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A functional approach for studying technological progress: Application to information technology ☆

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Abstract

This paper develops and assesses a broad functional category approach to arriving at metrics for assessing technological progress. The approach is applied to three functional categories of information technology — storage, transportation and transformation by first building a 100 plus year database for each of the three functional categories. The results indicate generally continuous progress for each functional category independent of the specific underlying technological artifacts dominating at different times. Thus, the empirical results reported in this study indicate that the functional category approach offers a more stable and reliable methodology for assessing longer time technological progress trends. Therefore, this approach offers the promise of being more useful in technological forecasting for large-scale change even as its ability to forecast specific dominant technological trajectories has been compromised.

Keywords: Functional category; Tradeoff metrics; Technological progress; Information technology

1. Introduction

Technological progress is the improvement in the efficiency of the production or use of a product, device, or process as the result of increasing experience that includes organizational and technological change as well as learning. It can be viewed as an extension of biological evolution with new concepts and new knowledge

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metaphorically representing the improving genome and improved technological systems and products being the result [1,2]. The progress of technological change is important in driving economic and cultural changes [3,4] and the desire to adapt beneficially can be aided by quantitative approaches.

The use of quantitative techniques to delineate technological progress has been the subject of significant previous investigations. A recent review article [5] covered much of these efforts as well as more conceptual issues in technological forecasting research. The earliest and perhaps paradigmatic studies such as those due to Martino [6] determine an appropriate metric to characterize a technological artifact and then empirically study time dependence of that metric to derive the most appropriate equation describing the technological progress. In Martino's [7,8] papers, he proposed that technology is often best described by multiple parameters and that the state of the art in a "technologically homogeneous" domain is represented by a tradeoff surface. Specific embodiments of technology and the resulting devices within such domains trade off attributes (based on engineering and use constraints) as made possible by the fundamental technological status at that point in time and thus occupy different places on the tradeoff surface. Progress is measured by movement (growth) of the tradeoff surface. Martino showed empirical results consistent with this proposal. Similar studies in other domains have used comparable approaches. For example, Manaqi [9] quantified the performance and progress of drilling ability with cost per well as a measure over the past 50 years—he proposed that a model combining field-level discovery, yield per unit of effort (YPE), and drilling cost best described the time dependence. Composite measures of performance as functions of time and cost have been used to measure technological change [10–12] in a similar way for other technological systems. These researchers recognized that the appropriate parameter to assess technical performance required domain-specific technological information. Thus, such parameters should be estimated by engineers who were experienced and knowledgeable in the domain and device of interest. Such engineers had sufficiently detailed knowledge of the attributes and components of the overall system to pick the best metrics for that technological device. The resulting approach can therefore be described as a bottom-up approach.

A possible alternative first discussed by Ayres [13] is an economy oriented top-down approach. Ayres noted that the technological difference between compact cars and luxury cars, for example, are very important to the engineers designing such artifacts but trends in such differences may have much less significance in determining overall economic and technological change. To estimate an overall impact, the bottom-up approach would have to construct aggregate measures from component attributes, but Ayres notes that this may obscure the relationship between cost, resource input, and performance and the possibility of unquantifiable variables may intervene. Moreover, he noted that the specific tradeoffs from bottom-up approaches would likely change as technology progresses allowing no consistent framework. Thus, he proposed a top-down approach to measuring technological change at the industry or sectoral level. He then suggested sectoral objectives from a material–process–product perspective that reflect the physical attributes of material, the functions performed by transformation activities, and the relationship between successive transformation stages. However, his technique emphasizes a material perspective of the economy as a whole and does not arrive at important technological measures that are independent of changes in industrial sectors. In this paper, the focus (as in Refs. [6–12]) is upon technological capability and not the economic impact, However, we follow Ayres in trying to construct a broader set of abstractions that cover technology more parsimoniously than single artifacts or even domains. Our aim is to construct a broader framework for viewing technology so that a more limited set of metrics might be able to describe technological progress. We believe that such an approach is more stable and understandable from a long-term point of view because it is not built upon a device-dependent basis.

In the work reported here, we study technological change by examining the time dependence of "Functional Performance Metrics (FPM)" arrived at from an overall technological functional classification of more breadth than previously employed in empirical, quantitative studies of technological progress. We empirically examine one key aspect, information, and three important functional categories, storage, transformation and transportation. For each of these three categories, we have built databases with two relevant FPMs over time for the past one hundred or more years to examine if the approach is applicable to long-term data. With our historical data, we then empirically examine the nature of technological progress over time and calculate the annual progress for each FPM. This paper thus attempts to contribute an approach for arriving at technological measures of progress at a higher level of abstraction and in applying it to one area to test its usefulness and also contribute to understanding of the comparative progress of technology.

2. The functional perspective

In order to measure the performance of an array of technologies with a limited set of metrics, we have to arrive at a reduced set of possible classifications that is yet inclusive relative to technological variety. Ropohl [14], Hubka and Eder [15], van Wyk [16–18] and Magee and de Weck [19] have contributed to evolving a functional technological classification system that is potentially useful in this regard. Expanding Ropohl's and van Wyk's work, Magee and de Weck [19,20] describe functional classification in terms of operands (Matter, Energy, and Information) being changed by operations (Transformation, Transportation, Storage, Exchange and Control) and the classification is illustrated with example systems in Table 1.

This approach for classifying dominant functional aspects of systems and subsystems has been proposed as a general classification system [14,17,19,20] and has been used in the design of systems using specific technologies [15]. In this paper, we use the framework to empirically assess progress in performance of the function over a series of specific technological embodiments. To achieve this assessment, the first step is to arrive at an appropriate measure of the performance for each functional category. These functional performance metrics are quite similar to the figure of merit discussed fairly generally by Girifalco [21]. However, as he and others use them, they are usually derived separately for many different devices and thus cannot be a contained set such as suggested by the 15 classes in Table 1. We do not recommend the broad functional set of metrics as a replacement for device-dependent metrics. For most devices and systems, design constraints and tradeoffs exist that combine and link categories from Table 1. In such cases, technological progress in the device or system will not simply be determined by reference to progress in categories in Table 1 because there is no basis for believing that all devices and systems can be simply decomposed to the categories of Table 1.

The empirical assessment performed in this research examines whether long-term studies are consistent with the framework, whether different possible metrics in a given class give consistent progress trends and how

Table 1
Functional technological classification with operands and operations [17,18]

Operation	Operand		
	Matter (M)	Energy (E)	Information (I)
Transform	Blast furnace	Lamps, electrical generator	***Analytic engine, Calculator***
Transport	Truck	Electrical grid	***Cables, Radio, Television***
Storage	Warehouse	Batteries, flywheels	***Magnetic tape and disk, Book***
Exchange	eBay Trading System	Energy markets	World wide web, wikipedia
Control	Health Care System	Atomic energy commission	Internet engineering task force

the different classes in Table 1 progress relative to one another and over long periods of time. In this paper we limit ourselves to information as the operand of interest and transformation, transportation and storage as the three operations. Further research on other operands and operations is the subject of ongoing research. For each of the three classifications studied further, we selected two functional performance metrics.

