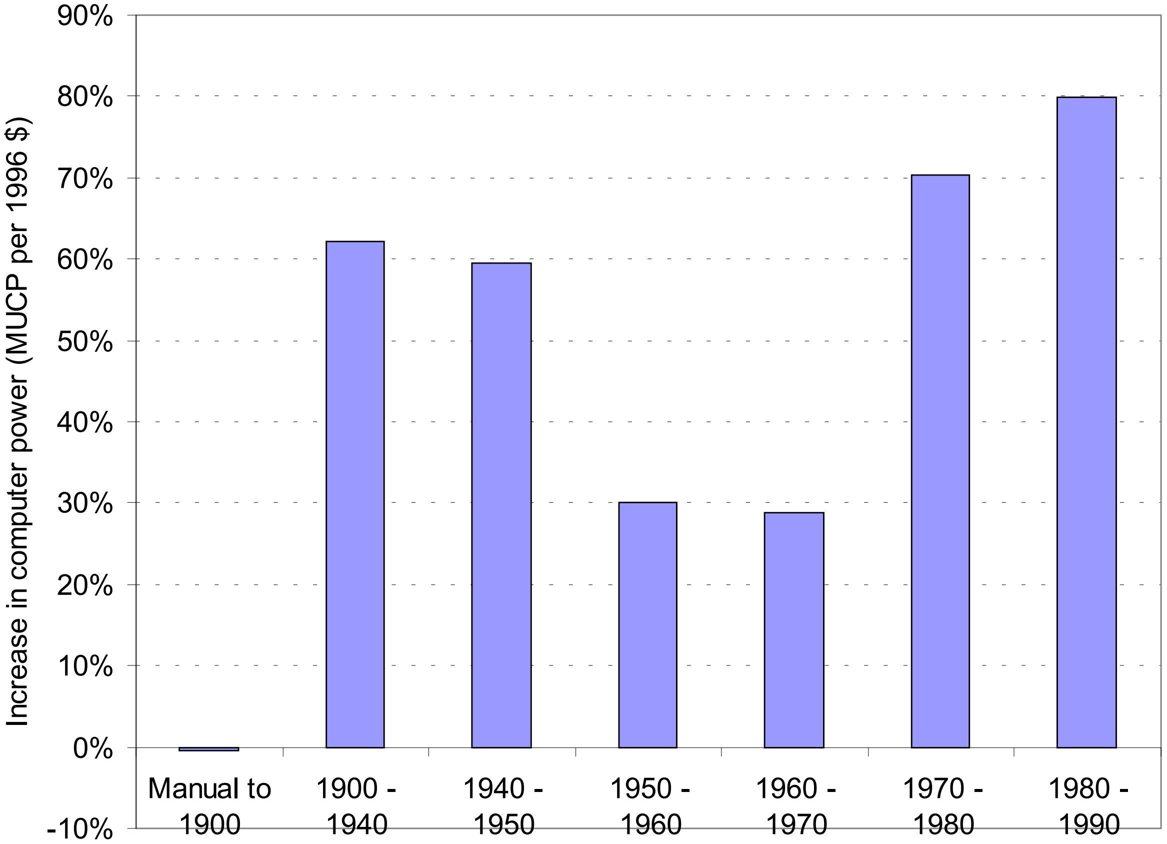

Figure 5. Annual **Rate of Growth of Computer Power by Epoch**
Real computer power is the rate of decline of real computation costs (with sign changed). This is calculated from the regression in Table 6.

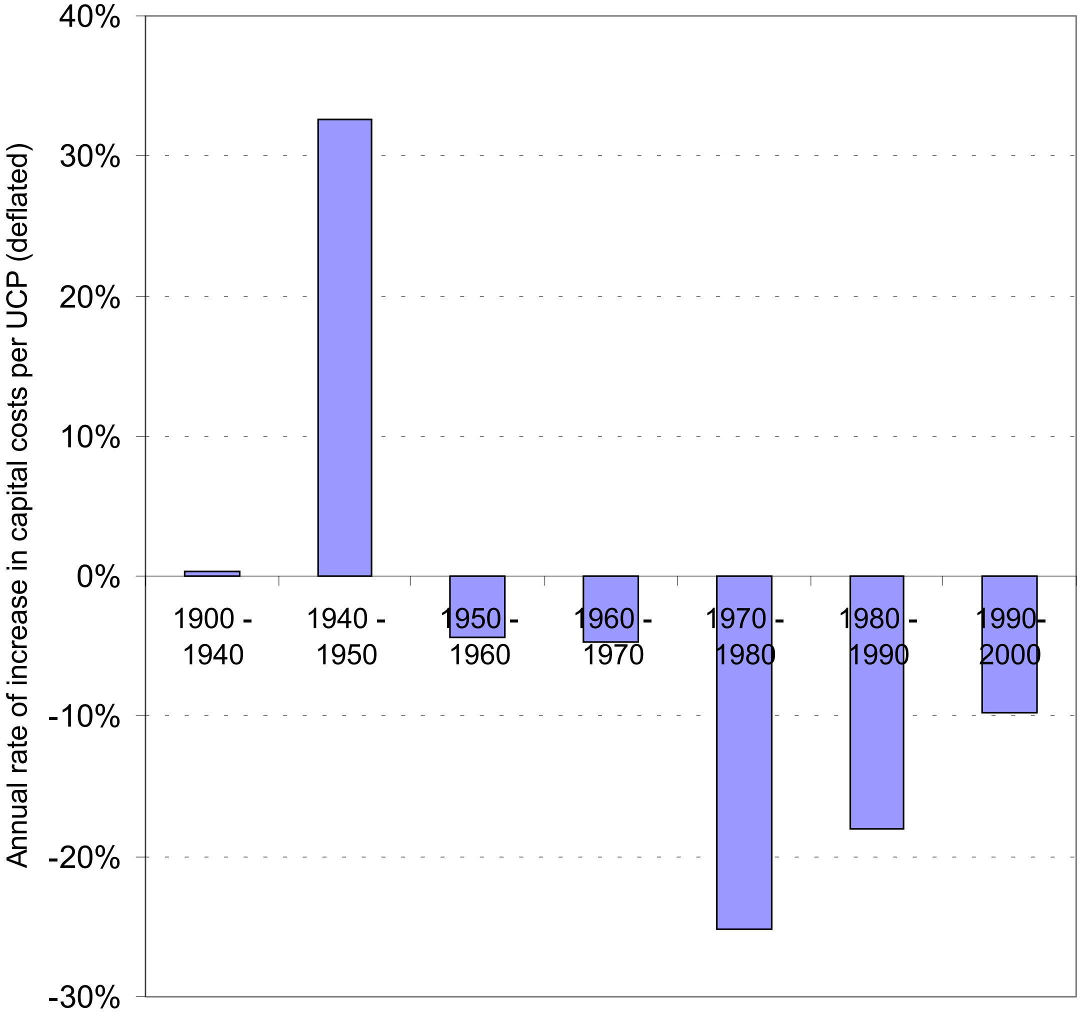

Figure 6. **Capital costs increases per computer for epochs**

These costs are deflated by the GDP price index.

