

A Lower-Cost Inkjet Printer Based on a New Printing Performance Architecture

The HP DeskJet 820C printer is the first HP inkjet printer in an evolutionary product plan that takes advantage of computer and operating system trends to make inkjet printing affordable for more users. The printer's integrated software, firmware, and digital electronics architecture uses the computational resources in the PC instead of duplicating these resources in the printer.

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The two Hewlett-Packard divisions in Vancouver, Washington are responsible for establishing and maintaining HP color inkjet printers as market leading personal products in the home and office computing environments. These divisions have a ten-year history of successful products starting with the original HP DeskJet printer in 1986 and culminating most recently with the introduction of the new HP DeskJet 820C (Fig. 1) in the spring of 1996.



Fig. 1. HP DeskJet 820C color inkjet printer.

Our competitors, of course, have also been introducing products, some of which incorporate newly developed technologies that strongly challenge the performance, print quality, and cost-effectiveness of our own. It is clear that our competitors are here for the long term, so we must develop long-term strategies to compete with them.

Aside from competition, we also have before us an excellent opportunity to broaden our printing solutions to embrace the needs of the entire family, a step well beyond the traditional "take work home" professional who has been our mainstay home customer. These new customers have distinctly different needs that will require insightful understanding as well as timely incorporation of focused innovations in our products.

At the beginning of the HP DeskJet 820C project, it was clear that our ability to retain and grow our market leadership depended heavily upon our ability to deal with these two powerful market dynamics. We knew that we had to simultaneously stay ahead of the competition and satisfy the rapidly increasing breadth of home printing needs. The ingredients for long-term success in this endeavor were equally clear:

- Technologies that result in continuously improving print throughput and quality
- Designs that earn adequate profits at reduced customer prices
- Designs that appeal to home customers by virtue of small size, attractive industrial designs, very quiet operation, and unparalleled ease of use
- Designs capable of high-volume production at multiple international factory sites
- The ability to design products to hit narrow market windows.

We realized that no single product program could successfully satisfy all of these criteria, so we needed to develop a phased approach. We decided that each new product development effort should leverage previous capabilities while incorporating a small set of new and innovative capabilities focused on our customer needs. These new capabilities would then be leveraged forward into succeeding efforts. In this fashion we could ensure a timely series of product introductions, each building upon previous successes and incrementally providing new capabilities that would ultimately satisfy all of our strategic initiatives. In addition to the market timeliness gained by a phased approach, we also knew that this plan would use scarce development resources in the most efficient manner.

Design Objectives

The HP DeskJet 820C printer is the first product in this evolutionary product plan. In keeping with our overall strategy, the primary objectives of the development program were to:

- Leverage the speed and print quality afforded by the new writing system developed for the HP DeskJet 850C
- Leverage the printing mechanism of the HP DeskJet 850C
- Innovate by offering this printing capability at a greatly reduced price for home customers
- Introduce in the spring of 1996.

While reduced cost and a spring 1996 introduction were clearly the primary objectives for the HP DeskJet 820C effort, we also decided to begin our journey towards consumer design by making industrial design changes that fit within the constraints of a leveraged mechanism and package.

Since we had decided to leverage the writing system, print mechanism, and package, we needed to examine the electronic, firmware, and software driver subsystems to find cost reduction opportunities. Based on our initial investigation we set a program goal to reduce direct material cost by 30%.

Design Approaches

Our first design tactic recognized two trends. First, newer generations of personal computers have more than enough bandwidth to take on some of the computing load that has until now resided in the printer itself. Second, software applications are rapidly moving away from MS-DOS[®] and into the Microsoft Windows[®] environment. In view of these trends, we decided that the HP DeskJet 820C printer would not support printing from standalone DOS applications. This enabled us to develop an integrated software, firmware, and digital electronics architecture that uses the computational resources in the PC instead of duplicating these resources in the printer. We call the architecture *Printing Performance Architecture*, or PPA. This architectural choice enabled us to achieve half of our 30% cost reduction goal by reducing RAM from 1M bytes to 128K bytes, ROM from 2M bytes to 64K bytes, and gate count in our largest ASIC by 25%. At the same time, higher-power PCs enabled us to maintain and in many cases improve system throughput.