3. Functional performance metrics

For each of the 15 functional categories in Table 1, one can derive a number of metrics specific to each functional category. For example van Wyk [17] discusses (for the 9 categories in his paper) examining the total amount of the operation performed with the operand over all time. If such an assessment was empirically done (and it has not), it would attempt to assess technological progress on a global and total basis. We did not employ such metrics in this work because they are dependent upon many non-technological factors (population and economic growth in various parts of the globe, etc.) and thus would not measure progress in functional technological capability—our aim. In this paper, following the insights about tradeoffs developed by Martino and others using the device-specific approach, we arrive at tradeoff based FPMs for our functional framework. Each of these tradeoff based FPMs takes the form output (desired performance) divided by input (traded off attribute).

Table 2 shows the three functions and six Functional Performance Metrics (FPMs) for measuring progress in information technology we examine in this paper. There are other possible FPMs for each of the three cases we study here based on the tradeoffs or limitations that the technology must overcome to be more useful. In this study, we attempt to choose the most important tradeoffs for each functional performance category. We examine two for each functional category to allow comparison and to make our assessment of trends more robust.

Storage is an operation where the matter, energy, or information is stored in limited space and is preserved (no change in state) for a certain time. For our first storage FPM the input selected is limited space (unit volume), and the output is the amount of information stored and the resulting first FPM for the information storage function is the amount of information per unit volume, Mbits per Cubic Centimeter. Since the function of storage has to maintain stored information for a certain time in limited space, time is an important element to consider as well in the output side. However, since we considered only non-volatile storage media for measuring the technological progress in this paper, time was excluded in our storage FPMs. The second

Table 2
Operation and functional performance metrics for measuring the progress in information technology

Operation	Functional performance metric	
	Name	Units
Storage	Amount of information per unit volume	*Mbits/cm^3
	Amount of information per unit cost	Mbits/U.S. dollar (2004)
Transportation	Bandwidth	**Kbps
	Bandwidth per Cable length per unit cost	Kbps/km/U.S. dollar (2004)
Transformation	Calculations per second	***MIPS
	Calculations per second per unit cost	MIPS/U.S. dollar (2004)

*Mbits: Megabits.
**Kbps: Kilobits per second.
***MIPS: Million Instructions Per Second.

FPM is a measure to quantify the value of performance in the function. The monetary cost (in 2004 U.S. dollars using the GDP deflator as the inflation adjustment) is used to measure the value as an input, and the stored amount of information (Mbit) is again the output in our second storage FPM.

The transportation operation is defined as the movement of matter, energy, or information to another location without state change within unit time. The first FPM for information transportation is defined as the amount of transported information per unit time which is the bandwidth (kbps). The amount of information that can be transported at a given time, bandwidth, is the effective measure for transportation rate since all of the technologies considered operate at the speed of light for the transmission speed. The second FPM in information transportation is also defined to measure the value of performance in transportation as bandwidth per 2004 U.S. dollar (again using the GDP deflator for inflation adjustment).

Transformation is an operation where the matter, energy, or information is transformed to other states. In the case of information technology, the state change of information takes place through computational processes so that the original information is transformed into various states of information. Time for transformation is taken as the most important input constraint and thus computational performance per unit time is the first FPM (MIPS) for transformation. As a second FPM, MIPS per U.S. 2004 dollar (again adjusting for inflation with the GDP deflator method), is used to measure the value of transformation. The information transformation FPMs have been used [22,23] and seen as significant in Information Technology but the separate functional categories of storage and transportation have not been as widely studied.

4. Case study: information technology

4.1. Characteristics of historical data

This study utilized archival data obtained from various books, public journals, and the US Census Bureau. We have developed a relatively comprehensive database using these references: (1) historical storage performance data including a information storage devices from 1890 to 2004 (a total of 36 references for 68 storage devices); (2) bandwidth and cost of undersea cable describing the information transportation capability from 1858 to 2004 (a total of 24 references for 41 undersea systems and the Internet backbone); (3) historical data on information transformation, including the yearly capability of transformation is estimated from 1900 to 2004 (a total of 6 references for 130 devices).

Since the performance of technological change is measured with various FPMs over the past 100–150 years, the reliability of historical data must occupy an important position in this work. As the historical data were recorded distributively through actual tests or measurements and reported in various publications, the possibility of data errors or inconsistency cannot be eliminated in long-term studies such as this one. Therefore, our historical database was established according to the following standards in order to have adequate consistency and reliability. In the first place, historical data of government reports were generally considered fairly reliable but data found in multiple sources were given the most weight. Secondly, we preferred utilizing data from reviewed journals where ongoing data appeared (e.g. IBM journal of research and development, IBM system journal, and IEEE transactions) as opposed to trade magazines or journals that published only one-off studies. In this study, cost is represented by monetary value in U. S. dollars. Inflation of the price of commodities was applied to the cost and its fluctuation in price (2004) is also applied to the cost with the GDP deflator method [24,25].

The performance data about the storage function are collected from 1900 to 2004 from various public journals and books. Lucky's book [26] gave the capacity of paper material while the price of paper was obtained from the statistical abstract of the United States [27] that is annually published by the Census Bureau. The data for punched cards, which are an important early information storage device, was found in various books and papers [28–30]. In the middle of the 1950's, magnetic tape and disk devices were developed. These devices became widely used and became the prototypical electronic storage devices to compare to other devices. IBM had an important role in technology development for magnetic tapes and disks and the IBM Journal of research and Development [31–35] and IBM System Journal [36] as well as IEEE Transactions on magnetics [37,38], were the most useful and reliable sources in these areas. The historical data about magnetic storage devices were obtained from high performance storage devices for servers, which were made in IBM. In the 1980s, existing storage device technologies were approaching an apparent capacity limit until researchers were able to develop a new storage method—the optical disk. Asian companies (e.g. Samsung, Hitachi, LG, and etc.) were extremely capable in this new method and the most useful data were found in Japan 21st magazine [39] and the IBM Journal of research and Development [40]. Detailed data and complete references for information storage devices are listed in Table A1 in the Appendix.

The early historical data about undersea cable were found in historical books and articles [41–48]. Valuable data in these books and articles included the construction process of undersea cable, the undersea cable installation data, specific values (e.g. lengths, transporting speeds, bandwidth, cable length, and construction cost). These were used in calculating the FPMs. The historical data regarding undersea cable construction before the 1950s was found in a report of the Federal Communication Commission [49]. Specific historical data describing information transportation capability are listed in Table A2 in the Appendix. Calculation performance data in information transformation were found in the following books and papers [22,23,29,50,51]. The historical data about information transformation and detailed references are listed in Table A3 in the Appendix.

4.2. Time dependence of the functional performance metrics

4.2.1. Storage

Assistance to human-based information storage began with stone and other media and was significantly improved starting with the use of papyrus in Egypt and then paper starting in China in AD 105 [52]. The utility of paper as a storage media was greatly improved when Gutenberg invented a letterpress printing method for making copies. Paper as a mode of information storage only began to have important competition during the 20th century as electrical and electronic technologies emerged. Fig. 1 illustrates the time dependence of the amount of information per unit volume (volumetric density) and amount of information per unit cost, from 1890 to 2004 in the information storage functional category.