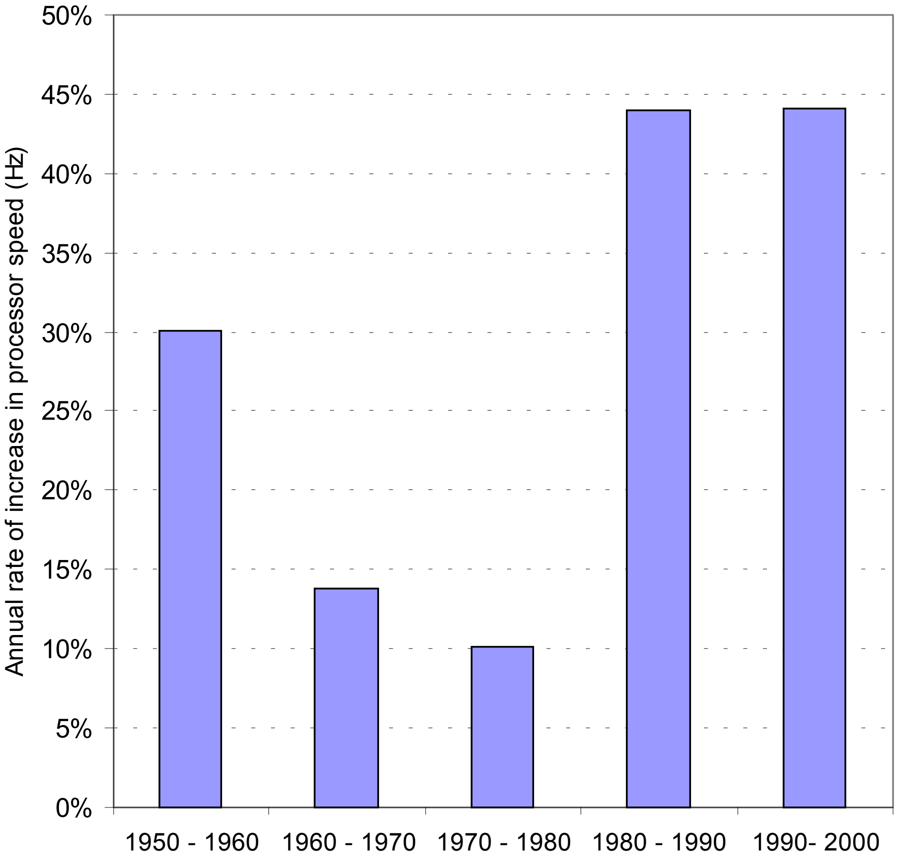

Figure 7. **Annual rate of increase in processor cycle speeds**

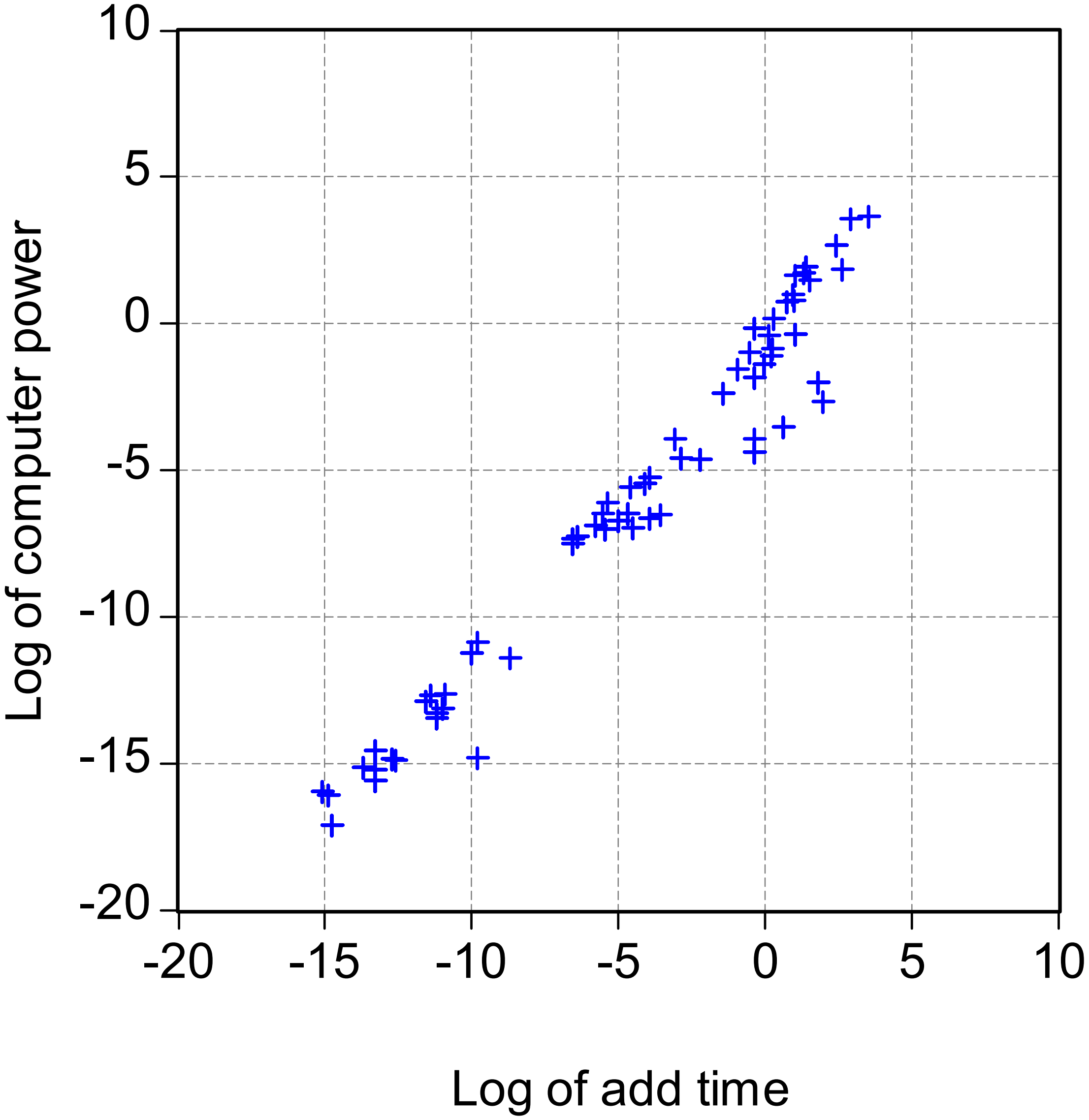

Figure 8. **Relationship between Addition Time and MUCP**

The graph shows the relationship between addition time (additions per second) and millions of operations per second or an associated benchmark. (Source is Appendix.)