A second critical design decision was to disallow simultaneous firing of the black and color print cartridges during a single print swath. While this strategy achieved an additional 20% of our overall goal, the obvious risk was a reduction in throughput for documents that contain juxtaposed black and color. However, we felt that our new system architecture would mitigate this risk and still allow us to meet our performance objectives. This single decision allowed us to simplify the drive electronics for the print cartridge to the point where they could be located on a small, carriage-mounted printed circuit assembly rather than on the main logic printed circuit assembly. This change, in turn, enabled two other very significant cost reductions. First, the interface between the logic and carriage printed circuit assemblies was dramatically simplified, allowing the use of standard and easily available cables and connectors rather than the custom designs that we had previously used. Second, using this new partitioning of analog functions, the design team was able to implement the required capability using two custom analog ASICs in contrast to the four that had been used in the DeskJet 850C.

An additional 10% of our cost goal was achieved by capitalizing on three cost saving opportunities in our power supply. First, the initial HP DeskJet 850 power supply was specified with significant margin to allow flexibility for the newly developed writing system in that product. However, the HP DeskJet 820C development team had the advantage of a stable writing system and therefore could specify power needs more precisely. Second, we modified the user interaction model with the printer's power functions and were able to eliminate some of the complex capabilities that were included in the HP DeskJet 850. Third, we specified our power supply at a very high level of abstraction to use the design expertise of our vendor base to deliver cost-optimal implementations.

Several sources contributed to the final 20% of our cost reduction goal. Our new system architecture and new partitioning of analog functionality allowed a significant reduction in the size of our printed circuit assemblies. Direct material cost savings were realized by elimination of the connectors and support components for interconnecting to Apple PCs. Focused design work to cost-optimize our EMI and ESD solutions eliminated many discrete electronic components.

As a result of our plan to leverage and our focus on limited but meaningful innovation, the HP DeskJet 820C was introduced to the market on schedule in the spring of 1996 following a development effort that exceeded objectives by achieving a 33% direct material cost reduction and actual performance nearly twice our initial expectations. The techniques responsible for this success have been carried forward and are already incorporated into the next products in our evolutionary process.

Printing Performance Architecture

The process of printing a document created on a computer involves several steps to transform and prepare the information. In the traditional Windows model used by inkjet printers, the printer driver software receives a description of the page from the application, transforms that description into a mechanism independent format that can be understood by the printer, and encodes it into a standard printer language. The encoded description is then transferred to the printer. The printer decodes the data and formats it for its particular printing mechanism. To encode the information for transfer to the printer, Hewlett-Packard developed a standard language called PCL (Printer Control Language). Because of the widespread use of HP printers, this language has become a de facto standard. PCL allows the computer to prepare an image for printing without detailed knowledge of the mechanical details of the printer.

For the Microsoft Windows environment, HP has always developed the software drivers for its inkjet printers. In the Windows model, the application sends a page description to the driver through the operating system. The description is in the form of drawing objects (lines, rectangles, text, etc.). The driver then rasterizes the description. Rasterization is the process of mapping the page description to an X-Y plane or bitmap. At this point, the data still must undergo several more transformations before it can be used to print. For example, the first bitmap may be 24-bit data at 300 dpi, whereas the inkjet mechanism may be 600 dpi and only able to put one of four colors at each pixel (black, cyan, magenta, yellow). Traditionally, the driver performed some of the needed transformations, but left many of the more compute-intensive ones to dedicated hardware and firmware in the printer.

After the driver has performed all of its computations, it encodes the information using the subset of PCL needed for bitmapped data. The printer in turn decodes the PCL and performs all of the necessary further computations to format the data for the printing mechanism. Manipulations the printer must perform include, but are not limited to, some color transformations, cutting the data into individual swaths, and separating the data into columns (inkjet cartridges are composed of two columns of staggered nozzles). This process is diagrammed in Fig. 2.