The ability to store information within a given volume has consistently increased with time as shown in Fig. 1a. We first note that the main figure is a logarithmically scaled graph and this is because such representation best reflects the progress. The small inset linear graph shows that a linear representation makes it appear that all change has occurred in the last few years and thus ignores the significant technological progress in several previous technological eras. The logarithmically scaled graph allows the trend in the FPM to encompass five different underlying technologies: paper, punch cards, magnetic tape, hard magnetic disks and optical disks. The hollow-circled data in Fig. 1a and b represents the best performance at a given time among five different storage devices. While the overall figures show no evidence of a limit being approached, specific technologies (particularly magnetic tape) can possibly be interpreted as reaching a limit or at least reducing their rate of overall improvement.

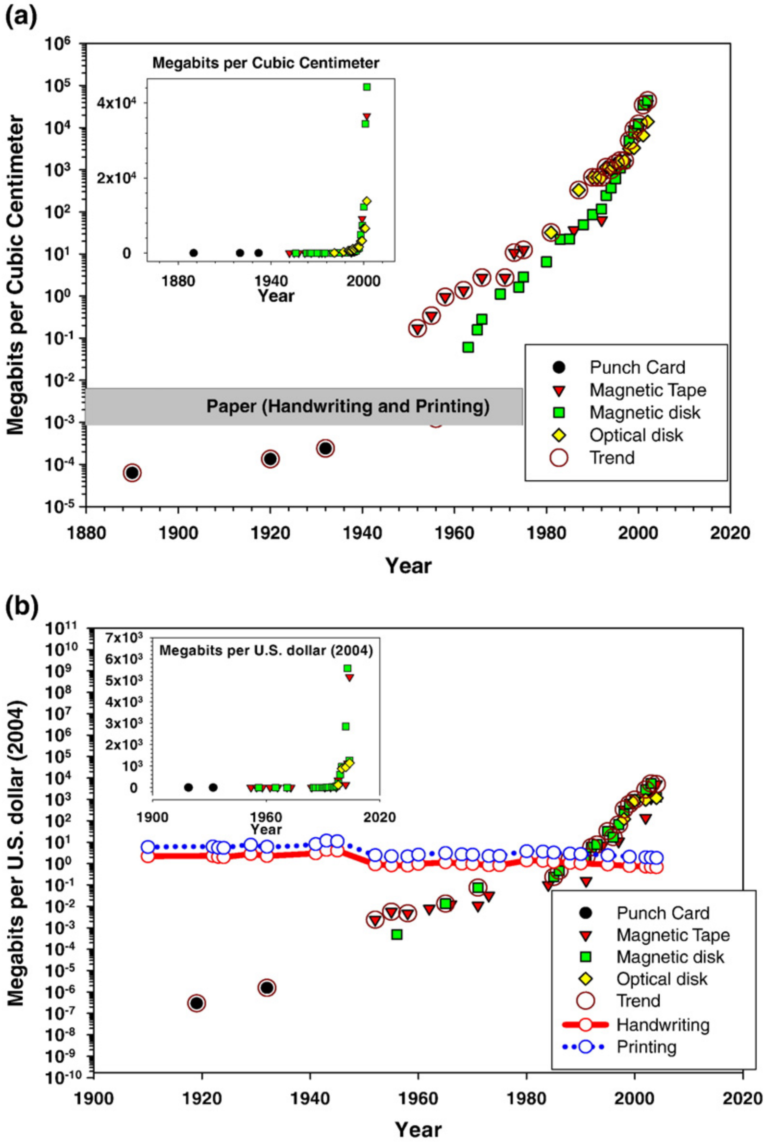

Fig. 1. Historical progress in information storage; (a) by Megabits per cubic centimetre and (b) by Megabits per cost (2004) in logarithmic scale. Only the hollow-circled data in (a) and (b) is treated in the quantitative fit in Section 5.2.

Electronic storage devices have surpassed paper and printed matter in the volumetric ability to store information only in the second half of the twentieth century. In Fig. 1a, a region labeled as handwriting and printing shows a range of the volumetric density for these technologies. In the case of handwriting, the volumetric density will differ among individuals and can also vary with written material situational details. For printing, fonts and size of letters as well as paper thickness influence volumetric density. In order to estimate the thickness of the paper, we examined the paper thickness of books that were published from 1890

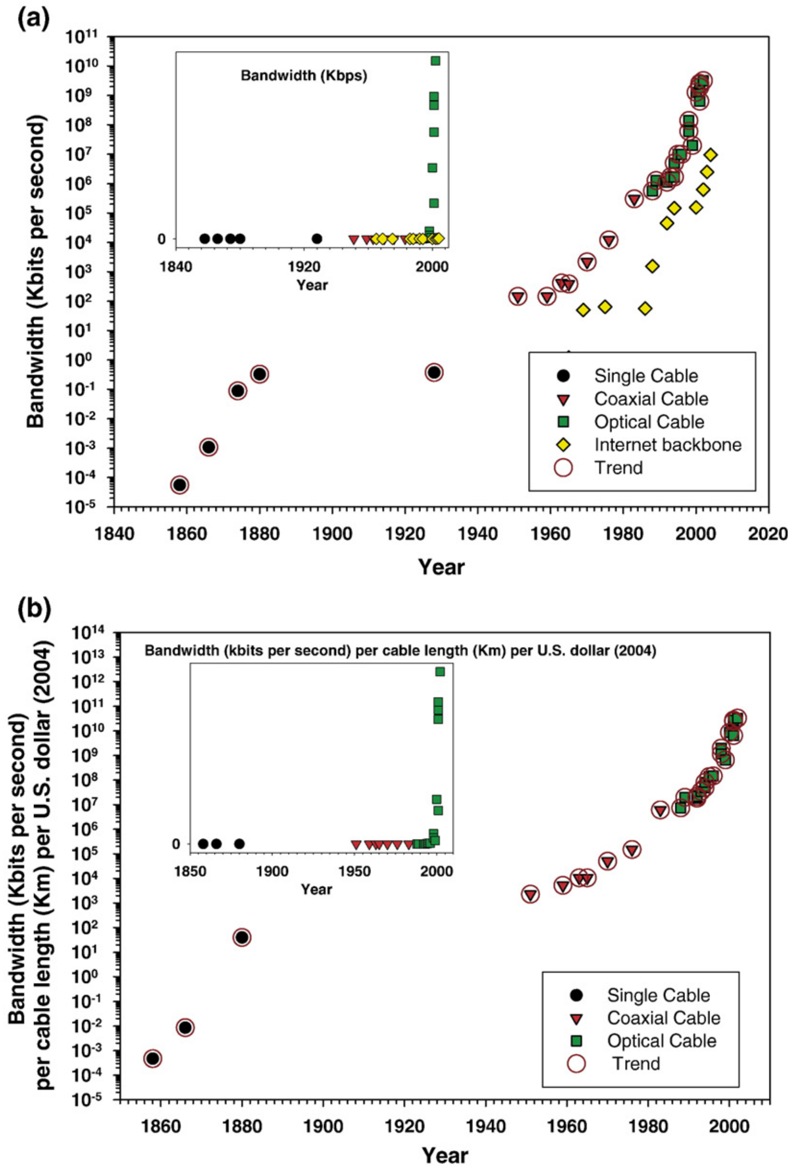

Fig. 2. Trend in Information Transportation Function for undersea cable system; (a) bandwidth (kilobits per second) and (b) bandwidth (kilobits per second) per cable length per cost (2004) in logarithmic scale. Only the hollow-circled data in (a) and (b) is treated in the quantitative fit in Section 5.2.

to 2004. The thickness of the paper gradually decreased and the annual rate of decrease in paper thickness (0.34%) is used in constructing Fig. 1a.