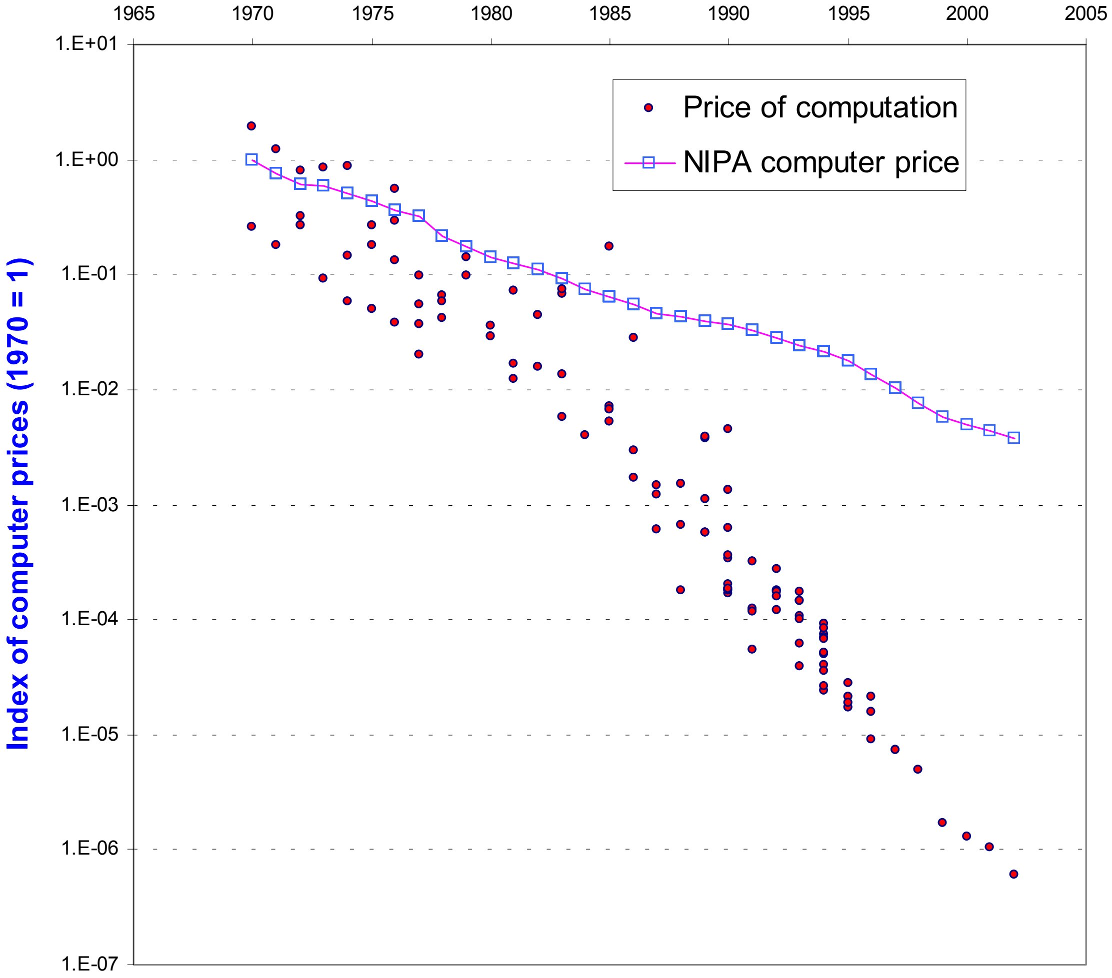

Figure 9. Comparison of Official Price of Computers and MUCP Measure

The upper line shows the official (BEA) price index for computers and peripherals. The dots show an index of the nominal price per MUCP. Both are in current prices and are indexed to equal 1 in 1970.

Appendix. Data and Sources for Computer Performance.

The underlying notes and research were primarily undertaken by Eric Weese.

Date	Name	Word Size (bits) [5]	Mem. (Bytes)	Clock (Hz)	Add time (+/s)	Multiply time (x/s)	Index of Computer Power	Cost current $	Capital cost (1996 $)	Capital cost per unit CP (1996 $)	Cost per unit CP (1996 $)	Cost per unit CP	For-mula used for power	Con-struc-tion	Log-ic	Sources	Notes
1890	By Hand	16.6			7.00E-02		3.68E-08	6.10E-02	1.00E+00	7.57E-01	1.64E+04	9.98E+02	[m2]			i	
1857	Scheutz Difference Engine	49.8			2.00E-01		2.63E-07	5.00E+03	6.37E+04	6.72E+03	6.80E+03	5.34E+02	[m2]	M	N	h	68
1874	Original Odhner	26.56			6.00E-02	2.00E-02	1.04E-07	1.96E+02	2.20E+03	5.85E+02	3.60E+03	3.22E+02	[m2]	M	N	efC	68
1890	Electrical Tabulator	288			5.30E-01		3.53E-07	5.00E+03	8.23E+04	6.48E+03	8.19E+03	4.98E+02	[m2]	E	N	abc	68
1895	Steiger Millionaire	33.2			5.00E-02	5.00E-02	1.18E-07	3.04E+02	5.60E+03	1.32E+03	6.79E+03	3.68E+02	[m2]	M	N	def	68
1902	Automatic Tabulator	288			2.50E+00		1.66E-06	7.50E+03	1.23E+05	2.05E+03	2.49E+03	1.52E+02	[m2]	E	N	ag	4
1905	Burroughs Model 9	29.88			3.00E-01	2.00E-02	2.47E-07	3.59E+02	5.63E+03	6.34E+02	3.62E+03	2.31E+02	[m2]	M	N	ijkf	68
1907	Adding Tabulator	33.2			3.00E+00	5.00E-02	2.00E-06	2.50E+03	3.68E+04	5.11E+02	8.89E+02	6.04E+01	[m2]	E	N	lb	68
1907	Powers Tabulator	288			6.00E-01		3.39E-07	8.00E+02	1.18E+04	9.64E+02	3.19E+03	2.17E+02	[a]	E	N	5	45
1911	Monroe Calculator						2.18E-08	3.50E+01	2.00E+02	2.55E+02	3.61E+04	2.56E+03	[m1]				
1919	Victor Model 110	26.56			3.00E-01	2.00E-02	1.69E-07	1.00E+02	7.12E+02	1.17E+02	5.59E+03	7.85E+02	[a]	M	N	s12	1
1919	IBM Tabulator						4.12E-08	2.00E+04	1.42E+05	9.61E+04	1.41E+05	1.98E+04	[m1]				
1920	Torres Arithmometer						3.58E-08	2.50E+04	1.56E+05	1.21E+05	1.74E+05	2.79E+04	[m1]				
1928	National-Ellis 3000						7.38E-08	1.50E+04	1.21E+05	4.54E+04	7.66E+04	9.52E+03	[m1]				
1929	Burroughs Class 16						7.38E-08	1.50E+04	1.19E+05	4.48E+04	7.59E+04	9.58E+03	[m1]				
1933	IBM Type 601	26.56			2.50E+00	1.70E-01	1.41E-06	7.50E+03	8.02E+04	1.58E+03	2.48E+03	2.32E+02	[a]	E	N	jmnJ	
1935	Marchant Model M	33.2		1.20E+03	3.00E-01	1.00E-01	1.69E-07	3.77E+02	3.74E+03	6.13E+02	9.25E+03	9.31E+02	[a]	M	N	146	46,47
1938	Zuse Z1	22	1.76E+02	1.00E+00	3.00E-01	6.00E-02	4.74E-07	5.27E+04	5.11E+05	3.00E+04	3.35E+04	3.46E+03	[m2]	M	S	tu	2
1939	Bell Labs Model I	26.56	3.25E+01		1.00E+01	2.00E-02	3.73E-07	2.00E+04	1.96E+05	1.46E+04	1.92E+04	1.95E+03	[m2]	R	N	ot	22
1939	Zuse Z2						4.24E-07	1.00E+04	9.82E+04	6.43E+03	1.04E+04	1.06E+03	[m1]				
1941	Zuse Z3	22	1.76E+02	5.30E+00	1.70E+00	3.00E-01	2.54E-06	6.50E+03	5.89E+04	6.43E+02	1.36E+03	1.50E+02	[m2]	R	S	opt	3
1942	Atanasoff Berry Computer	50	3.75E+02	6.00E+01	3.00E+01	5.00E-01	1.12E-05	7.00E+03	5.88E+04	1.46E+02	3.22E+02	3.84E+01	[m2]	V	N	q	8
1942	Bell Labs Model II						1.03E-06	5.00E+04	4.20E+05	1.13E+04	1.52E+04	1.80E+03	[m1]				
1943	Colossus						2.24E-04	1.00E+05	7.98E+05	9.90E+01	1.18E+02	1.48E+01	[m1]				
1944	Harvard Mark I	76.36	6.84E+02	3.30E+00	3.30E+00	1.70E-01	3.28E-06	2.00E+05	1.56E+06	1.32E+04	1.52E+04	1.95E+03	[m/k]	R	S	rtS9#	4
1944	Bell Labs Model III	19.92	2.38E+01			1.00E+00	8.73E-07	6.50E+04	5.07E+05	1.61E+04	1.87E+04	2.40E+03	[m/k]	R	S	o9	
1945	Zuse Z4	32	2.56E+02		2.00E+00	3.00E-01	3.10E-06	1.28E+04	9.76E+04	8.75E+02	1.58E+03	2.08E+02	[m2]	R	S	yu	7,13
1946	ENIAC	33.2	8.25E+01	1.00E+05	5.00E+03	3.85E+02	1.47E-03	4.87E+05	3.30E+06	6.25E+01	6.53E+01	9.65E+00	[m/k]	V	S	tzL9#	9,10,23