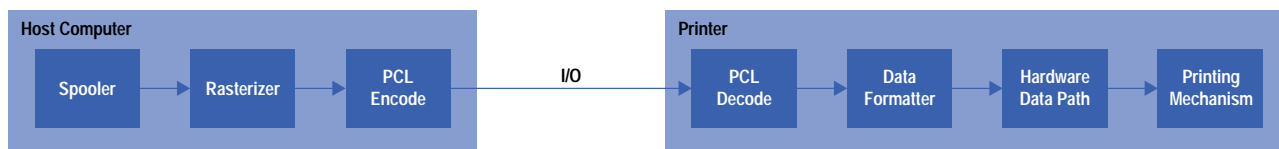


Fig. 2. Traditional PCL printing model.

The process in the MS-DOS environment is similar with two exceptions. One, the application must perform the rasterization for all graphics and PCL encoding, and two, the printer will accept nonrasterized text, alleviating the need for the application to do it. Because of this second difference, previous inkjet printers were required to have extensive memory-intensive fonts built into them. In addition, the printer had to contain firmware and hardware to rasterize the fonts. Since the data manipulations performed were extensive, they required a powerful microprocessor and significant amounts of dedicated hardware.

The concept of the new Printing Performance Architecture, or PPA, is to change this model by eliminating some of the steps. Because modern personal computers have powerful microprocessors and a large amount of system memory, the task of data formatting for the print mechanism is moved entirely to the host computer. Also, because the data is no longer in a PCL-compatible format, PCL is not used to transmit the data to the printer. Instead, a very simple proprietary protocol was developed. The protocol is simple enough that the hardware can automatically depacketize the data without help from the firmware. The data is then directly used to print the image on the page. This process is diagrammed in Fig. 3.

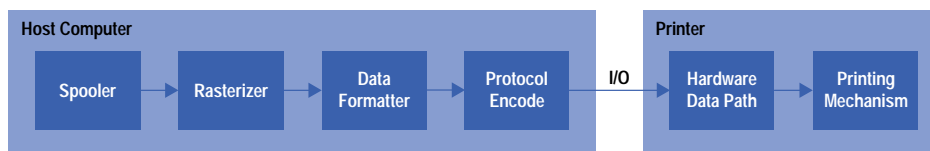


Fig. 3. New Printing Performance Architecture (PPA) printing model.

Advantages of PPA

The primary advantages of PPA are cost and performance. A PPA printer can deliver performance similar to a traditional non-PPA printer at a reduced cost. Alternatively, it can deliver higher levels of performance at a similar cost. The reasons for the cost advantage fall into two areas: less memory is required (both RAM and ROM), and a lower-performance microprocessor can be used in the printer because the microprocessor doesn't have to touch the data.

Memory costs are a significant portion of the material cost of a low-end printer. A PPA printer requires significantly less ROM and RAM. First, the PPA printer doesn't have to store any internal fonts. Traditional printers supported both the

Windows environment and the DOS environment. The printing model in the DOS environment requires the printer to store font information. A DOS application sends an ASCII code for the desired text character. To print that character, the printer needs a bitmap for that character in its ROM. In contrast, applications in the Windows environment send only bitmapped graphic information to the printer, never ASCII text. Because the PPA printer is designed exclusively for the Windows environment, it doesn't need to store the fonts in ROM.

Second, because the printer doesn't do any PCL decoding, swath cutting, or data formatting, the printer requires much less firmware, again saving ROM. The primary functions of the printer firmware are mechanism control, input/output, and the user interface. In the HP DeskJet 820C, the firmware is stored in only 64K bytes of ROM. Because there is so little, it was possible to integrate the ROM into the digital ASIC. Previous non-PPA printers of similar capability used 512K bytes or more of ROM.

Finally, because the processor doesn't touch the data and doesn't need to create any intermediate forms of the image data, the printer requires less RAM. The HP DeskJet 820C uses a 128K-byte DRAM. The previous generation, non-PPA printer used 512K to 1M bytes of RAM. Because there are fewer memory ICs, the memory cost for a PPA printer is much lower. The reduced number of memory devices also reduces the printed circuit board area, again saving cost.