During the last 100 years, storage devices also improved consistently for performance against the cost constraint. Fig. 1b shows the progress of the performance per cost in the information storage functional category. Not until the early 1980s did electronic storage devices move ahead of handwriting and press printing's performance per cost. Despite perceptions of sudden change, Fig. 1 shows that the status of the actual performance of non-paper technologies has more or less continuously increased for about 100 years.

4.2.2. Transportation

Technological assistance to human-based information transportation probably started with animal based transport of paper-based information and early developments also include smoke, light and other signals sent a distance. However, since the middle of the nineteenth century, significant technological development has occurred in the information transportation functional category as information became widely used and transported by dedicated communication devices.

The undersea cable system is an important documented example that fully represents progress of the transportation capability of information technology. Because of its documentation (particularly relative to cost) and that it covers all aspects of the technological progress in information transportation; the undersea cable system was studied to assess the progress in performance for this technological functional category. Moreover, study of undersea cable defines a system with a consistent basis for cost comparison whereas other environments for installation would make cost comparison too variable to arrive at meaningfully comparative data.

In 1858, the first international telegraph was successfully laid between Newfoundland and Valentia in Ireland and we use this as the initiation of undersea information transportation technology. The FPMs for information transportation are plotted in Fig. 2 in a logarithmically scaled graph. The linear inset graph again demonstrates that much of the progress is invisible in such a plot confirming the superiority of the logarithmically scaled representation.

The technological progress of information transportation for undersea cable occurred with single cable technology from the 1850s to the 1940s. Until the 1890s, the performance of single cable technology rapidly increased, but the progress clearly slowed at the beginning of the 1900s apparently reaching a limit. However, in the 1950s, progress resumed based on coaxial cable. In the 1980s, optical cable was first introduced in the undersea cable to support concurrent transport of high volumes of voice and text information as well as video information as the Internet service began to emerge. Optical cable has been commonly used in information transportation since the beginning of 1990s and the progress of information transportation has continued its rapid pace. The progress is visible for the undersea cable data and the Internet backbone data (shown for reference) which has lower bandwidth than the undersea cable but progresses at a very similar rate during this period. In this functional category, a limit is apparently seen to single cable information transportation but overall the figures show no tendency towards "bending over". Thus, the empirical evidence for this category as found for storage is to show no limit when the overall functional progress (as opposed to particular underlying technology embodiments) is examined.

4.2.3. Transformation

Humans have consistently generated new information through reasoning from previous information and experience. Early technological devices including counting devices were developed to aid humans in this information transformation functional area. Since the beginning of the last century, more elaborate calculation devices for extending human ability were developed and progress in information transformation accelerated.

The technological change in this functional category was particularly characterized by development of computers. For the category of information transformation, we utilize computation devices to investigate the functional technological progress. Fig. 3 shows the time dependence of the two FPMs for information transformation. It is again noted that the logarithmically scaled graphs are the appropriate representation

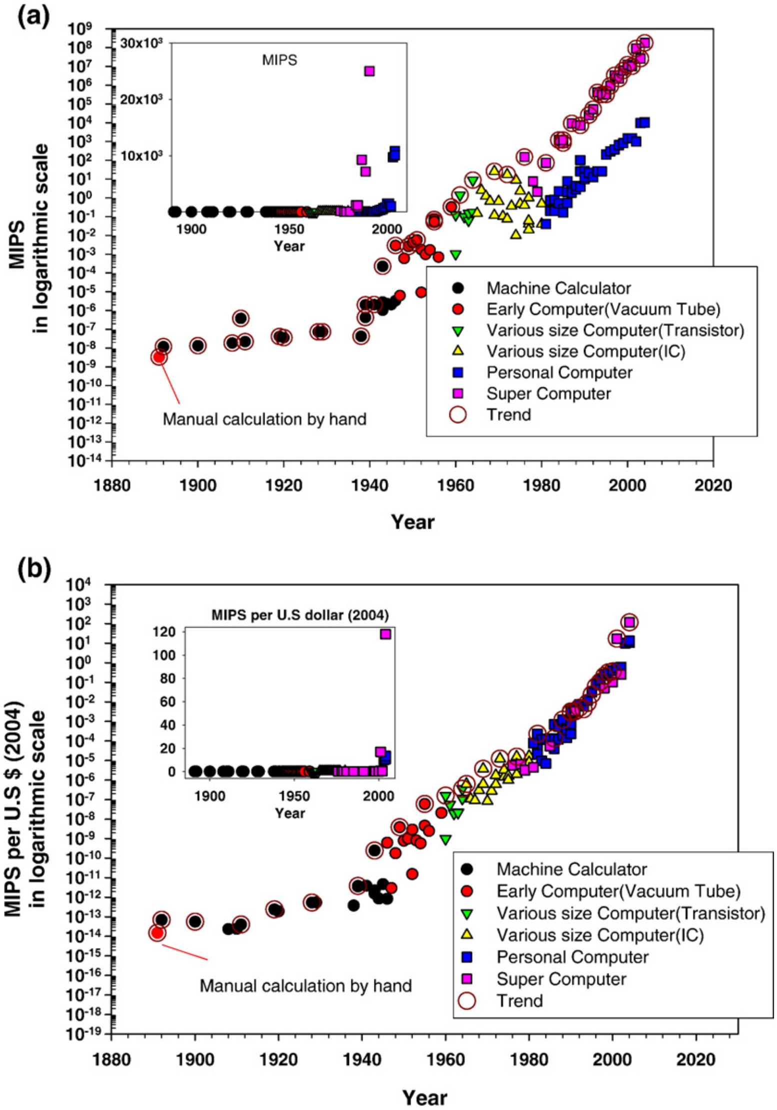

Fig. 3. Progress of information transformation; (a) calculations per second (Million instructions per second, MIPS) (b) calculations per second (Million instructions per second, MIPS) per U.S. dollar (2004) in logarithmic scale. Only the hollow-circled data in (a) and (b) is treated in the quantitative fit in Section 5.2.

as the linear version fails to show very important improvements occurring over much of this 100 plus year trend. One can also note that relatively consistent improvement on this exponential scale is shown for both FPMs over the entire time period. As previously noted for information transformation metrics of this type [22,23], the curves describe in a continuous way a very wide range of technologies starting with early mechanical analogue devices. The trend continues through early (vacuum tube) electronic systems and relatively smoothly joins with the multiple generations of Integrated Circuits (IC). It is these generations of ICs that have been characterized by Moore's law for the past 40 years on similar plots.

Beyond about 1975, the data for personal computers and super computers are clearly differentiated in Fig. 3a. In the period just before 1975, various sizes of computers are included (super, large, mini, micro and etc.) and thus the data shown is quite scattered.[2] If size as well as time were contained in our FPM, the data would be much more tightly arrayed. This is seen in Fig. 3b where MIPS/$ is plotted and the various sizes of computers lead to much less data scatter. After about 1980, market demand and industry cost structure resulted in PC's and supercomputers (now veering towards fundamental technology even more aligned with personal computers) being the only important computer types and they progress at very similar rates in Fig. 3a.

