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Introduction to Topical Issue on Non-Impact Printing Technologies

In this paper, we present an overview of the technologies of importance in computer output printing, providing a background for the succeeding papers in this issue. IBM workers have played a key role in the evolution of computer printers from a few marginally reliable complex mechanisms to an industry which today counts annual sales of over ten billion dollars worldwide. Thus, in this necessarily brief description of the different technologies we mention those in which the IBM role was particularly noteworthy, with specific mention of machines which brought the technologies to the marketplace.

The evolution of computer printing technology

• *Introduction*

The following discussion is not intended to be an exhaustive review of computer printing technology. Rather, it highlights what we believe are the key technologies and milestones in its development. Other surveys (Refs. [1–4], for example) should be consulted for additional details.

• *Origins of impact printing*

Although some of the mechanisms now used in computer printers were invented about 125 years ago, roughly contemporaneous with the activities of Charles Babbage, the true birth of this technology can probably be traced to the years around World War I, and the development by IBM (and others) of the "Printing Tabulator." These movable-bar, parallel-printer mechanisms sufficed through the Second World War up to the introduction of the first true computers. Those computers and their successors of the early fifties were able to generate output data so quickly that the printers were unable to keep pace, whether they were serial "stick" teleprinters or typebar machines, or the much faster printers used in tabulators.

• *The first high-speed printer*

The recognition of this "I/O bottleneck" stimulated a wide range of activity in the area of new electromechanical devices, all with the objective of providing much faster and much more reliable printers to meet the demands of the new computers. One of these early printers was a parallel printer in which every print position was served by a wheel, on the rim of which was an engraved type font [5]. To print a character, the wheel was rotated to the desired position and then driven into a ribbon, marking the paper. Printers of that type were capable of speeds of the order of 600 lines per minute. However, although the IBM 407 Accounting Machine worked well at 150 lines per minute, at higher speeds the technology had some important limitations. In particular, the timing of the wheels was difficult to control, so that a horizontal line of printing tended to be excessively wavy. Moreover, the printers were not able to sustain the reliable performance that has since come to be expected of impact line printers.

• *Wire matrix printing*

Around 1950, another printer was invented in IBM, the "wire matrix printer," used first in the 026 key punch. In this type of printer, characters are built up on the paper from an array of dots; each dot is made by driving a wire (about 0.3 mm in diameter) into a ribbon. Later high-speed wire matrix printers, the 720 and 730 wire code-rod printers, had a 5×7 array of wires for each print position, and thus were able to print an entire line of characters in parallel—at speeds as fast as 1000 lines per minute. These machines were first delivered in 1955 with the 700-series computers [5]. This early technology has become one of the dominant serial printer technologies of the eighties, realized in most cases by moving a print head with one (or two) vertical columns of 5, 7, 9, 18, or 24 wires serially across the page, at speeds beyond 400 characters per second. A parallel configuration, a printer with 128 separate wires and their drivers, is exemplified by the 550-line-per-minute IBM 5225. In some printers of this type, high-quality copy, usually called "(near) letter quality," can be obtained by indexing the head or the paper (or both) a fraction of the wire spacing between printed dots.

• *Color impact printing*

One capability of wire matrix printing that was first capitalized on by IBM is its ability to print color graphics. By utilizing a ribbon with bands of different colors and a simple cam arrangement to move the ribbon vertically with respect to a print head, the IBM 3287 "Color Accent" printer became the first widely used, inexpensive color printer. This color capability is now widely available, using ribbons with either additive or subtractive dye combinations.

• *The print chain*

Wire matrix printers did not come close to solving the problem of the I/O bottleneck, in spite of their present success. What was needed was a really high-speed, reliable printer. The IBM 1403 was the first printer to meet the need, and it must still be recognized as one of the most successful peripheral devices, as well as technical innovations, in the history of computing [5, 6]. The key to the success of the 1403 was to separate the hammer from the type element, greatly simplifying the mechanism, while at the same time moving the individual type slugs past the stationary hammers horizontally, thus solving the vertical registration problem of prior wheel printers. The 1403N1 of 1964 replaced the "chain" with a train, and printed at 1100 lines per minute; the 3211, a 1970 follow-on, got the speed up to about 2000 lines per minute; later developments in this line represent today's leading impact line printing technology. These later models, such as the recently announced 3600-line-per-minute IBM 4248, the fastest impact printer in the industry, take advantage of an innovation exemplified by the Genicom ®Terminet printers, the placing of all the characters on a "single continuous element," which became an engraved (etched) metal character band which still moves past a stationary hammer bank, now at speeds approaching a mile a minute.