The second factor in saving cost comes from the need for less microprocessor horsepower. In a PPA printer, the processor does not do swath cutting and formatting of the data. Its primary functions are mechanism control, input/output, and the user interface. This requires a less complex and consequently less expensive microprocessor. The HP DeskJet 820C uses a Motorola 68EC000. The 68EC000 can be configured with either an 8-bit or a 16-bit data bus. In the HP DeskJet 820C, the processor is used in 8-bit mode. This reduces the bus width in the digital custom ASIC, again saving area and hence cost.

Finally, because of the simplified data path in the printer (the data path is the path the data takes from the input/output port, through the ASIC, and out to the print cartridge), it was possible in the HP DeskJet 820C to design a data path in which the processor doesn't touch the image data. A dedicated hardware data path is always much faster, albeit less flexible, than a data path in which the processor must transform or handle the data. A full hardware data path is not limited to a PPA architecture, but is much easier to accomplish in a PPA printer because of the simplified data path.

Challenges of PPA

While PPA has some significant advantages, it also brings with it some challenges:

- DOS is supported only through Windows and not in a standalone environment.
- PPA hosts must be more powerful than hosts for an equivalent non-PPA printer.
- The printer driver requires detailed knowledge of the printing mechanism.
- PPA required a change in the development and manufacturing paradigm at the HP Vancouver Division.

The PPA architecture does not support printing in the traditional standalone DOS environment. In the Windows environment, all information sent to the printer is bitmapped graphics. The data is prepared under the control of a single, HP-designed and optimized printer driver. In the older DOS environment, application vendors write their own printer drivers. Applications send ASCII codes to the printer and expect the printer to use its own internal fonts to generate the bitmapped characters. The applications have no knowledge of the printing mechanism and hence are unable to do any swath cutting or data formatting.

The HP DeskJet 820C does support printing from a DOS application if the application is run under the Windows environment. Windows allows DOS-only applications to be run in a *DOS box*. Printing in this environment uses the standard Windows printing mechanism and hence the HP driver.

PPA printers require a higher-powered host than non-PPA printers to achieve comparable levels of performance. Because the job of swath cutting and data formatting is now done by the PC, more computing power is required. On the HP DeskJet 820C, acceptable levels of performance are achieved with a 66-MHz Intel486-based machine with 8M bytes of RAM.

PPA required a shift in the HP Vancouver Division's development and manufacturing paradigm. Having designed and built PCL-based printers for over 15 years, all of the division's tools and processes were centered around this type of printer. For instance, over the years the manufacturing and customer assurance organizations had developed many tools based around PCL printers for doing production tests and exercising the printer in environmental tests. None of these tools work with a PPA printer. Similarly, the firmware test organization had to revise its tests completely. Because the HP DeskJet 820C printer has only 64K bytes of ROM, extensive demo pages and self-test pages could no longer be included in the printer.

Because of the high level of integration and because the architecture follows the paradigm that "the processor doesn't touch the dots," it is difficult to observe the flow of data through the machine. This made debugging problems during development quite challenging. This problem was solved in several steps. First, the ASIC design team did extensive simulations. Second, the team used a hardware emulator to emulate the digital ASIC. This emulator had a mechanism that provided ports to internal nodes so that they could be observed with a logic analyzer. Finally, simple patterns were devised and sent through the architecture that simplified problems and made debugging possible.

Finally, in the PPA environment, the driver must have knowledge of the printing hardware. This makes the driver less universal and the job of leveraging the driver to future products more difficult. The driver was carefully organized and

modularized so the hardware dependent pieces can be changed while the underlying driver features can be leveraged into future products.

Inside the Printer

Inkjet printing is a complicated process that involves tying together several electromechanical subsystems that work together to create the printed page. All inkjet printers consist of these major subsystems regardless of the particular implementation used for each one. Fig. 4 shows the HP DeskJet 820C printer with its top cover removed and the major subsystems labeled.