1947	Bell Labs Model V	23.24	8.63E+01			1.25E+00	4.56E-06	5.00E+05	3.06E+06	1.86E+04	1.91E+04	3.12E+03	[m/k]	R	S	o9	21 30,31,3
1948	Harvard Mark II	46	5.52E+02	6.00E+01	8.00E+00	4.00E+00	1.34E-05	3.00E+05	1.74E+06	3.60E+03	4.10E+03	7.08E+02	[m/k]	R	S	TU9	2
1948	IBM SSEC	63.08	1.31E+03		3.50E+03	5.00E+01	1.29E-03	6.00E+06	3.47E+07	7.49E+02	7.58E+02	1.31E+02	[m2]	V	P	HK3	20,44
1948	IBM 604	16.6	1.28E+01	5.00E+04	2.00E+03	7.10E+01	9.32E-04	2.96E+04	1.71E+05	5.11E+00	1.47E+01	2.54E+00	[m2]	V	S	KL	28 15,16,1
1949	Manchester Mark I	40	6.40E+02	1.00E+05	5.50E+02	1.00E+02	1.03E-03	4.90E+05	2.84E+06	7.69E+01	8.14E+01	1.40E+01	[m2]	V	P	DEF	7
1949	EDSAC	36	2.30E+03	5.00E+05	7.10E+02	1.90E+02	1.54E-03	1.00E+05	5.79E+05	1.05E+01	1.20E+01	2.06E+00	[m2]	V	P	DMN	25, 26
1950	SEAC						4.16E-03	8.00E+05	4.58E+06	3.06E+01	3.29E+01	5.75E+00	[m1]	0	0	0	39,40,4
1951	LEO	17	4.35E+03	5.15E+05	7.70E+02	8.00E+01	9.17E-04	4.90E+05	2.62E+06	7.93E+01	8.74E+01	1.63E+01	[m2]	V	P	W	1,43
1951	Univac I	39.84	4.88E+03	2.25E+06	3.50E+03	5.20E+02	5.26E-03	7.50E+05	4.01E+06	2.12E+01	2.54E+01	4.75E+00	[m/k]	V	P	L9#	48,49
1952	EDVAC	44	5.63E+03	1.00E+06	1.20E+03	3.50E+02	1.20E-03	4.67E+05	2.46E+06	5.69E+01	6.34E+01	1.20E+01	[m/k]	V	S	L9#	11,23
1952	Zuse Z5	35	5.25E+01	4.00E+01	1.00E+01	2.50E+00	1.90E-05	7.50E+04	3.95E+05	5.78E+02	7.14E+02	1.36E+02	[m2]	R	S	u	
1952	IBM CPC						1.76E-03	1.00E+05	5.26E+05	8.31E+00	9.77E+00	1.86E+00	[m1]				33,34,3
1952	Harvard Mark III	53.12	1.33E+03	6.40E+04	2.50E+02	8.30E+01	6.58E-04	6.00E+05	3.16E+06	1.33E+02	1.53E+02	2.91E+01	[m2]	V	S	UVL	5
1952	ORDVAC	40	5.12E+03		2.00E+04	1.40E+03	9.85E-03	6.00E+05	3.16E+06	8.91E+00	9.69E+00	1.84E+00	[m/k]	V	P	L9	23
1953	Ferranti Mark I*	40	2.08E+03	1.00E+05	8.30E+02	4.60E+02	2.26E-03	2.24E+05	1.16E+06	1.43E+01	1.55E+01	2.99E+00	[m2]	V	P	DE	24
1953	IBM 650						9.66E-04	2.00E+05	1.04E+06	2.99E+01	3.27E+01	6.29E+00	[m1]	0	0	0	0 36,37,3
1953	Whirlwind I	16	4.10E+03	1.00E+06	1.25E+05	4.00E+04	1.98E-02	3.00E+06	1.56E+07	2.19E+01	2.25E+01	4.33E+00	[m/k]	V	P	XA9#	8,50
1955	Librascope LGP-30						7.01E-04	3.00E+04	1.52E+05	6.01E+00	1.00E+01	1.98E+00	[m1]	0	0	0	0
1956	IBM 704	36	3.69E+04		4.20E+04	4.20E+03	9.42E-02	2.00E+06	9.78E+06	2.88E+00	3.10E+00	6.34E-01	[m/k]	V	P	L9#	0
1956	ERMETH	53.12	1.33E+02	3.00E+04	2.50E+02	6.00E+01	5.60E-04	2.50E+05	1.22E+06	6.06E+01	6.58E+01	1.35E+01	[m2]	V	P	OPQ	27
1956	ETL Mark III	16	2.56E+02	1.00E+06	1.80E+03	1.30E+03	3.86E-03	8.00E+03	3.91E+04	2.82E-01	1.03E+00	2.11E-01	[m2]	T	P	G	19
1956	LEO II	39	5.06E+03	4.00E+06	3.00E+03	3.00E+02	4.29E-03	3.21E+04	1.57E+05	1.02E+00	2.37E+00	4.84E-01	[m2]	V	P	DW	42,43
1957	ETL Mark IV	19.92	2.38E+03	1.80E+05	3.00E+02	2.00E+02	7.08E-04	1.50E+04	7.10E+04	2.78E+00	6.99E+00	1.48E+00	[m2]	T	P	G	18,19
1957	Zuse Z22	38	1.19E+02	1.50E+05	1.70E+03	1.00E+02	1.55E-03	4.50E+04	2.13E+05	3.81E+00	5.73E+00	1.21E+00	[m2]	V	P	uR	29
1957	Univac II	39.84	9.75E+03		8.30E+03	6.00E+02	1.93E-02	9.70E+05	4.59E+06	6.61E+00	9.24E+00	1.95E+00	[m/k]	T	P	L9#	48,49
1959	IBM 7090						3.26E-01	3.00E+06	1.37E+07	1.17E+00	1.26E+00	2.77E-01	[m1]	0	0		
1960	Digital PDP-1	18	9.22E+03		1.30E+06	3.30E+03	6.85E-02	1.10E+05	4.96E+05	2.01E-01	2.48E-01	5.51E-02	[m/k]	T	P	L9#	
1960	IBM 1620						1.03E-03	2.00E+05	9.01E+05	2.43E+01	5.57E+01	1.24E+01	[m1]	0			
1961	Zuse Z23	40	1.28E+03	1.50E+05	1.00E+04	6.00E+02	1.00E-02	5.00E+04	2.23E+05	6.18E-01	9.50E-01	2.13E-01	[m2]	T	P	RYZ	
1961	BRLESC	68	3.48E+04	5.00E+06	2.00E+05	4.00E+04	6.59E-01	2.00E+06	8.91E+06	3.76E-01	3.91E-01	8.77E-02	[m/k]	V	P	L9	12,23
1961	Atlas						1.40E+00	5.00E+06	2.23E+07	4.42E-01	4.56E-01	1.02E-01	[m1]				
1962	Univac III	24	2.46E+04		1.25E+05	1.20E+04	1.59E-01	3.90E+05	1.71E+06	2.99E-01	3.64E-01	8.27E-02	[m2]	T	P	L9#	48
1962	Burroughs 5000	48	2.46E+04		5.00E+05	5.00E+04	6.87E-01	6.00E+05	2.64E+06	1.07E-01	1.22E-01	2.77E-02	[m/k]	T	P	L9#	