• *Single-element printers*

"Single-element" serial printers are an old concept; some of the oldest mechanical typewriters in the IBM collection have all the characters engraved on a cylinder, which is rotated and then, acting as the hammer, driven into the paper—usually pressing against a ribbon [7]. These Civil War era writing machines are direct antecedents of the stick printers mentioned above and, to a lesser extent, of the well-known ®SELECTRIC ball. The problem with stick printers is that, although they are reasonably fast (up to 40 characters per second), the quality of printing they form is not high by current standards, since the typefaces strike the paper at an angle and, in addition, the printing force depends on the location of the character on the stick.

• *The SELECTRIC ball*

The SELECTRIC, first shipped in 1961, solved the problem of nonuniform force by placing the characters on the surface of a sphere. The SELECTRIC mechanism not only produced print quality that is still the standard of excellence in the office, but it also enabled the user to choose from among a wide range of fonts which could be interchanged by the simple step of inserting a new ball [7]. Although limited to a speed of 15 characters per second, the SELECTRIC immediately became the dominant technology for electric typewriters, finding increasingly wide usage as a computer output printer and, as the application developed, as the printing mechanism for the first word processors (the IBM MTST and MCST) [8] and electronic typewriters.

• *Wheel printers*

In serial printing, as in parallel printing, innovation was followed by innovation. Another early mechanical typewriter displayed the font on the face of a disk which was rotated and then driven into a ribbon. The print mechanism used in the IBM 3610 Document Printer of 1974 adapted this disk to a 30-character-per-second output printer. In earlier models, the disk (again, acting as the hammer) was inked before being driven into the paper, but the ink roller and inked disk combination was more complex than it appeared, and a ribbon mechanism was reintroduced.

• *The daisy wheel*

Even with the innovation of an interposer between the hammer and the characters on the rigid disk, print quality and speed remained limited. Engineers at the Diablo Corporation, now a Xerox subsidiary, once again applied the concept of separating the hammer from the font-carrying element, with several further innovative steps. They split the wheel, so that each letter was at the end of a flexible finger, or "petal," and they used dc servomotors to position the carrier of the print mechanism and to rotate the "daisy wheel." (IBM's more recent offerings utilize dc stepper motors to achieve these functions.) This was a classic example of applying new concepts in electronics to improve mechanical devices, and it resulted in what is today virtually the only competitive technology for serial engraved printing; dozens of vendors now offer such printers. With burst speeds as high as 60 characters per second, an inexpensive reliable mechanism, and print quality approaching that of the SELECTRIC, the daisy wheel, with the band and the wire matrix, has become one of the dominant impact printing technologies of this decade.

• *Non-impact printing*

Impact printing has not been the only means for making marks on paper under electronic control. From the earliest days of electrical science, inventors have sought phenomena that could eliminate the ribbon, the impact, or both from the complex impact printing mechanisms [4]. Not surprisingly, Thomas Edison was one of these, and he invented an early electrochromic teleprinter, in which current flowing through a silver electrode in contact with paper wetted by an electrolyte caused the deposit on the paper of a small black silver dot. Other clever schemes followed, and the art of non-impact printing, as it came to be called, developed along two different paths. In one, as in Edison's approach, the paper itself was treated in some manner, thus replacing some of the printer mechanism by the physical or chemical mechanism built into the paper. An approach recently explored at IBM, called Molecular Matrix Printing, is a relatively direct descendant of the early Edison scheme, based as it is on an electrochromic chemical reaction [9]. The alternative to use of a treated paper is a non-impact technology which allows the use of (almost) any paper or surface, thus reducing the complexity (and cost) of the paper, albeit at the price of added complexity in the print head.

• *Electrographic printing*

One of the first special paper printing technologies to gain reasonably widespread use was known as electrographic printing. This used a paper with a multilayer structure, the top being a white pigmented conducting layer such as zinc oxide or titanium dioxide. Beneath this was a black layer, applied to the top surface of the paper (or other substrate). Current flowing through the top conducting layer vaporized it, leaving visible a dark spot. Thus, an image could be printed by passing an electrode (or array of electrodes) over the paper and pulsing current at selected spots. Limited by the roughness of the paper and the thickness of the coatings to relatively poor quality, compounded by the odor of the burning organic binder, this technology has practically disappeared today.