5. Data analysis and results: growth model and technological progress

In Section 4, we discussed the qualitative trends of technological progress regarding information technology over time periods exceeding 100 years in each FPM. In this section we examine the quantitative results that can be extracted from these results. There are two major issues to address. The first is to explore which growth curve is best at describing the results accurately. The second is the comparative growth rate of the FPMs to assess the relative success overcoming various constraints facing each functional category and to see what quantitative differences among categories is found.

5.1. Growth curve

A number of researchers have advocated the use of S-curves as a guide in the management of technology. Becker and Speltz [53] and Foster [54] draw strong implications for managers from technology observation. According to these authors, when the S-curve of technology which is currently employed has passed its inflection point, a new S-curve is rising below at rapid rate and it may intersect with the current S-curve of technology. Finally, the new S-curve is substituted for the current S-curve while its performance surpasses the performance of the current technology [54,55]. Therefore this "linked S-curve theory" would follow the dotted line in Fig. 4.

Although certain technologies have apparent exponential growth patterns, the fact that limits exist is well established in technological forecasting [7,8]. In some measures of technological progress that depend on economic or population constraints or that have actual calculable physical limits, representations that recognize limits are necessary. However, in cases where no limit is calculable and differing technological approaches are possible, the empirical evidence does not support building limits into projections. In the case of information technology, Moore [50] who projects that the growth of a number of transistor on an integrated circuit will increase exponentially is on a stronger empirical foundation than Buzbee and Sharp [56] who utilized the Gompertz curve (one type of S-curve widely used) to represent and forecast the performance of supercomputers. As shown in Figs. 1, 2, and 3, the historical data increases continuously and exponentially with time. Thus, the overall trend (dotted line—Fig. 4) appears exponential for these categories even if individual technological embodiments are S-curve shaped.

5.2. Progress rate

Progress rate has been widely used to characterize technological change. It is defined as the percent increase in performance per year. Figs. 1, 2, and 3 indicate graphically that an exponential behavior is

[2] In fitting this data to equations (Section 5.2), data from only the largest computers are included as most comparable to earlier eras.

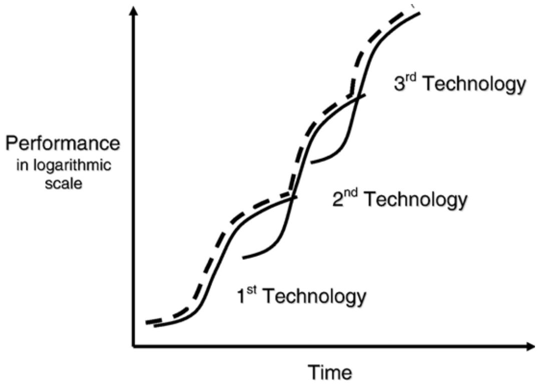

Fig. 4. The "linked S-curve Theory": growth of technology in form of individual S-curves [55].

exhibited for all three categories and all 6 FPMs. Therefore, estimating the annual progress was done by regression analysis of an exponential curve for the comparable data in these figures. These comparable data included all the undersea cable data (but not the Internet backbone data) in Fig. 2 and only the data for the largest computer types in Fig. 3. The hollow-circled data in these figures represent the best performance among various technologies at a given time; it is used to perform the regression analysis. Table 3 shows the result of the regression analysis for technological progress in information technological functional categories. The annual progress is represented as percentage (%) and it is estimated in a 95% confidence interval. For all FPMs, the exponential curve shows moderately high correlation ($r^2 > 0.9$ for all but the bandwidth data for the entire period) with the historical data and thus quantitative progress will be discussed from these data.

There are two different periods for the regression analysis results shown in Table 3. Because of the stasis in information transportation in the early part of the 20th century, we fit all FPMs for their entire period as well as for 1940–present. The elimination of the stasis for transportation and thus having all $r^2 > 0.9$ leads us to primarily consider the 1940–present results in the following part of the paper but the qualitative conclusions for the entire period are basically the same.

Table 3
Technological progress in information technology

Operation	Functional performance metric				
	Name	Whole period		1940–present	
		R^{2*}	Annual progress [a] (%)	R^{2*}	Annual progress [a] (%)
Storage	Amount of information per unit volume	0.92	20.8 ± 1.6	0.93	26.1 ± 2.2
	Amount of information per unit cost	0.94	26.2 ± 3.1	0.87	26.8 ± 4.9
Transportation	Bandwidth	0.88	18.9 ± 2.7	0.90	34.7 ± 4.9
	Bandwidth per Cable length per unit cost	0.88	19.1 ± 2.8	0.92	33.3 ± 4.3
Transformation	Calculations per second	0.94	36.8 ± 2.7	0.96	41.5 ± 2.4
	Calculations per second per unit cost	0.95	30.9 ± 2.5	0.95	37.3 ± 4.7

R^{2*} is rounded off to the second decimal place.
[a] The annual progress and error were estimated in 95% confidence interval.

Table 3 shows that for both FPMs the progress rate is greatest for the transformation function and least for storage. In addition, Table 3 indicates that progress is very similar in the cost-constrained FPM and the other FPM for all three functional categories. *T* tests were performed to make the comparison between the functional categories and between the two FPMs in each category (see Appendix Tables A4 and A5). These results show that substantial statistical significance exists for the differences between progress in different functional categories (storage < transportation < transformation) but not between progress in FPMs in a given functional category.

6. Discussion

This paper describes a high level functional approach to measuring technological progress and is the initial application of that approach over long periods of time. Previous researchers exploring technological progress quantitatively have tended to focus on single underlying technologies (or even on particular embodiments of technology) and over relatively short-term historical data. We should note again that such studies are superior to the approach here if one is focused upon a specific device and time period. The approach based upon study of tradeoffs critical in a particular device and specific time period can easily be shown to have advantages relative to the broader functional approach utilized here when decisions relative to that device in that time period are to be made. In this section, we briefly discuss the other side of the coin—some possibly important insights that come about as a result of using the broader approach. All of these indications have to be offered as tentative. Results from other studies using this approach will also be instructive as this paper covers only three of the 15 functional categories in Table 1.

One interesting observation is that we see statistically significant difference in technological progress among the three information technology functional categories. Importantly we also have seen that differences between progress rates for different metrics and for different technological embodiments within a functional category appear relatively small. Thus, this first empirical study by the functional approach indicates that such an approach does have more long-term stability than approaches based upon specific devices.

Although detailed differences among technological rates of progress are well-known and even assumed, having a more stable set of improvement rates in a framework that describe the longer-term trends has interesting potential implications for assessing social and larger scale changes affected by technological progress. As one example, consider the cross-over seen in Fig. 1b in the early 1980s when other storage media finally became more cost-effective than paper and print. This cross-over is an important factor in the increasing realization since that time that we are undergoing a transition to an "information-dominated" social milieu and the feeling that the change is sudden and surprising. However, the improvement in the non-paper storage devices had been continuously underway for more than 50 years prior to the cross-over and thus better anticipation may have been possible.