Date	Name	Word Size (bits) [5]	Mem. (Bytes)	Clock (Hz)	Add time (+/s)	Multiply time (x/s)	Index of Computer Power	Cost current $	Capital cost (1996 $)	Capital cost per unit CP (1996 $)	Cost per unit CP (1996 $)	Cost per unit CP	For-mula used for power	Con-struc-tion	Log-ic	Sources	Notes
1963	IBM 7040	36	1.47E+05		1.10E+06	2.50E+04	1.32E-01	1.90E+06	8.26E+06	1.73E+00	1.84E+00	4.23E-01	[m/k]	T	P	L9#	67
1963	Honeywell 1800	48	1.97E+05		1.25E+05	8.30E+04	8.68E-01	1.60E+06	6.96E+06	2.23E-01	2.39E-01	5.49E-02	[m/k]	T	P	L9#	51
1964	CDC 6600	60	9.83E+05	1.00E+07	3.30E+06	1.00E+06	3.51E+01	7.50E+06	3.21E+07	2.54E-02	2.61E-02	6.08E-03	[m/k]	T	P	L@#	51,52
1964	Digital PDP-6						1.69E-01	3.00E+05	1.29E+06	2.11E-01	2.76E-01	6.44E-02	[m1]				
1965	IBM 1130	16	8.19E+03		1.25E+05	3.85E+04	1.25E-02	3.26E+04	1.37E+05	3.03E-01	1.20E+00	2.84E-01	[m/k]	T	P	@#	57,54,53
1965	IBM 360/65	64	1.31E+05	5.00E+06	7.14E+05	2.08E+05	7.03E+00	1.63E+06	6.83E+06	2.70E-02	2.96E-02	7.05E-03	[m/k]	T	P	@#	8
1965	Digital PDP-8	12	4.10E+03		3.33E+05		3.01E-02	2.10E+04	8.83E+04	8.15E-02	4.53E-01	1.08E-01	[k]	T	P	7#	
1966	IBM 360/44	32	3.28E+04	4.00E+06	5.00E+05		5.19E+00	3.62E+05	1.48E+06	7.92E-03	1.08E-02	2.65E-03	[m/k]	T	P	7#	55
1966	IBM 360/75						2.54E+00	5.00E+06	2.04E+07	2.24E-01	2.33E-01	5.69E-02	[m1]				
1968	Digital PDP-10						6.55E-01	3.00E+06	1.14E+07	4.84E-01	5.08E-01	1.34E-01	[m1]				
1969	Univac 1106	36	7.86E+05		6.67E+05	2.73E+05	5.72E+00	1.67E+06	6.05E+06	2.94E-02	3.22E-02	8.88E-03	[m/k]	T	P	7	
1969	CDC 7600						2.57E+01	1.00E+07	3.62E+07	3.92E-02	4.01E-02	1.11E-02	[m1]				
1969	DG Nova						1.17E-01	7.60E+03	2.75E+04	6.54E-03	7.46E-02	2.06E-02	[m1]				
1970	Digital PDP-11/20	16	8.19E+03	3.57E+06	2.25E+05	4.40E+03	3.27E-01	2.80E+04	9.64E+04	8.19E-03	4.50E-02	1.31E-02	[m/k]	T	P	7#	59
1970	GE-635						6.49E-01	2.00E+06	6.88E+06	2.95E-01	3.32E-01	9.64E-02	[m1]				
1971	IBM 370/145	64	1.64E+05	4.93E+06	4.67E+05	5.00E+04	2.71E+00	7.00E+05	2.29E+06	2.35E-02	2.95E-02	9.00E-03	[m/k]	T	P	7#	
1971	SDS 920						1.05E-01	1.00E+05	3.28E+05	8.67E-02	2.03E-01	6.20E-02	[m1]				
1972	Digital PDP-11/10	16	8.19E+03		1.70E+05	3.30E+03	2.50E-01	2.50E+04	7.86E+04	8.74E-03	4.24E-02	1.35E-02	[m/k]	T	P	7#	63
1972	IBM 370/135	32	9.83E+04	3.64E+06	2.37E+05	3.90E+04	1.18E+00	4.88E+05	1.53E+06	3.60E-02	5.02E-02	1.60E-02	[m/k]	T	P	7#	60
1972	IBM 360/195						1.73E+01	8.00E+06	2.51E+07	4.04E-02	4.18E-02	1.33E-02	[m1]				
1972	Honeywell 700						7.50E-02	1.20E+04	3.77E+04	1.40E-02	1.26E-01	4.01E-02	[m1]				
1973	IBM 370/125	16	9.83E+04	2.08E+06	1.04E+05	7.50E+03	3.69E-01	3.54E+05	1.05E+06	7.94E-02	1.25E-01	4.21E-02	[m/k]	T	P	7#	
1973	Prime Computer 100						3.60E-01	8.50E+03	2.53E+04	1.95E-03	1.37E-02	4.61E-03	[m1]				
1974	IBM 370/115	16	6.55E+04	2.08E+06	6.90E+04	4.40E+03	2.13E-01	1.11E+05	3.02E+05	3.94E-02	1.18E-01	4.32E-02	[m/k]	T	P	7#	61
1974	MITS Altair						1.00E-02	5.00E+02	1.37E+03	3.79E-03	7.97E-03	2.92E-03	[m1]				
1974	IBM 370/168						8.88E+00	2.00E+06	5.46E+06	1.71E-02	1.99E-02	7.29E-03	[m1]				
1975	IBM 370/168-3	32	1.05E+06	1.25E+07	6.25E+06	1.30E+06	3.89E+01	3.18E+06	7.93E+06	5.67E-03	6.30E-03	2.52E-03	[m/k]	T	P	7#	56
1975	DG Eclipse						4.70E-01	5.00E+04	1.25E+05	7.38E-03	3.35E-02	1.34E-02	[m1]				
1975	Digital KL-10						2.30E+00	5.00E+05	1.25E+06	1.51E-02	2.22E-02	8.88E-03	[m1]				
1976	IBM 370/138	16	5.24E+05	3.64E+06	3.79E+05	4.00E+04	2.15E+00	3.30E+05	7.79E+05	1.01E-02	1.59E-02	6.71E-03	[m/k]	T	P	7#	62
1976	Digital PDP-11/34	16	3.28E+04	5.56E+06	2.28E+05	4.30E+03	4.17E-01	3.00E+04	7.09E+04	4.72E-03	3.46E-02	1.46E-02	[m/k]	T	P	7#	0
1976	Digital PDP-11/70						4.00E-01	1.50E+05	3.55E+05	2.46E-02	6.61E-02	2.80E-02	[m1]				
1976	Cray I						1.50E+02	1.00E+07	2.36E+07	4.38E-03	4.54E-03	1.92E-03	[m1]				
1977	IBM 370/148	32	1.05E+06	5.56E+06	8.08E+05	6.25E+04	4.42E+00	7.00E+05	1.55E+06	9.78E-03	1.07E-02	4.83E-03	[m/k]	T	P	7#	
1977	Apple II						2.00E-02	1.30E+03	2.89E+03	4.01E-03	6.11E-03	2.75E-03	[m1]				
1977	TRS-80						4.00E-02	2.00E+03	4.44E+03	3.08E-03	4.14E-03	1.86E-03	[m1]				
1977	Commodore PET						6.00E-02	1.50E+03	3.33E+03	1.54E-03	2.24E-03	1.01E-03	[m1]				
1978	IBM 3031	64	2.10E+06	8.70E+06	2.00E+06	3.33E+05	1.47E+01	1.46E+06	3.02E+06	5.71E-03	6.87E-03	3.31E-03	[m/k]	T	P	7#	65
1978	Digital VAX 780	32	1.31E+05	5.00E+06	2.50E+06	1.56E+05	6.38E+00	2.56E+05	5.31E+05	2.31E-03	4.32E-03	2.08E-03	[m/k]	T	P	7#	64
1978	CDC IPL						7.50E+00	5.00E+05	1.04E+06	3.84E-03	6.11E-03	2.95E-03	[m1]				
1979	IBM 4331	8	5.24E+05		4.76E+05	3.40E+04	2.19E+00	1.50E+05	2.87E+05	3.64E-03	9.47E-03	4.95E-03	[m/k]	T	P	7#	66
1979	Nanodata VMX200						2.10E+00	3.00E+05	5.74E+05	7.60E-03	1.37E-02	7.14E-03	[m1]				
1980	TRS-80 M3						4.00E-02	1.20E+03	2.10E+03	1.46E-03	2.51E-03	1.43E-03	[m1]				
1980	Sun I						4.84E-01	3.00E+04	5.26E+04	3.02E-03	3.11E-03	1.77E-03	[m1]				
1981	IBM PC	16	1.64E+04	4.77E+06			2.00E-01	3.50E+03	5.61E+03	7.79E-04	9.89E-04	6.17E-04	[mcc]	M	P	%	
1981	CDC Cyber-205						7.32E+01	9.00E+06	1.44E+07	5.48E-03	5.82E-03	3.63E-03	[m1]				
1981	Commodore VIC 20						4.00E-02	2.79E+02	4.47E+02	3.11E-04	1.36E-03	8.48E-04	[m1]				
1982	Commodore 64	8	6.55E+04	1.00E+06			2.00E-02	5.95E+02	8.98E+02	1.25E-03	3.34E-03	2.21E-03	[mcc]	M	P	%	
1982	Sun 2						7.41E-01	2.00E+04	3.02E+04	1.13E-03	1.19E-03	7.87E-04	[m1]				
1983	Apple IIe	8	6.55E+04	1.02E+06			2.00E-02	1.40E+03	2.03E+03	2.82E-03	4.93E-03	3.39E-03	[mcc]	M	P	#%	
1983	Digital VAX 750	32	1.05E+06	3.13E+06			6.50E-01	8.50E+04	1.23E+05	5.27E-03	5.34E-03	3.68E-03	[mcc]	M	P	#	
1983	IBM PC/XT	16	6.55E+04	4.77E+06			2.50E-01	5.00E+03	7.26E+03	8.07E-04	9.75E-04	6.71E-04	[mcc]	M	P	#%	
1983	TRS-80 M4						2.00E-01	1.00E+03	1.45E+03	2.02E-04	4.12E-04	2.84E-04	[m1]				
1984	Apple Macintosh	16	1.31E+05	7.70E+06			5.00E-01	2.50E+03	3.50E+03	1.94E-04	2.78E-04	1.99E-04	[mcc]	M	P	#%	
1985	Digital VAX 785	32	2.10E+06	6.02E+06			1.69E+00	2.00E+05	2.71E+05	4.46E-03	1.19E-02	8.78E-03	[mcc]	M	P	#	
1985	IBM PC/AT	16	2.62E+05	6.00E+06			6.40E-01	5.00E+03	6.78E+03	2.94E-04	3.60E-04	2.65E-04	[mcc]	M	P	#%	
1985	Cray 2						8.24E+02	1.00E+07	1.36E+07	4.57E-04	4.88E-04	3.60E-04	[m1]				
1985	L.Edge XT-7.16						2.60E-01	2.00E+03	2.71E+03	2.90E-04	4.51E-04	3.33E-04	[m1]				
1985	Atari 800XL						1.65E-01	8.50E+02	1.15E+03	1.94E-04	4.49E-04	3.31E-04	[m1]				
1986	Sun 3						2.12E+00	1.00E+04	1.33E+04	1.74E-04	1.94E-04	1.46E-04	[wdn]				
1986	Digital VAX 8650						9.19E+00	1.25E+05	1.66E+05	5.02E-04	1.87E-03	1.41E-03	[wdn]				