• *Electroerosion printing*

A lineal descendant, known as electroerosion printing, is still a contender for certain important applications, and is the printing technology used in the recently announced IBM 4250. In electroerosion printing, the top layer of the "paper" is a thin (tens of nm) aluminum layer, under which there is a black nonconducting lacquer layer. The aluminum can be very smooth, allowing extremely high definition spots; also, it has no need for a binder, so there is no odor. Finally, as Al is a very good conductor, the whole process is much faster and more efficient than its predecessor. The major drawback is that it has not been possible to make the aluminized layer "feel" like paper, or to have the white look of "plain" paper from all viewing angles. This is not a relevant concern for the 4250, however, since in that machine the output is used for "camera-ready copy" in publishing applications.

• *Thermal printing*

A much more pervasive special paper printing technology is thermal printing, which has found application both in quite "portable" terminals such as the TI "Silent 700" type terminal, in the IBM 3102 terminal printer, and in facsimile printers. Thermal printers use a paper in which there is a heat-induced chemical reaction; i.e., heat causes a dye to be formed and/or to become colored. Heat is provided by an array of solid state heating elements: semiconductors, thin-, or thick-film resistors. The heating elements are either in a vertical column (perhaps 9 elements high) which sweeps across the page; in a two-dimensional array (often 5×7 elements) which also sweeps across the paper, but which can print a character in the same time the vertical columnar array takes to print a column; or in a full-page-width horizontal array, which thus prints a full horizontal raster line in this time. The key speed limitation of these printers is the time needed for a heating element to cool down, of the order of milliseconds, so that printers in which a single array prints a line of characters in sequence are limited to maximum speeds of 50 to 100 characters per second. Additional limitations are imposed by the heat sensitivity of the paper, its cost, and its less than "bond" paper appearance.

• *Electrostatic printing*

Due to the relatively high cost of the the complex thermal paper, high-speed special paper printers use yet another technology, sometimes called electrostatic printing (as embodied in the IBM Scanmaster, the ®Versatec printers, and the Honeywell PPS family of printers). In these machines, an array of styli deposits charge on a dielectric-coated paper-like substrate (potentially on both sides); this charged latent image is then developed by a liquid or powder toner, similar to the process used in low-cost copiers. Paper web speeds of about 40 inches per second have been achieved in a system that has significantly less complexity than electrophotographic printers, discussed below—achieved, however, with the constraints of special paper.

• *Electrophotographic printing*

In contrast with these special paper printing technologies, each of which is limited to a relatively narrow application niche, printers based on the ubiquitous electrophotographic copying technology now are available at speeds of from eight pages per minute to about 250 pages per minute [4]. Developing a printer based on Chester Carlson's invention was a high-priority, and exceedingly challenging, problem almost from the first demonstration of it in a successful copier. The first to be marketed was the Xerox 1200, in which photographic images of the characters, mounted on a drum, were illuminated by an array of flash lamps and projected onto the photoconductor drum of a copier engine (then to be toned by a bath of black thermoplastic particles, transferred to paper, and fixed by heat).

• *Laser/electrophotographic printing*
The IBM 3800, announced in 1975, was a far more successful electrophotographic printer [10, 11]. Not only did it make use of a scanned laser beam to write the latent image on the photoconductor (which in the IBM machines has been one of a family of organic photoconductors), but it set a new standard for reliability at usage rates orders of magnitude higher than were required for office copiers. Since the introduction of the 3800, IBM and many other companies have been shipping similar machines in great numbers, including the IBM 6670, the first machine to combine copying and printing (although, at about 36 pages per minute, nearly an order of magnitude slower than the 3800). The current technical trends are reviewed in the paper by Lee et al. in this issue [12], and one specific development, flash fusing, is reviewed by Baumann [13]. Today, the range of applicability of electrophotographic printers (most of which use a laser, although some use linear arrays of LEDs, or fiber optic CRTs) extends to below ten pages per minute, with nearly 100 000 addressable spots per square inch on high-quality plain paper. Many of the machines can feed sheets, as distinct from fan-fold or roll, and print on both sides of the page (known as "duplex" printing). The 3800 Model 3, IBM's latest and most powerful such printer, is discussed in the papers of Miller [14], McMurtry et al. [15], Barrera and Strietzel [16], Crawford et al. [17], and Borch and Svendsen [18] in this issue.