As a second example, the progress in information transportation technology (reasonably continuous for the past 100 plus years) has been the foundation for successive waves of large-scale communication mode changes. Until the middle of the 1930s, the undersea cable system was used only for telegraphic transmission and only text information was transmitted so moderate bandwidth was adequate to transport the desired information. By the middle of 1940s, undersea transportation of information was focused on telephonic transmission. The telephonic service required higher bandwidth than telegraphic transmission, because voice as well as text was transmitted. In the early 1980s, optical fiber cable and transmission technology became commercial and its first service, TAT8, was introduced, so that the capability of information transportation was further increased. With the introduction of the Internet in the 1990s, information transportation capability has grown to contain various information content such as voice, pictures, image, and text, where the telephone system contained only voice and the telegraph contained only text. The increased bandwidth of information transportation is the key enabler of these aspects of Internet service and could be said to have made possible the Internet. It is clear that a wide-spread Internet before the technological progress in Information transportation achieved during the 70s, 80s and 90s would not have been possible. Some might even want to argue that the continued progress in information transportation capability "caused" the Internet. While this interpretation might be possible to support, it is less controversial to simply say the progress in information transportation "enabled" the Internet more than is generally recognized or discussed. Similarly, the significant progress in information storage capability enabled such devices as IPODs etc.

As a third example, the continuous nature of Fig. 3 suggests that progress in information transformation has been steady over widely disparate technological embodiments of computers. This continuity might be taken as suggesting that some new information transformation embodiment such as a quantum or optical computing might well continue (at least on a global long-term basis) the trends seen in Fig. 3 even if ICs reach a limit. Thus, the current debates [50,56] about when Moore's law will fail (that is when IC's will reach a limit) while very important to specific corporate technological decisions may be less important to consider relative to the overall impact of information technology on society [22,23].

As a second observation, the results suggest that these three categories (six FPMs) are a reasonable set to overall quantitatively describe the technological progress of information functionally over the long-term. Within a given functional category, one might expect that tradeoffs among constraints would remain somewhat consistent, so that FPMs based on different input constraints would tend to achieve the same annual progress rates over the long-term of interest in this study. The small distinction between the cost-constrained FPM and the other FPM as compared to the distinction between functional categories supports this concept. However, this result must remain preliminary until progress within other functional categories and with other FPMs is studied in more detail. Nonetheless, the consistency of Internet backbone data in Fig. 1 and the PC data in Fig. 3 with our core data and the consistency in progress over generations of technology in each functional category is further evidence from this study of the meaningfulness and stability of the categories and FPMs. If further work supports this observation of stability in other categories in Table 1, the important suggestion emerges that a fairly limited set of progress growth rates (rather than the seeming infinite set implied by device-dependent studies) can be used to understand overall technological progress. Such a result also opens up a research question about explaining the magnitudes of rates of change in different functional categories based upon other technical, economic and social factors and principles.

Acknowledgement

We acknowledge our co-workers at MIT in the Engineering Systems Division and in the Center for Innovation in Product Development, for their helpful comments and discussions of this work. This work was supported by the Korea Research Foundation Grant funded by Korean Government (MOEHRD, Basic Research Promotion Fund) (KRF-2005-214-D00225).

Appendix A

Table A1
Historical storage devices' performance data in information storage

Year	Handwriting		Printing		Punch card		Tape		Hard disk		Optical disk	
	Mbits/cc	Mbits/$	Mbits/cc	Mbits/$	Mbits/cc	Mbits/$	Mbits/cc	Mbits/$	Mbits/cc	Mbits/$	Mbits/cc	Mbits/$
1890	3.0E− 4[27, 28, 29, 30]		7.0E− 4[27, 28, 29, 30]		6.3E− 05[31]							
1900	3.0E− 4[27, 28, 29, 30]		8.0E− 4[27, 28, 29, 30]									
1910		2.187[27, 30]		5.945[27,29,30]								
1919						2.97E− 07[32]						
1920					1.0E− 04[7,10]							
1922		2.312[27, 30]		6.250[27,29,30]								
1923		2.045[27, 30]		5.530[27,29,30]								
1924		1.982[27, 30]		5.360[27,29,30]								
1929		2.786[27, 30]		7.562[27,29,30]								
1932		2.258[27, 30]		6.104[27,29,30]	2.0E− 04[7,10]	1.57E− 06[32]						
1941		2.993[27, 30]		8.099[27,29,30]								
1943		4.334[27, 30]		11.745[27,29,30]								
1945		4.052[27, 30]		10.981[27,29,30]								
1952	4.0E− 4[27, 28, 29, 30]	0.909[27, 30]	0.001[27, 28, 29, 30]	2.466[27,29,30]			0.172[15,16]	2.38E− 03[15,16]				
1955	4.0E− 4[27, 28, 29, 30]	0.817[27,28, 31]	0.001[27, 28, 29, 30]	2.217[27,29,30]			0.343[15,16]	0.006[15,16]				
1956	4.0E− 4[33, 28, 29, 30]		0.001[27, 28, 29, 30]						1.2E− 03[11,14]	4.86E− 04[25]		
1958		0.793[27, 28, 31, 36]		2.152[27,29,30]			0.954[15,16]	0.005[15,16]				
1960		0.963[27, 28, 31, 36]		2.614[27,29,30]								
1961												
1962							1.373[15,16]	0.008[15,16]				
1963									0.061[11,14]			
1964												
1965		1.135[27, 28, 31, 36]		3.073[27,29,30,33]					0.159[11,14]	0.013[1]		
1966							2.746[15,16]	0.013[15,16]	0.281[11,14]			
1968		0.992[27, 28, 31, 36]		2.686[27,29,30,33]								
1970		0.961[27, 28, 31, 36]		2.601[27,29,30,33]					1.111[11,14]			
1971							2.746[15,16]	0.011[15,16]		0.075[1]		
1973		0.835[27, 28, 31, 36]		2.260[27,29,30,33]			10.727[15]	0.032[15,16]				
1974									1.627[11,14]			
1975	3.0E− 4[33, 28, 29, 30]	0.841[27, 28, 31, 36]	9.0E− 4[27,28,29,30]	2.275[27,29,30,33]			12.498[17]		2.848[11,14]			
1979												
1980		1.402[27, 28, 31, 36]		3.801[27,29,30,33]					6.509[11,14]			
1981											32.217[18]	
1983	3.0E− 4[27, 28, 29, 30]	1.335[27, 28, 31, 36]	9.0E− 4[27,28,29,30]	3.617[27,29,30,33]					22.146[11]			
1984								0.100[25]				
1985		1.196[27,28,31,36]		3.240[27,29,30,33]					22.782[11]	0.236[11]		
1986							36.614[17]			0.459[11]		
1987											329.900[19]	
1988	4.0E− 4[27,28,29,30]	1.074[27,28,31,36]	1.1E− 3[27,28,29,30]	2.910[27,29,30,33]					49.213[11]	1.595[11]		
1990		1.018[27,28,31,36]		2.758[27,29,30,33]					86.122[11]	1.763[1]	659.800[24]	
1991	4.0E− 4[27,28,29,30]		0.001[27,28,29,30]					0.156[25]		2.019[11]	659.800[24]	
1992							64.075[17]		118.110[11]	5.864[11]	659.800[24]	

(continued on next page)

Table A1 (*continued*)