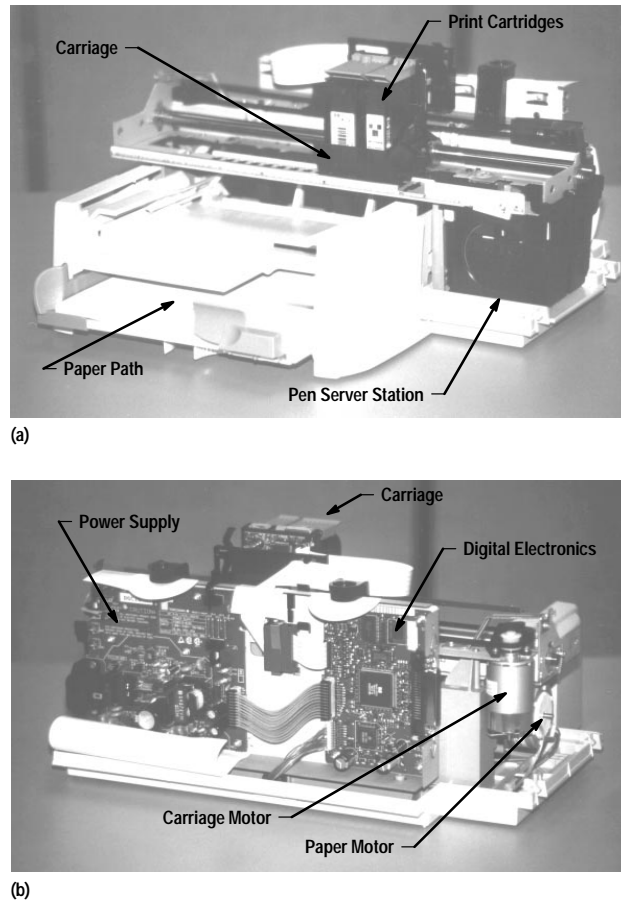


Fig. 4. HP DeskJet 820C printer subsystems.

Paper Path. The paper path is responsible for moving paper through the printer. The user inserts paper or envelopes into the input tray. At the appropriate time, a single piece of paper is picked from the stack and begins moving through the printer. Each time the carriage finishes a pass over the paper, the paper is advanced an appropriate amount to prepare for the next pass of the carriage. At the end of a page, the paper is “kicked,” or deposited in the output tray, where the user can remove it. In the HP DeskJet 820C, a single electric motor is used to move the paper. Paper movement is open-loop—there is no feedback about the actual paper position. The paper path in the HP DeskJet 820C gracefully handles a variety of paper sizes and thicknesses as well as envelopes.

Carriage. The carriage holds the pens used in the printer. To print a swath of data, the printer moves the carriage across the page at a constant speed, firing the pens at appropriate times. A single motor is used to move the carriage. Carriage movement is a closed-loop process. The carriage’s position is tracked using an LED, which shines on a photoreceptor and a strip of plastic made up of alternating light and dark regions placed between the LED and the photoreceptor. As the carriage moves across the page, logic recognizes when the LED is in front of a dark region and when it is in front of a transparent region. Using this information, it tracks the carriage’s position on the page. In addition to holding the pens, the carriage holds a printed circuit board. On the board are parts that connect electrically to the pens and a portion of the electronics needed to drive the pens. In the HP DeskJet 820C, all electronics directly used to fire the pens are located on the carriage board (see [Article 5](#)).

Print Cartridges. The print cartridges in the HP DeskJet 820C are user-replaceable cartridges that contain both the ink and the mechanism for placing the ink on the paper (thermal inkjet). They are often referred to simply as the “pens.” The pens are the same as those used in the HP DeskJet 850 and 870 printers. There are two pens: a black pen and a color pen. The black pen has 300 nozzles spaced at 1/600 inch. The swath height for black is therefore 1/2 inch. The color pen holds three colors of ink: cyan, magenta, and yellow. Each color is printed with a series of 64 nozzles spaced at 1/300 inch. The swath height is therefore approximately 1/5 inch. Colors other than cyan, magenta, and yellow are created by placing dots of these three colors in close proximity in appropriate ratios. Since at a distance of more than a few inches the resolution of the eye is not great enough to discern the individual dots, they blend together visually, forming the desired colors.