• *Magnetic printing*
Well before IBM had successfully demonstrated a satisfactory electrophotographic printer, it had been working on an even older technology, magnetography. In this approach the latent image is written on a magnetic surface with a magnetic head (or an array of heads). This image is then developed with a magnetic toner, which is transferred to paper and fixed. In the early IBM models, which were delivered to a customer over 35 years ago, the ink was a liquid. With the striking advances in magnetic materials and transducers of the last two decades, magnetic printing has re-entered the arena, and several companies have announced products, while more have reported prototypes. With the capability of speeds of close to 200 pages per minute, and some process simplifications in comparison with electrophotography, magnetic printing is still a potentially promising alternative to today's technology [4].

• *Drop-on-demand ink jet printing*
Another technologically important non-impact printing technology to which IBM has made important contributions is ink jet printing, in which ink is forced from a small nozzle (or array of nozzles) under computer control, such that the dots of ink on the paper form a desired image. Two modes of operation have been practiced. In the first to be tried (and the one of most current interest), a droplet of ink is ejected only when a spot is desired—the propulsive force usually being provided by a piezoelectric element. The papers by Bogy and Talke [19] and by Fromm [20] report some new findings on the fluid dynamics of this process. In the last few years a number of companies have introduced printers of this type; although the quality of alphanumeric printing is not now comparable to SELECTRIC quality, it is quite good, and speeds of several hundred characters per second are feasible. In addition, feeding subsets of the nozzles with inks of different colors allows the potential for color printing of very good quality. The paper by Lee, Mills, and Talke describes an experimental high-quality color printer of this type [21].

• *Synchronous ink jet printing*
The other important mode of operation has been called synchronous ink jet printing. This type of printing, invented by Richard Sweet and first introduced into the marketplace by A. B. Dick, was, however, first developed to a state of high print quality and performance in the IBM 6640 [22]. This technology is based on a phenomenon of great interest to nineteenth century physics, the capillary jet. When ink is ejected from a nozzle under modest pressure, and the nozzle is coherently excited—for example, by a piezoelectric transducer at a frequency of 100 kHz—the emerging stream can be broken up into an extremely regular array of droplets at the exciting frequency. Selectively charging these droplets and passing them through a high-voltage deflection field results in a fluid ink analog of a cathode ray tube, allowing selective placement of droplets on paper; where no droplet is desired, the droplet is uncharged, and passes undeflected through the high-voltage electric field, to be caught for recirculation by a catcher, or gutter. The IBM 5258 (the latest version of the 6640) has a high-quality-mode speed of 92 characters per second, and a draft-mode speed of 184 characters per second. One experimental printer, utilizing an array of 240 nozzles and capable of printing ten times faster than the 6640, is described in the paper by Darling et al. [23].

• *Thermal transfer printing*
The last non-impact printing technology we mention here, known as thermal transfer printing, has only recently gained prominence. Combining a thermal print head with a ribbon, it allows a relatively low-cost, moderate-speed, good-quality printer using plain paper. In this class of printer, a standard thermal print head heats a reasonably standard film ribbon (which is in intimate contact with a relatively smooth paper or other surface). At a certain temperature, the ink softens and flows or "tacks" onto the paper, forming a black spot. Printers with serial speeds of 50 characters per second are readily achievable and, as in the older class of thermal printer, a full line array of heaters allows speeds of more than five pages per minute. IBM has for some time been carrying on

an advanced technology program in a related technology, referred to as resistive ribbon thermal transfer printing in the patent literature [24]. In this approach, the head provides only current to the ribbon; the current heats the ribbon locally because a finite, but small, resistance has been built into the top layer of a multilayer ribbon; beneath this is an aluminum ground plane, and the layer closest to the paper is a thermoplastic toner, as in pure thermal transfer printing.

Current trends

• *Color printing*

Even a casual observer of the printer scene is sure to notice some fundamentally important trends in the function recently announced printers are offering. Perhaps the most obvious is the growing importance of color, as the number of color display terminals grows. Thus far, although several of the non-impact printing methods have the potential to generate high-quality color, the most common implementation chosen for color is the wire matrix method, with drop-on-demand ink jets also being made available for that purpose. It seems inevitable that the role of color printing will accelerate greatly in the coming decade.