Date	Name	Word Size (bits) [5]	Mem. (Bytes)	Clock (Hz)	Add time (+/s)	Multiply time (x/s)	Index of Computer Power	Cost current $	Capital cost (1996 $)	Capital cost per unit CP (1996 $)	Cost per unit CP (1996 $)	Cost per unit CP	For-mula used for power	Con-struc-tion	Log-ic	Sources	Notes
1986	MIT XT-8						5.34E-01	5.00E+02	6.64E+02	3.45E-05	1.13E-04	8.52E-05	[m1]				
1987	Dell PC Limited 386-16	32	1.05E+06	1.60E+07			2.15E+00	4.50E+03	5.80E+03	7.49E-05	9.44E-05	7.32E-05	[mcc]	M	P	#*	
1987	Macintosh II						1.91E+00	3.00E+03	3.87E+03	5.63E-05	7.82E-05	6.07E-05	[wdn]				
1987	Sun 4						1.02E+01	1.00E+04	1.29E+04	3.51E-05	3.92E-05	3.04E-05	[wdn]				
1988	Macintosh IIx						3.90E+00	9.30E+03	1.16E+04	8.26E-05	9.33E-05	7.48E-05	[wdn]				
1988	CompuAdd 386-16						2.80E+00	2.10E+03	2.62E+03	2.60E-05	4.09E-05	3.28E-05	[m1]				
1988	PC Brand 386-25						1.15E+01	2.45E+03	3.05E+03	7.38E-06	1.10E-05	8.83E-06	[wdn]				
1989	Sun SparcStation 1	32	1.68E+07	2.00E+07			1.00E+01	9.00E+03	1.08E+04	3.00E-05	3.42E-05	2.85E-05	[mcc]	M	P	#	
1989	Mark 386						1.29E+01	1.20E+04	1.44E+04	3.10E-05	3.43E-05	2.85E-05	[m1]				
1989	Wang VS 10000						1.03E+02	5.10E+05	6.12E+05	1.65E-04	2.26E-04	1.88E-04	[m1]				
1989	Macintosh SE/30						3.90E+00	6.49E+03	7.79E+03	5.55E-05	6.62E-05	5.52E-05	[m1]				
1989	Solbourne 5/500						2.55E+01	5.00E+04	6.00E+04	6.54E-05	2.30E-04	1.91E-04	[m1]				
1990	Dell System 425E	32	4.19E+06	2.50E+07			8.70E+00	7.90E+03	9.13E+03	2.92E-05	7.72E-05	6.68E-05	[mcc]	M	P	#*	
1990	Stardent 3000						2.73E+01	8.90E+04	1.03E+05	1.05E-04	2.58E-04	2.23E-04	[m1]				
1990	Amiga 2500/30						1.95E+01	4.70E+03	5.43E+03	7.74E-06	9.88E-06	8.55E-06	[m1]				
1990	Acer 1200						2.00E+01	1.10E+04	1.27E+04	1.77E-05	1.97E-05	1.71E-05	[m1]				
1990	MVME165						1.66E+01	4.00E+03	4.62E+03	7.74E-06	1.03E-05	8.87E-06	[m1]				
1990	Power VEISA						2.21E+01	5.80E+03	6.70E+03	8.43E-06	1.03E-05	8.93E-06	[m1]				
1990	Dell 320LX						1.25E+01	2.90E+03	3.35E+03	7.45E-06	1.08E-05	9.34E-06	[wdn]				
1990	Macintosh IIfx						1.00E+01	9.87E+03	1.14E+04	3.17E-05	3.59E-05	3.10E-05	[m1]				
1990	Amiga 3000						1.25E+01	3.30E+03	3.81E+03	8.48E-06	1.18E-05	1.02E-05	[m1]				
1990	VMPM868KD						1.25E+01	2.90E+03	3.35E+03	7.45E-06	1.08E-05	9.34E-06	[m1]				
1990	Step 486/33						1.75E+01	1.00E+04	1.16E+04	1.83E-05	2.07E-05	1.79E-05	[m1]				
1991	Dell 433P	32	2.10E+06	3.30E+07			1.11E+01	5.00E+03	5.58E+03	1.40E-05	1.77E-05	1.59E-05	[mcc]	M	P	#*	
1991	Gateway 486DX2/66						5.30E+01	3.90E+03	4.35E+03	2.28E-06	3.06E-06	2.75E-06	[wdn]				
1991	ACT 468/33						2.18E+01	3.40E+03	3.79E+03	4.83E-06	6.74E-06	6.04E-06	[m1]				
1991	Slimline SP486DX						2.18E+01	3.60E+03	4.02E+03	5.12E-06	7.02E-06	6.30E-06	[m1]				
1991	Macintosh Quadra 900						2.20E+01	3.30E+03	3.68E+03	4.65E-06	6.54E-06	5.86E-06	[m1]				
1992	AST Bravo						1.29E+01	1.40E+03	1.52E+03	3.28E-06	6.51E-06	5.97E-06	[m1]				
1992	IBM PS/2 55-041						1.06E+01	2.00E+03	2.18E+03	5.71E-06	9.63E-06	8.84E-06	[wdn]				
1992	AST Premium II						1.32E+01	2.80E+03	3.05E+03	6.42E-06	9.57E-06	8.79E-06	[m1]				
1992	IBM PS/2 90						2.24E+01	9.60E+03	1.05E+04	1.30E-05	1.48E-05	1.36E-05	[wdn]				
1992	NEC Powermate						2.18E+01	4.80E+03	5.23E+03	6.66E-06	8.57E-06	7.87E-06	[wdn]				
1993	Dell XPS-P60	32	8.39E+06	6.00E+07			6.20E+01	3.00E+03	3.19E+03	1.43E-06	2.10E-06	1.98E-06	[mcc]	M	P	#*	
1993	Aberdeen Mini						1.62E+01	2.80E+03	2.98E+03	5.10E-06	7.67E-06	7.22E-06	[m1]				
1993	IBM Valuepoint						2.61E+01	3.60E+03	3.83E+03	4.07E-06	5.67E-06	5.33E-06	[m1]				
1993	Acer Power						4.45E+01	3.50E+03	3.72E+03	2.32E-06	3.26E-06	3.06E-06	[m1]				
1993	Ambra Desktop						2.11E+01	2.40E+03	2.55E+03	3.36E-06	5.33E-06	5.01E-06	[m1]				
1993	DECpc LPV						1.66E+01	2.90E+03	3.08E+03	5.16E-06	7.67E-06	7.21E-06	[m1]				
1993	AST Pemmia						1.62E+01	3.60E+03	3.83E+03	6.56E-06	9.13E-06	8.59E-06	[m1]				
1994	NEC 486SL DX2						3.19E+01	3.80E+03	3.96E+03	3.45E-06	4.76E-06	4.57E-06	[m1]				
1994	Vesa						2.00E+01	1.20E+03	1.25E+03	1.74E-06	3.83E-06	3.67E-06	[m1]				
1994	AT&T System 3260						4.40E+01	2.50E+03	2.60E+03	1.64E-06	2.59E-06	2.49E-06	[m1]				
1994	IBM 433/DX/Si						2.61E+01	1.80E+03	1.87E+03	2.00E-06	3.60E-06	3.45E-06	[m1]				
1994	Micron 466 Wndsrvr						5.47E+01	3.60E+03	3.75E+03	1.90E-06	2.67E-06	2.56E-06	[m1]				
1994	AST Premia GXP/90						9.86E+01	5.80E+03	6.04E+03	1.70E-06	2.13E-06	2.04E-06	[m1]				
1994	AT&T Globalyst 600						9.86E+01	4.80E+03	5.00E+03	1.41E-06	1.83E-06	1.76E-06	[m1]				
1994	ZEOS Contenda 386						2.00E+01	1.00E+03	1.04E+03	1.45E-06	3.54E-06	3.40E-06	[m1]				
1994	Gateway 2000 486						1.62E+01	1.00E+03	1.04E+03	1.79E-06	4.37E-06	4.19E-06	[m1]				
1994	PowerMac 7100/66						1.00E+02	2.90E+03	3.02E+03	8.39E-07	1.26E-06	1.21E-06	[m1]				
1994	PowerMac 8100/80						1.20E+02	4.25E+03	4.43E+03	1.02E-06	1.37E-06	1.32E-06	[m1]				
1995	Dell Dimension XPS P133c	32	1.68E+07	1.33E+08			1.40E+02	3.90E+03	3.98E+03	7.89E-07	1.09E-06	1.07E-06	[mcc]	M	P	#*	
1995	PowerMac 8500/120						1.80E+02	4.00E+03	4.08E+03	6.29E-07	8.63E-07	8.47E-07	[m1]				
1995	PowerMac 9500/132						2.00E+02	5.30E+03	5.40E+03	7.50E-07	9.61E-07	9.42E-07	[m1]				
1995	Intel Xpress/60						7.00E+01	2.00E+03	2.04E+03	8.09E-07	1.41E-06	1.38E-06	[m1]				
1996	Gateway P5-75						9.20E+01	2.00E+03	2.00E+03	6.04E-07	1.07E-06	1.07E-06	[m1]				
1996	Power Tower 180e						3.00E+02	3.30E+03	3.30E+03	3.06E-07	4.48E-07	4.48E-07	[m1]				
1996	PowerMac 7600/132						1.60E+02	3.00E+03	3.00E+03	5.21E-07	7.87E-07	7.87E-07	[m1]				
1997	Dell Dimension XPS D266	32	6.71E+07	2.66E+08			3.54E+02	3.10E+03	3.04E+03	2.39E-07	3.61E-07	3.68E-07	[mcc]	M	P	#*	
1997	Gateway G6-200						3.50E+02	2.95E+03	2.89E+03	2.30E-07	3.54E-07	3.61E-07	[m1]				
1998	Dell PW410-450	32	1.34E+08	4.50E+08			6.23E+02	3.90E+03	3.78E+03	1.68E-07	2.40E-07	2.48E-07	[mcc]	M	P	#*	
1999	Dell Dimension XPS T	32	1.34E+08	6.00E+08			1.18E+03	1.90E+03	1.81E+03	4.26E-08	8.12E-08	8.51E-08	[mcc]	M	P	#*	
2000	Dell PW420-1000	32	2.68E+08	1.00E+09			1.84E+03	2.50E+03	2.34E+03	3.54E-08	6.07E-08	6.49E-08	[mcc]	M	P	#	
2001	Dell PW330-1.5	32	2.68E+08	1.50E+09			2.50E+03	2.85E+03	2.61E+03	2.90E-08	4.77E-08	5.22E-08	[mcc]	M	P	#	
2002	Dell Dimension 4300S	32	2.68E+08	1.70E+09			2.76E+03	1.11E+03	9.98E+02	1.00E-08	2.72E-08	3.02E-08	[wdn]	M	P	WDN	