Year	Handwriting		Printing		Punch card		Tape		Hard disk		Optical disk	
	Mbits/cc	Mbits/$	Mbits/cc	Mbits/$	Mbits/cc	Mbits/$	Mbits/cc	Mbits/$	Mbits/cc	Mbits/$	Mbits/cc	Mbits/$
1993									246.063[11]	7.824[1]	1154.650[24]	
1994								6.997[25]	369.095[11]		989.700[24]	
1995		0.901[27,28,31,36]		2.443[27,29,30,33]					615.159[11]	32.463[1]	1385.580[24]	
1996	4.0E− 4[27,28,29,30]		1.1E− 3[27,28,29,30]						1107.286[11]	17.217[11]	1649.500[24]	
1997								10.797[25]	1414.865[11]	65.900[11]	1649.500[24]	
1998								342.976[25]	4921.270[11]	206.299[1]	3167.040[24]	118.624[22]
1999		0.764[27,28,31,36]		2.072[27,29,30,33]			9153.562[17]		7381.902[11]	605.785[11]	3299.000[24]	
2000	4.0E− 4[27,28,29,30]		1.2E− 3[27,28,29,30]						12,303.174[11]	973.911[11]	6597.999[24]	876.520[22]
2001									34,448.886[11]		6597.999[24]	
2002	5.0E− 4[27,28,29,30]	0.720[27,28,31,36]	1.5E− 3[27,28,29,30]	1.952[27,29,30,33]			36,614.246[17]		44,291.430[11]	2854.493[11]	13,855.798[24]	951.498[22]
2003	7.0E− 4[27,28,29,30]	0.701[27,28,31,36]	0.002[27,28,29,30]	1.901[27,29,30,33]			61,023.744[17]	1138.561[25]	86,122.200[11]	5558.450[11]		
2004	1.5E− 3[27,28,29,30]	0.673[27,28,31,36]	0.004[27,28,29,30]	1.824[27,29,30,33]			93,001.628[33]	5155.834[33]	3290.556[35]	1269.841[34]	48,689.240[34]	1142.857[22]

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Table A2
Historical data of undersea cable in informatiobn Transportation

Year	Bandwidth kbps	Band per cost per length kbps/Million $/km	Name
1858	5.55556E− 05	0.000468078	Telegraph[4,5,8]
1866	0.001	0.008535898	Telegraph[4,5,7,8]
1874	0.088	–	Telegraph[4,5,10]
1880	0.325	39.49713542	Telegraph[4,5,6]
1928	0.373	–	Telephone[4,5]
1951	144	2270.617824	TAT1[2,4,5,13,14,15,18]
1959	144	5193.400858	TAT2[17,18,19]
1963	414	10,567.76241	TAT3[17,18,19]
1965	384	10,570.62614	TAT4[17,18,19]
1965	1.2	–	APARNET (Internet backbone)[20]
1969	50	–	APARNET (Internet backbone)[21]
1970	2160	49,910.24116	TAT5[17,18,19]
1975	64	–	APARNET (Internet backbone)[21]
1976	12,000	149,645.3688	TAT6[4,5,9,13,14,19]
1983	300,000	6,062,432.675	TAT7[1,4,5,9,13,14]
1986	56	–	APARNET (Internet backbone)[21]
1988	1540	–	T-1, NSFNET (Internet backbone)[22]
1988	560,000	7,284,500.202	TAT8[3,4,5.13,14,16]
1989	1,260,000	19,701,271.45	PTAT-1[16]
1992	45,000	–	T3,NSFNET (Internet backbone)[23]
1992	1,120,000	18,346,118.66	TAT9[12,13,14,16]
1992	1,120,000	21,725,475.71	TAT10[16]
1993	1,680,000	34,811,248.7	TAT11[16]
1994	145,000	–	Asynchronous transmission mode (Internet backbone)[20]
1994	1,680,000	49,101,556.32	Columbus-2[16]
1994	4,976,000	80,195,977.31	CANTAT-3[15]
1995	9,953,000	136,549,664.4	TAT-12[4,5,11,13,14,16]
1996	9,953,000	148,070,658.9	TAT 13[4,5,11,13,14,16]
1998	139,340,000	1,971,340,798	Atlantic crossing-1[16]
1998	59,718,000	1,163,138,165	Gemini[16]
1999	19,908,000	654,158,315	Columbus-3[16]
2000	155,000	–	OC-3c (Internet backbone)[24]
2000	1,273,984,000	8,555,095,412	Yellow/Atlantic crossing-2[16]
2001	1,910,976,000	23,846,945,541	360 Atlantic[16]
2001	2,388,720,000	25,620,289,257	FLAG Atlantic 1[4,5,9,16]
2001	636,928,000	6,405,148,833	TAT-14[16]
2001	2,547,968,000	27,176,122,256	TyCom Global Network-TransAtlantic[16]
2002	622,000	–	OC-12c (Internet backbone)[24]
2002	3,184,496,000	32,946,120,727	Apollo[4,5,9,16]
2003	2,500,000	–	OC-48c (Internet backbone)[24]
2004	9,500,000	–	OC-192c (Internet backbone)[24]

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Table A3
Historical data of computation speed and cost in information transformation

Date	MIPS	MIPS/Cost	Machine
1892	1.19E− 08	6.98E− 14	By_Hand[3]
1891	3.33E− 09	1.50E− 14	Ohdner[3]
1900	1.33E− 08	5.58E− 14	Steiger_Millionaire[3]
1908	1.85E− 08	2.34E− 14	Hollerith[3]
1910	3.77E− 07	2.44E− 14	Analytical_Engine[2,3]
1911	2.18E− 08	4.02E− 14	Monroe_Calculator[3]
1919	4.12E− 08	2.41E− 13	IBM_Tabulator[3]
1920	3.58E− 08	1.90E− 13	Torres_Arithmometer[3]
1928	7.38E− 08	5.38E− 13	National-Ellis_3000[3]
1929	7.38E− 08	5.40E− 13	Burroughs_Class_16[3]
1938	4.24E− 08	3.80E− 13	Zuse-1[3]
1939	4.24E− 07	3.77E− 12	Zuse-2[3]
1939	2.00E− 06	3.56E− 12	BTL_Model_1[3]
1941	2.04E− 06	3.91E− 12	Zuse-3[3]
1943	1.03E− 06	2.25E− 12	BTL_Model_2[3]
1943	2.24E− 04	2.44E− 10	Colossus[3]
1943	2.83E− 06	1.54E− 12	BTL_Model_3[3]
1944	2.33E− 06	8.66E− 13	ASCC_(Mark_1)[3]
1945	2.04E− 06	4.67E− 12	Zuse-3[3]
1946	3.29E− 06	8.44E− 13	BTL_Model_5[3]
1946	2.89E− 03	6.18E− 10	ENIAC[1,2,3,4]
1947	6.22E− 06	2.95E− 12	Harvard_Mark_2[1,2,3,4]
1948	5.97E− 04	1.79E− 10	IBM_SSEC[3]
1949	2.55E− 03	3.82E− 09	EDSAC[1,2,3,4]
1950	4.16E− 03	7.88E− 10	SEAC[3]

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Table A3 (*continued*)