• *Quality printing*

The definition of "print quality" is subjective, although strongly correlated with quantifiable aspects of the printing such as contrast, resolution, and spot size. The paper by Crawford et al. in this issue offers a detailed discussion of the engineering considerations and measurements [17]. For our purposes here, however, a suitable non-quantitative scale of quality (beginning with the lowest) runs as follows: data processing quality, draft quality, near-letter quality, letter quality, correspondence quality, and (several gradations of) graphic arts quality. This scale does not take into account the dependence of the perceived quality on whether the printer is restricted to a particular type of paper, among other limitations.

Several important trends are at work here. In one, the capability of wire matrix printers to offer a combination of high-speed draft-mode printing and slower-speed near-letter quality has apparently led many users to accept alphanumeric quality which, although quite presentable, is clearly poorer than that obtainable with engraved type. On the other hand, the print quality that is being offered from non-impact printers using such technologies as ink jet and electrophotography is improving. Again, the quality is not up to that obtainable from engraved type with film ribbon, but it has gotten closer. In addition, in a few cases the quality achievable from "computer" printing technologies is even approaching the superior quality until recently only available from a photocomposer. Thus, the trend in print quality is toward excellence, but excellence detectably short of traditional engraved SELECTRIC quality. The desire for quality is particularly strong at the low end, where single printer work stations need to be able to handle some correspondence applications, and at the high end, where page printers generate forms and compete directly with offset printers.

• *Image printing*

Printing with fully formed characters is certainly not disappearing. However, the applications for which this type of high-quality printing is preferred—for either esthetic or economic reasons—have narrowed to essentially two: electronic typewriters or word processors, almost exclusively being offered by daisy wheel printing (as in the IBM Displaywriter), and higher-speed DP printers, almost exclusively being provided by engraved band printers. In these two applications (the traditional core of computer printing requirements), the long experience with the technology has resulted in low cost and reliable hardware. This, combined with the performance enhancements one gets from tabbing, skipping, and the ability to print carbon copies, has resulted in the continued price/performance superiority of printers based on these two approaches.

Virtually all other printers now available are image printers, capable of printing a dot almost anywhere on a page. This all-points-addressable capability has meshed extremely well with the explosive growth of personal computers, since many interesting personal computer applications require the display and printing of graphics. Similarly, the impact matrix printers, with their ability to print different fonts, electronically selectable (including the Chinese characters, kanji, also used in Japan), combined with their speed/quality tradeoff ability, have been found to be cost-effective in an increasing number of applications.

A complementary trend at the high end of printer function is the ability to print documents approaching the quality of books "on demand." This capability has opened many new applications to computer printing—not only the creation of camera-ready copy for many printing and publishing tasks but also the actual creation of the document or form itself, in a finished, up-to-date hard copy, readily correctable and with no need for hard inventory. Both the low-end and the high-end desire for image printing capability seem certain to grow, particularly as color printing matures and host system support for the more demanding jobs is developed.

• *Distributed printing*

Early printers were big, expensive and, after the introduction of the train, fast. These attributes combined to force the printer into the computer center with the central processing units and direct access storage devices (DASD) which were also big, expensive, and fast; economics dictated a large centralized computing facility. The remarkable improvements in the miniaturization of logic and memory components have been the driving force in spreading this computing power throughout an enterprise and, with the personal computer, throughout society. This has been greatly aided by a related, although far less striking, development in the storage density of DASD devices, as well as in the development of much smaller—and less expensive—hard and floppy disk drives suitable for use at an individual work station.

Printers, too, have moved out of the computer center. Today, in fact, it is often difficult to tell the difference between a computer terminal printer, a word processor—and a typewriter. As the power of such printers has grown, so, too, has the desire for an individual user to have a personal print station. Even the laser/electrophotographic printers have begun to play a major role in the distribution of printing, as machines that were first economical only at speeds of several pages per second are now offered at speeds less than ten pages per minute. Again, the vastly greater function of these non-impact image printers has been a key factor in their emergence as important elements in the printing hierarchy.

• *Low-noise printing*
Distributed printing would be difficult to accept if the printers were still noisy impact machines of the early sixties. However, the evolution of non-impact printers has practically eliminated noise as a concern in many important applications of printers. Where impact printing is still a cost-effective solution, technology has made possible effective, inexpensive sound-absorbing covers which, combined with better control of the impact noise to start with, allow one to sell an impact printer which is quiet enough to be placed in almost any workplace. Consequently, it seems unlikely that any future printing technology will be acceptable if it is noisy. It is to be expected that only printers in isolated computer centers will be acceptable if they are noisy, and such installations should be a declining portion of the total.