For sources and notes, see pages that follow.

Key to Appendix.

Construction

M The machine was completely mechanical in nature, or used electricity only to drive the mechanical components.
E The machine relied on electrical contacts, but no more advanced technologies.
R The machine was constructed principally from relays.
V The machine was constructed principally from vacuum tubes.
T The machine was constructed principally from transistors.
M The machine was constructed using microprocessors.

Note: Categorizations past 1960 are approximate, and should be verified if used.

Logic

N None. Each computation had to be entered manually by the operator.
S Sequence controlled. A sequence of commands could be read by the machine, which would then execute them in order.
P Fully programmable. A computer that was capable of looping and conditional branching, and stored programs in read-write memory.

Note: Rojas makes a detailed argument in *Annals* 20(3) that most sequence-controlled machines could emulate a fully programmable machine. This highly theoretical argument, however, involves an exponential decrease in operating speed. Thus, the distinction given above still seems valid under normal operating conditions.

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* Various computer magazine advertisements. See documentation for details.

% Various computer websites. See documentation for details.

Notes

1 Mechanical calculator speeds appear to be fairly similar in this time period. The Office Machines Research Service gives only two speeds, one for “non-listing adding machines with direct registration,” and one for “listing adding machines and non-listing adding machines with pre-set-up.” The Victor falls into the pre-set-up category, and thus this speed is given.

2 Cost is in 1989 DMs, and was the cost of rebuilding the Z1 according to original specifications. The historic cost is unknown.

3 Price does not include labour, as Zuse himself built the machine.

4 Cohen lists cost as $200,000. Augarten claims $500,000. Bashe describes in some detail how there was an absolute ceiling of $100,000 on the project, and Lake aimed for a cost of $50,000 to $60,000. In *Annals*, Bashe states that the final cost was “several times” this ceiling. Cohen's number is used.

5 In addition to listed memory, there were 501 bits of sequence data used in calculations. This appears to be read-write memory, so it has been included in the calculations.

6 Cost does not include labour. With 11 to 15 engineers, it took a month to produce each unit.

7 Cost is the total of a five-year lease plus buyout. Only one unit was produced, and it was leased to sell in this fashion.

8 Augarten claims that the addition speed is only 2 per second; this is probably a misunderstanding about the parallel nature of the computer. Burks appears to be the authoritative source, and they give the addition speed as 30 per second. Burks' number is used.

9 Weik gives total army appropriations as $486,804.22. This may not include some costs borne by the University of Pennsylvania, such as floor space. Kempf gives total costs as approximately $750,000, but his ENIAC configuration includes later modifications, such as a 100 word magnetic core memory that was not part of the original machine. Augarten claims $500,000, including transportation expenses, which were probably substantial. Davis notes that transportation of the completed machine cost $100,000 - a significant fraction of total cost.

10 Clock rate could vary between 60kHz and 125kHz according to Kempf. 100kHz was given as the clock rate by Weik. This is within Kempf's range, and is also mentioned by Augarten. This number is used.

11 EDVAC was a stored program computer; however, it does not seem to have supported conditional branching.

12 A 24,576 word drum memory was also present; however, it was mainly used for backup, and thus is not included.

13 Modifications to the Z4 around 1950 added a conditional branch operator, and the programmers at ETH-Zurich developed a method of compiling a program on to punched cards that were intended for data. However, since these capabilities were not part of the original design of the machine, and programs were not generally stored in the memory, it has been listed as sequence-controlled.