Date	MIPS	MIPS/Cost	Machine
1951	5.75E− 03	1.00E− 09	UNIVAC_I[3]
1952	9.33E− 06	1.54E− 11	Zuse-5[3]
1952	1.76E− 03	2.91E− 09	IBM_CPC[3]
1953	9.66E− 04	8.08E− 10	IBM_650[1,2,3,4]
1954	1.70E− 03	5.74E− 10	EDVAC[1,2,3,4]
1955	6.94E− 02	5.96E− 08	Whirlwind[3]
1955	5.36E− 02	4.61E− 09	IBM_704[4]
1956	7.01E− 04	2.49E− 09	Librascope_LGP-30[3]
1959	0.326	2.07E− 08	IBM_7090[3]
1960	0.00103	9.93E− 10	IBM_1620[3]
1960	0.124	1.59E− 07	DEC_PDP-1[3]
1961	1.4	5.46E− 08	Atlas[3]
1962	0.0989	1.96E− 08	Burroughs_5000[3]
1963	0.063	2.25E− 08	IBM_7030[3]
1963	0.15	2.14E− 08	Honeywell_1800[3]
1964	0.169	1.14E− 07	DEC_PDP-6[3]
1964	8.76	3.55E− 07	CDC_6600[3]
1965	0.15	6.20E− 07	IBM_1130[3]
1966	2.54	1.08E− 07	IBM_360/75[3]
1967	1.24	9.05E− 08	IBM_360/65[3]
1968	0.655	2.99E− 07	DEC_PDP-10[3]
1969	25.7	6.16E− 07	CDC_7600[3]
1969	0.1175	3.71E− 06	DG_Nova[3]
1970	0.649	8.19E− 08	GE-635[3]
1971	0.105	2.78E− 07	SDS_920[3]
1972	17.3	5.98E− 07	IBM_360/195[3]
1972	0.075	1.73E− 06	Honeywell_700[3]
1973	0.36	1.24E− 05	Prime_Computer_100[3]
1974	8.88	1.41E− 06	IBM-370/168[3]
1974	0.01	6.37E− 06	MITS_Altair[3]
1975	0.47	3.27E− 06	DG_Eclipse[3]
1975	2.3	1.60E− 06	DEC-KL-10[3]
1976	0.4	9.83E− 07	DEC_PDP-11/70[3]
1976	150	5.53E− 06	Cray-1[3]
1977	0.02	6.03E− 06	Apple_II[3]
1977	1	1.96E− 06	DEC_VAX_11/780[3]
1977	0.04	7.84E− 06	TRS-80[3]
1977	0.06	1.57E− 05	Commodore_PET[3]
1978	7.5	6.29E− 06	CDC_IPL[3]
1979	2.1	3.18E− 06	Nanodata_VMX200[3]
1980	0.04	7.99E− 06	TRS-80_M3[3]
1980	0.484	1.65E− 05	Sun-1[3]
1981	73.2	4.41E− 06	CDC_Cyber-205[3]
1981	0.04	7.77E− 05	Vic_20[3]
1982	0.238	3.91E− 05	IBM_PC[3]
1982	0.741	2.13E− 05	Sun-2[3]
1982	0.2	2.30E− 04	Commodore_63[3]
1983	0.2	1.20E− 04	TRS-80_M3[3]
1983	0.799	9.55E− 06	Vax_11/750[3]
1984	0.52	1.29E− 04	Macintosh-128K[3]
1984	2.26	7.01E− 06	Vax_11/785[3]
1984	1187.5	–	VP-200/1[7]
1985	824	5.26E− 05	Cray-2[3]
1985	0.26	8.33E− 05	L.Edge_XT-7.16[3]
1985	0.165	1.24E− 04	Atari_800XL[3]
1985	1187.5	–	SX-2/1[7]
1986	2.05	1.34E− 04	Sun-3[3]

(continued on next page)

Table A3 (*continued*)

Date	MIPS	MIPS/Cost	Machine
1986	7.71	4.03E− 05	DEC_VAX_8650[3]
1986	0.534	6.97E− 04	MIT_XT-8[3]
1987	2.5	5.59E− 04	Mac_II[3]
1987	1.87	1.25E− 04	Sun-3[3]
1987	9250	–	CM-200/16k/512[7]
1989	25.5	3.67E− 04	Solbourne_5/500[3]
1989	7150		iPSC/860/128[7]
1990	12.5	2.83E− 03	Amiga_3000[3]
1991	25,000	3.22E− 03	SX-3/44/4[7,11]
1992	52,500	–	CM-5/256/256[7]
1993	408,750	–	Intel XD/S140[7]
1994	26.1	1.20E− 02	IBM_333/DX/Si[3]
1994	315,625	–	Cray/SGI T3DS-MP 150[7]
1995	317,750	–	Intel XP/S-MP 150/3072[7]
1996	300	7.83E− 02	Power_Tower_180e[3]
1996	920,500	–	Hitachi CP-PACS/2048/2048[7]
1997	3,345,000	–	Intel ASCI Red/9152[7]
1998	650	2.50E− 01	Mac_G3/333[3]
1998	2,228,750	5.04E− 02	Cray/SGI T3E1200/1084
1999	750	2.94E− 01	Pentium_II/355[3]
1999	820	3.36E− 01	Pentium_III/500[3]
1999	5,949,000		Intel ASCI Red/9632
2000	1500	1.03E− 01	Mac_G3/500_dual[3]
2000	12,345,000	3.93E− 01	ASCI White,SP Power3 375 MHz/8192[7,8]
2001	10,147,500	1.64E+02	Alpha Server SC ES45/1 GHz/3024[7,8]
2002	1000	5.97E− 01	iMac G3/700[3]
2002	89,650,000	2.52E− 01	Earth-Simulator/5120[7,9]
2003	9726	1.01E+ 01	Pentium IV 3.2G[5,6]
2003	25,700,000	–	1100 Dual 2.0 GHz Apple G5/Mellanox Infiniband 4X/Cisco GigE/2200[7]
2004	10,810	1.08E+ 01	Pentium IV 530[5,6]
2004	176,800,000	1.35E+ 01	IBM BlueGene/L[7,9,10]
2004	10,065	1.18E+ 02	Athlon63 3800[5,6]

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II. MIPS in a supercomputer was estimated from GFLOPS that is measured in maximal LINPACK (benchmarking) performance achieved. Pentium III 500 MHz Processor was used to estimate MIPS from GLOPS through the LINKPACK.

Table A4
Result of T test between various FPMs in functional categories

Comparison by FPMs	Comparison by periods	Storage			Transportation			Transformation		
		T	p	df	t	P	df	t	p	df
First FPM vs. second	Whole period	2.499	0.000	52	0.127	<0.05	58	3.304	0.000	109
(cost-constrained) FPM	1940 to present	0.245	<0.05	47	0.437	<0.05	50	2.374	0.000	81
First FPM vs. first FPM	Whole period vs. 1940 to present	2.400	0.000	55	5.856	0.000	55	3.029	0.000	81
Second FPM vs. second FPM	Whole period vs. 1940 to present	0.212	<0.05	44	5.562	0.000	53	3.076	0.000	109

The region where the significant difference does not exist.

Table A5
Result of T test between functional categories in each FPM

Comparison of functions	Comparison of FPMs	Whole period			1940–present		
		t	p	df	t	p	df
Storage vs. transportation	Mbits/cc vs. kbps	1.433	0.050	57	3.038	0.000	49
	Mbits/$ vs. kbps/km/$	3.460	0.000	51	2.023	0.000	46
Transportation vs. transformation	Kbps vs. MIPS	9.638	0.000	77	2.842	0.000	59
	kbps/km/$ vs. MIPS/$	6.399	0.000	90	1.466	0.050	72
Transformation vs. storage	MIPS vs. Mbits/cc	8.611	0.000	74	8.233	0.000	58
	MIPS/$ vs. Mbits/$	2.447	0.000	85	3.570	0.000	68

The region where the significant difference does not exist.

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