• *Reliability*
No overview of printers would be complete without mentioning reliability. Dramatic improvements have been made—not only in the failure rate of the basic mechanism, but also in total system availability and mean time to repair. The need to be cost-effective—with a quality product—would indicate that this trend will certainly continue. The important improvements have been achieved in great part through the introduction of low-cost electronics. Printers now have integrated diagnostics so the host system is no longer required to provide the diagnostic function. Pre-stored problem-solution routines further reduce downtime (the time needed to complete a service action) and increase the efficiency of service personnel. As electronics costs, especially those of microprocessors, continue to decline, the ability to distribute "intelligence" throughout the machine will lead to new and better ways to avoid failures and downtime.

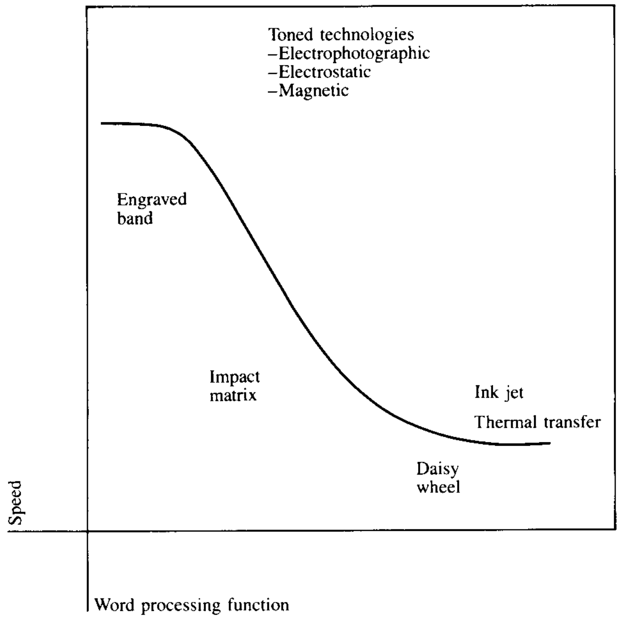

Figure 1 Relative speed and word processing function capabilities of various printing technologies.

Summary

There are many ways of trying to show how the various printing technologies and implementations relate to one another. Comparisons can be found with normalized parameters such as price per line per minute or characters per second plotted against speed. Another measure used is the total cost incurred. For example, the price of the printer, its supplies, and service costs can be normalized to a page of output (i.e., cents per page). The cost of the paper required by the printer to perform the job also must be considered.

We have selected speed (characters per second, lines per minute, or pages per minute) and "word processing function." Word processing function is print quality to a great degree, but also includes elements such as variable character pitch, cut sheet paper feed, and extended character sets. Although this is obviously a qualitative concept, it is surprisingly useful, and allows the comparison shown in **Figure 1** to be constructed. Non-impact printing, except for the daisy wheel and for some inroads by serial wire matrix printing in the low-speed arena, is well established in the higher-function, high-print-quality applications. Toned technologies, led by electrophotography, dominate the medium- and high-speed areas. A major area of interest and activity for the future will be at the lower speeds. Here, electrophotographic, ink jet, and thermal transfer approaches will vie with daisy wheel and impact matrix printing for dominance.

On a more global point, one can identify another challenge for non-impact printing technologies. This is to further improve in price/performance and/or total cost so as to match or surpass its more mature competitor, impact printing. This indeed is a challenge because impact technology cannot be expected to remain stagnant. Non-impact printing already enjoys some success in the overall high-speed end of the spectrum. Here its superior speed, print quality, and potential for savings in the cost of forms have enabled it to establish a significant presence.

Concluding comment

All the varied market pressures, combined with today's technical options, place us at an exciting time for output printing. The wealth of technical thought and achievements described in the following papers certainly attests to this point. Printing itself is more than a thousand years old, but computer printing is barely a tenth that age; modern printing technologies are younger still. Nevertheless, there is little question that there have been more innovations in printing in the past quarter century than in all the years prior to that (although it is doubtful whether any of these innovations can be compared with the inventions of movable type and the printing press in their importance to society). Our feeling is that technical innovation on this scale will continue, and that computer output printers in coming years will offer important improvements in nearly every functional area.

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