14 Five processors calculated in parallel on a paper tape running at 5,000 characters per second. Tony Sale claims that they were capable of up to 100 boolean operations per character. This would place the additions per second significantly higher than 5,000.

15 The 128 word main memory was augmented by 1024 word drum memory.

16 Popplewell (cited in Campbell-Kelly) reports that an engineer and a programmer were generally required for operation; however, the Mark I has a single person console, and seems to have been designed for one-person operation as well. Lavington reports that a Dr. Glennie would periodically lock himself in the computer room alone in order to carry out extensive top-secret calculations for atomic weaponry. Weik lists two engineers as necessary.

17 Price is not that of the 1949 prototype, but rather of a virtually identical 1951 model that was manufactured for Manchester by Ferranti.

18 A staff of one is perhaps an exaggeration. Searching for large primes, the Mark IV calculated by itself for over 100 hours.

19 Cost given only covers components, since the researchers were already employed by the institution. Construction of the Mark III took about a month with a staff of four. Construction time for the Mark IV was not given, but was probably about the same.

20 Multiplication speed is for 14 digit numbers.

21 The machine would run alone at night, and if a failure was detected it would transfer control to its second processor. During the day, Ceruzzi states that "an operator" was present. Given the reliability of the machine, it seems unlikely that more than one technician was needed.

22 Augarten claims that the machine could only multiply once a minute, which seems far too slow given the capabilities of later machines in the series. One possibility is that he confused real multiplication with complex multiplication. Ceruzzi states that the machine took about a minute to complete a complex multiplication.

23 Staffing was given as the number of full time employees required to run the computer around the clock. This number has been divided by three to obtain the number of employees per shift, which seems to be more comprable to the numbers used for other machines. All staffing numbers determined this way were rounded up, because Weik's data shows fairly significant economies of scale in staffing around the clock. It is unclear why running a computer for three shifts would take fewer than three times the number of employees required to run it for one shift, but this appears to be the case.

24 Weik claims 768 words of memory. Lavington's number is used, on the grounds that he wrote no fewer than two books about early British computers.

25 Moravec claims cost is $100,000. Theodoulidis states that the final cost was unknown, but quotes an EDSAC project member as saying it must have been under a million dollars. Lavington mentions that the university received a £2,500 donation, and used some of its own money as well. Thus, the price must have been somewhere between £2,500 and $1,000,000. In the absence of better information, Moravec's number is used.

26 Staffing is never explicitly given; however, Wheeler states that "even when operators were provided to run the computer, test runs were usually run by the authors of the programs." This seems to imply that the computer can be run quite well by one person. Wheeler goes on to describe how people could qualify to use the computer alone at night. Because of this evidence, the staff requirement is listed as one person.

27 Voltz gives a multiplication speed that would yield 100 multiplications a second; however, Schwarz and Gutknecht both give a slower speed. The slower speed is used.

28 Weik lists a variety of staffing requirements, ranging from 2 people to 9. 4 seems to be about average, thus this number is used.

29 The EPE article cites the other Zuse publication in its bibliography. The are a number of disagreements between the two sources, most notably a DM 70,000 difference in price. Since the EPE article is by the same author, but published later, its values are regarded as correct.

30 Cost is from Moravec, and is thus highly suspect. Little information is available on this machine, since it was similar to the Mark I, but built four years later.

31 Staffing is estimated from the Mark I staffing.

32 The Mark II consisted of a left half and a right half, which could be run together or separately. The memory and speed numbers are double that given in the sources to reflect the capabilities of the machine as a whole.

33 Welch gives $400,000 as an estimate of the cost, before construction began. Weik lists the cost as $600,000. Since Weik obtained his information after construction was complete, his number is used.

34 Campbell and Strong list the cycle speed as 1/250th of a second. However, this is also the time it takes for the machine to perform one addition. Given that the machine is unlikely to be able to perform a complete addition in only one clock cycle, Weik's clock speed of 64kHz is used instead. The number that Campbell and Strong give appears to be the speed of rotation for the memory drum.

35 The only speed figures available include memory access time. True speed figures would thus be somewhat higher.

36 Whirlwind began operations in 1949, with only 256 words of memory. In 1951, the computer was fully operational, with 1024 words of memory. 1024 words of core memory were added in 1953, creating dramatic performance and reliability improvements.

37 Actual costs are difficult to ascertain, because basic research comprised a large portion of project costs. The cost listed is the one supplied by Redmond and Smith as an estimate of construction costs. The 1953 computer model is used because the cost was given for this model.

38 Staffing was probably included in the cost figure, since the machine was operating as it was being built, and the technicians were all lab staffers.

39 Cost includes some basic research, and thus is probably slightly too high.

40 Multiplication speed was not available, and is estimated based on the multiplication speed of the LEO II.

41 Staffing was not given, and the numbers used are the lowest possible. Bird explicitly mentions that the LEO had a full-time employee whose only job was to test vacuum tubes. There was also a “senior operator”, and presumably one or more junior operators.

42 Staffing estimate is based on almost no evidence, and should not be used.

43 LEO and LEO II computer time could also be purchased by the hour. Time on the LEO cost £50 per hour in 1954, while time on the LEO II cost somewhere around £35. “This was subject to haggling,” Bird reports.

44 Staffing requirements are unknown, but wages would have been included in hourly cost.

45 Truesdell reports that the Powers tabulator was somewhat faster than the older Hollerith model. The actual speed may thus be somewhat higher than the speed given; however, the basic method of tabulation was still the same, thus the speed difference would not be too great.

46 No reliable cost has been found yet. The value given should be treated with some caution.

47 Multiplication speed represents the worst-case scenario. Average multiplication speed would probably be somewhat higher.

48 Cost represents the base system only, without any peripherals. Any actual installation of the system would cost more than the given price.

49 Staffing numbers varied considerably. The median was used.

50 Whirlwind was an experimental machine, one that was operational long before it was declared complete. Knight's KOPS comes from the 1950 Whirlwind, which he lists as costing a little over $700,000. The final 1953 machine may have had much greater capabilities.

51 Storage access time included in addition time. Addition speed should be much higher.

52 Knight gives cost as $1,000,000. Weik claims $7,000,000 to $8,000,000. Average of Weik's numbers used.

53 Phister gives cost as $25,880.

54 Knight gives date as 1965, Moravec as 1967. Knight's date used.

55 Phister gives cost as $119,900.

56 McCallum gives cost as $2,900,000 for a machine with 6MB memory. Phister gives this cost as a machine with no memory. Phister's cost is used.

57 McCallum gives word size as 32 bits, Phister as 64 bits. Phister's word length is used.

58 Phister gives cost as $960,300.

59 McCallum gives cost as $5,200, which seems a bit low.

60 Phister gives cost as $281,000.

61 Phister gives cost as $122,150.

62 Phister gives cost as $367,060.

63 Phister gives cost as $6,000, which seems a bit low.

64 McCallum gives cost as $500,000.

65 Phister gives cost as $1,000,000.

66 Phister gives cost as $67,000.

67 The commercial KOPS seems suspiciously low. There is no easy way to verify the accuracy of this number.
68 Multiplication is estimated as repeated addition.
69 Labor utilization factor varies from 1 to 100 percent of staffing depending upon machine.

Notes to Linking of Different Series

[1] Phister separated from Knight because only calculated commercial benchmark.
[2] Index of commercial to average was 0.84 for period 1951-66. This is used to create splice between Knight and Phister.
[3] Takes ratio of Knight-Pfister spliced and omits outliers. Mean is 22.74.
[4] Multiplies Knight-Pfister index by 22.74 (see [3]).
[5] Digits are converted to bits by $\log_2(10) = 3.32$

Formula used for computer power

[m1] Moravec as in original source
[m2] Moravec as recalculated with data from this study
[a] Add-time/1.77
[m/k] Geometric mean of new Moravec and Knight-Pfister.
[k] Knight-Pfister index.
[mcc] McCallum index
[wdn] Constructed by author