Pen Service Station. To maximize the life of the pens and to maintain optimum print quality over that life, it is necessary to service the pens. Servicing includes but is not limited to such actions as capping the pens when not printing so that they do not dry out and wiping them on occasion to prevent ink buildup. The service station includes all the electrical and mechanical parts necessary to perform the servicing actions. In particular, it includes a motor that is used to actuate actions such as wiping and capping. The motor is controlled by an open-loop process.

Power Supply. A power supply is needed to provide energy to the printer. The power supply accepts an ac signal from a standard outlet and converts it to the dc voltages and currents used to power the printer. Because the HP DeskJet 820C will be sold worldwide, it is capable of running on all permutations of 50/60Hz and 110/220V inputs found around the world.

Digital Electronics. The digital electronics are responsible for controlling all of the other electromechanical parts. The digital electronics generally include at least one of each of the following: a microprocessor, a ROM, a DRAM or SRAM or both, a block of custom logic, and an EEPROM. The microprocessor controls all mechanism movements, I/O, the user interface, and print data manipulation if necessary. The ROM holds firmware, and in previous products but not in the HP DeskJet 820C, fonts. The volatile memory is used to hold firmware variables and print data and commands that arrive over the I/O port. The custom logic implements printer-specific functions that require hardware support. The EEPROM holds information that must be retained through a power cycle. In the HP DeskJet 820C, the microprocessor, the ROM, the custom logic, and an SRAM are all integrated into a single ASIC (see [Article 3](#) and [Article 4](#)).

Case. The case is the part of the printer that the customer sees, so every effort is made to make it attractive. The case includes a small panel of LEDs and buttons by means of which the user interacts with the printer. The front panel of the HP DeskJet 820C is very simple, consisting of just two buttons and three LEDs. The case also has a door that can be lifted to gain access to the pens.

Driver. In addition to the physical part of the printer, all printer products require a software driver, which resides on the host computer. The driver allows applications software running on the PC to interact with the printer. In most modern operating systems, an application that wishes to print calls the printer driver through the operating system. This model allows the printer manufacturer to supply the driver, so application suppliers don't have to. The exception to this model is DOS, which requires the driver be integrated into the application. Because of the simplifications that can be made to the printer, the HP DeskJet 820C only works with Windows applications, or DOS applications running in a DOS box (see above and [Article 2](#)).

HP DeskJet 820C Printing Sequence

To begin the printing sequence, the user chooses Print from the appropriate menu in the application. The application formats the page into the standard description format used by the Windows operating system. Using this format, the application passes a description of the page to the printer driver. The driver reformats the page into a form appropriate for sending to the printer. In the process of reformatting the image, the driver performs various transformations to map the image to the inkjet printing technology. In previous HP inkjet printers, the format used to send data to the printer was PCL, a page description language. In the HP DeskJet 820C, the format is a bitmapped image that can be used to fire the printheads with minimal further transformations.

Once the image is in the right format, data is sent to the printer over the I/O cable. Before the data can be printed, the driver must send commands to the printer that tell it to prepare to print a page. When the driver sends these commands, the printer first uncaps the pens and services them to prepare them for printing. Then it picks a piece of paper and advances it to the first spot where printing will occur.

After the printer is prepared and has enough data in its local memory to print an entire swath, it performs a print sweep by moving the carriage across the page. As it moves the carriage, it pulls data out of its local memory, performs some final formatting, and uses the data to fire the printheads at appropriate times. After the sweep has been completed, the printer advances the paper, waits for enough data to print the next swath to arrive over the I/O, and then, upon command from the driver, prints the data. The process repeats for the rest of the page. At end of the page, again upon command from the driver, the printer kicks the paper, depositing it in the output tray. Assuming that there are no further pages to be printed, the printer then parks the carriage over the service station, caps the pens, and performs other cleanup pen servicing. The printer then waits patiently until the next time it is called upon to print.

Summary

The advance of personal computer horsepower and the uniformity of the Windows printing environment in which HP has control of the printer driver have made it possible to change from the PCL printer model to a PPA printer model. The customer benefit is that PPA printers can provide equivalent levels of performance at a much lower cost.

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